Reconstructing long-term woodland cover changes and their environmental legacy using Scottish estate plans (c.1740-1835) and GIS

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Abstract

Understanding long-term woodland dynamics is regarded as essential to investigating the legacy of past human actions and adequately conserving woodland habitats of higher ecological and cultural value. In Scotland, direct evidence of woodland extent and management is usually scarce and incomplete before the mid-nineteenth century First Edition Ordnance Survey maps (OS). For this PhD thesis, historical plans of private estates, underutilised in the UK, are proposed to fill this gap. Although each of these plans covers only a small area, they were drawn at large scale, permitting a detailed and accurate depiction of woodland prior to the First Edition OS.

This research collates 352 Scottish estate plans, dated c.1740 to c.1835, from both private and public collections. Hundreds of these plans are privately-owned and had been previously unavailable to researchers. A GIS-based method is implemented to integrate the spatial information of a large variety of historical plans into a homogenous database. The consistency in the depiction, accuracy and reliability of estate plans enables spatially explicit reconstructions of the woodland cover extent for two time series, namely T1 (1740-1799) and T2 (1801-1833). These reconstructions cover a total of 107,700 ha in Nithsdale and Annandale (Dumfries and Galloway) and can be compared with the First Edition OS maps (i.e. T3, c.1860) and modern data (i.e. T4, 2014). The uncertainties resulting from the challenges of working on a large variety of plans drawn by different mapmakers are also assessed. This assessment uses a conceptual framework that explores in a chronological manner the uncertainty arisen from the estate plans production to their practical use for research on woodland cover changes.

Quantitative analysis based on the reconstructions shows a marked and consistent growth in woodland cover during the eighteenth and nineteenth centuries. While the woodland covered about 3% of the study area in T1, it increased to 4.5% in T2, and to between 6.5 and 8.5% in T3. The lowest coverage in the study area occurred, at the latest, some time in the mid-eighteenth century with an upper estimate of 2.5% of woodland coverage. Although it is not possible to determine to what extent the trends observed in the study area apply to the rest of Scotland, this research casts doubt on the methods and assumptions that may have led previous research to overestimate the amount of past woodland cover for the whole Scotland.

Change detection analysis allowed mapping and quantification of where the woodland was new, lost or extant between two time series. Trajectory analysis enabled the tracking, mapping and categorising of the various historical trajectories of present-day broadleaved woodland since the eighteenth century. Along with the study of various woodland metrics, these spatial analyses underline how the present-day woodland cover has been progressively shaped by plantations and clearance at different spatio-temporal rates. In addition, a modelling approach using binary logistic regression allows a better understanding of past woodland distribution and changes in relation to landscape physical contexts such as slope steepness, elevation, soils and distance to the nearest streams. Hence, these models highlight changes in woodland plantation practices over time and space. Other historical sources, including the first and second Statistical Accounts of Scotland (1791-1845), offer a complementary insight into tree composition of past woodland cover, management practices and the reasons that encouraged planting woodland. These sources indicate how the temporal resolution of the mapping reconstruction may still underestimate the magnitude of past woodland changes.

Estate plans can also provide a rare insight into the history and ecology of the so-called 'ancient woodland sites'. Defined in Scotland as continuously wooded since c.1750, these sites have been compiled in the Scottish Ancient Woodland Inventory (AWI) using evidence from official historical mapping, namely the Roy map (c.1750) and First Edition OS mapping (c.1860). At present, ancient woodlands are recognised as areas of greater ecological and cultural value that deserve priority for UK woodland conservation. A comparison between the Scottish AWI and the woodland reconstructions in T1 and T2 indicates that the former is largely inaccurate. The amount of 'pseudo-ancient woodland' – of more recent origin than expected in the AWI – is estimated to reach at least 40% of the woodland compiled in the AWI. This discrepancy is discussed in the light of a new assessment of spatial accuracy of the Roy map and First Edition OS maps. In addition, the logistic regression models of past woodland cover can help distinguishing the pseudo-ancient woodland from the probable ancient woodland in the AWI.

Using evidence from estate plans, 41 native woodland sites of different continuity classes were selected for botanical survey. Although ancient woodland sites are likely to exhibit more species supposed to be 'indicators' of ancient woodland, several recent woodland sites are very similar in plant assemblage to those of ancient woodlands. The occurrence of many indicator species of ancient woodland in non-ancient woodland habitats indicates how rapidly these species can establish themselves in recent woodlands, helping to blur the distinction between woodland habitats of different continuities. While critically assessing the current criteria for defining ancient woodland and the applicability of those criteria to woodland conservation, this study suggests that, depending on the connectivity to ancient woodland, environmental conditions and history of woodland, relatively recent plantations (i.e. plantations made after c.1750) could deserve the same recognition as ancient woodland for conservation.

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Author’s Declaration

I declare that the work outlined and described in this thesis has been carried out by myself unless otherwise acknowledged. This thesis is completely my own composition and has not, in whole or part, been submitted for any other degree at this or any other university.

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Abbreviations

A.D.	Anno Domini
AIC	Akaike information criterion
ASNW	Ancient semi-natural woodland sites
AUC	Area under the (ROC) curve
AWI	Ancient Woodland Inventory
AWP	Ancient woodland indicator plant
c.	circa
CI	Confidence intervals
CP	Control point
DAMP	Dumfries Archival Mapping Project
DCA	Detrended correspondence analysis
DEM	Digital Elevation Model
DMF	Digital Medium Format
DSL	Dictionary of the Scots language
DSLR	Digital Single Lens Reflex
ENND	Euclidean nearest neighbor distance
ER	Earliest (mapping) record
GIS	Geographic Information System
LR	Logistic regression
NCC	Nature Conservancy Council
NFI	National Forest Inventory
NLS	National Library of Scotland
NRS	National Records of Scotland
NSA	New Statistical Account of Scotland
NWSS	Native Woodland Survey of Scotland
OR	Odds ratio
OS	Ordnance Survey
OSA	Old Statistical Account of Scotland
PAR	Perimeter-area ratio
PAWS	Plantations on Ancient Woodland Sites
ppi	pixels per inch
RHP	Register House Plans
RMSE	Root Mean Square Error

ROC	Receiver Operating Characteristics
SNH	Scottish Natural Heritage
SSSIs	Sites of Special Scientific Interest
T(1,2,3,4)	Time series (1, 2, 3, 4)

Chapter 1

Introduction

Europe's woodland has undergone major changes resulting from long-term and complex interactions with human activities. Deforestation, use and management of wood resources, tree plantation and introduction of non-native tree species have shaped the distribution and character of present-day woodland (Rackham, 1993; Hermy and Verheyen, 2007; Kirby and Watkins, 2015). A better understanding of the long-term changes is crucial to investigate woodlands' environmental legacy and to adequately conserve and manage existing valuable woodland (Foster et al., 2003; Holl and Smith, 2007; Davies, 2011; Szabó et al., 2017). Traditional ecological field methods alone cannot provide the depth of information needed to understand when and where the changes occurred, the form they took and how diverse woodlands develop.

For this PhD thesis, historical estate plans (c.1740-1835), hitherto underutilised in the UK, are proposed as a source to address this gap and supplement the corpus of historical maps generally used in Scotland. While providing detailed evidence of past woodland cover, these relatively old plans offer a valuable time perspective for reconstructing long-term woodland history and investigating the long-lasting implications of past changes. It is also assumed that evidence from estate plans can enhance our understanding of the history and ecology of the so-called 'ancient woodland sites', identified in Scotland as wooded without interruption since at least c.1750 (Kupiec, 1997) – ancient woodland sites have been recognised as areas of greater ecological and cultural value that deserve priority for UK woodland conservation (Goldberg et al., 2007; Houses of Parliament, 2014).

This opening chapter examines why estate plans offer a unique opportunity to supplement the more commonly used historical cartographic sources available in Scotland for reconstructing past woodland cover and changes. This chapter then introduces the notion of ancient woodland and discusses the potential of estate plans to critically assess this concept and its applicability to woodland conservation. The presentation of the main aims of this interdisciplinary research is followed by an introduction to the study area and an outline of the thesis content.

1.1 Using Scottish historical maps to investigate long-term woodland cover changes

Historical maps are valuable and unique in being able to provide spatially explicit evidence of landscape changes during recent centuries. In parallel, the development of Geographic Information Systems (GIS) has enhanced the possibility of spatial studies based on historical cartographic evidence and thereby opened new avenues for quantitative and qualitative studies of past woodland cover changes (e.g. Wulf et al., 2010; Skaloš et al., 2012; Kaim et al., 2014; De Keersmaeker et al., 2015). The integration of historical maps into GIS can thus help to link woodlands' current distribution and characteristics with their historical context.

The historical Scottish landscape was surveyed multiple times between the sixteenth and the nineteenth centuries. The accuracy of successive maps tended to increase as the surveying tools and techniques were improved. Timothy Pont (c. 1565-1614) drafted the earliest known detailed mapping of Scotland. His maps were compiled, revised, and completed during the seventeenth century, in particular by Robert Gordon of Straloch (1580-1661) (Stone, 1989; Fleet et al., 2011). The whole corpus of maps for Scotland was first published in the fifth volume of Joannes Blaeu's *Atlas Novus* (1654) (Fleet et al., 2011). Although the original manuscripts are today regarded as most valuable for historical studies (Fleet, 2000), the Pont maps present various inaccuracies, including the approximate extent and location of woodlands (Smout, 2001). These inaccuracies limit the potential of theses historical maps for investigating in detail past woodland cover changes.

In the course of the mid-eighteenth century, the Roy military survey of Scotland (1747-1755) – known as 'the Roy map'– was completed. Covering the entire Scottish mainland, this topographic survey was undertaken in the aftermath of the Jacobite rising of 1745 and became a prime source of information for historical studies of eighteenth century Scotland (Whittington and Gibson, 1986; Smout et al., 2005; Fleet et al., 2011). The Roy map has also acted as the basis for the 'Scottish Ancient Woodland Inventory' that compiles woodland sites that are believed to have been continuously wooded since at least c. 1750 (Kupiec, 1997; Goldberg et al., 2007).

The First Edition Ordnance-Survey (OS) of Scotland was carried out during the years 1843-1882. The 25-inch to the mile survey (1:2500) covers only a part of Scotland and was completed with the smaller scale 6-inch to the mile survey covering the whole of the country (1:10,560) (Oliver, 2013). In comparison with previous maps covering larger parts of Scotland, the First Edition OS maps show the boundaries of the woodland cover with greater detail. In addition, these maps are more informative concerning the name, structure and character of a wood (e.g. broadleaved, coniferous, mixed woodland and open woodland) (Harley, 1979).

In contrast with the First Edition OS maps, the potential of the Roy map for mapping of past woodland appears limited. This military survey was achieved with surveying instruments considered of lower accuracy (Whittington and Gibson, 1986) and it provides considerably less detail concerning woodland than does the First Edition OS maps. In addition, caution has been advised as ‘Roy’ has been proved unreliable in several instances (Whittington and Gibson, 1986; Smout et al., 2005; Fleet et al., 2011). According to Smout et al. (2005), only a fraction of the woodland would have been recorded by Roy’s surveyors.

The county maps – produced during the late eighteenth and early nineteenth centuries in most of the UK (Macnair et al., 2016) – are additional and valuable sources of information on past woodland cover. However, despite being probably more reliable than the Roy map, the county maps were drawn at a relatively small scale (i.e. one inch to one mile; 1:63,360) (Macnair et al., 2016). The woodland boundaries are depicted only roughly when compared to the First-Edition OS maps and little additional information is provided about the woodland cover. In sum, little is known with confidence about woodland cover’s global extent and changes before the time of the First Edition OS. By extension, the environmental legacy of relatively recent changes in the woodland cover and management practices has not been fully explored.

Historical estate plans can address this gap. In Scotland, estate plans were drawn mostly in the course of the eighteenth and nineteenth centuries (Adams, 1971). During this period, new agricultural practices, including improvement (e.g. liming, draining, and crop rotation) and enclosure of lands, led to major transformation in the Scottish landscape (Adams, 1971; Fleet et al., 2011). The long-standing forms of landscape inherited from medieval practices, such as infield-outfield – the division of arable lands according to their location and productivity, runrig – which controlled the periodic allocation of land to the tenants, and commonty – where common property rights applied, were progressively replaced by the grid-like pattern of rectangular enclosed lands (Adams, 1971; Turnock, 2005; Fleet et al., 2011). The so-called ‘Scottish agricultural revolution’ encouraged Scottish landowners to commission surveyors to map their estates, which led to the massive production of estate plans until the First Edition OS maps were published (Adams, 1971; Fleet et al., 2011).

Although each of these plans covers a small area, they were drawn at a larger scale and finer resolution which permitted a more detailed and accurate depiction of the woodland cover boundaries, closer to that of the First Edition OS maps. In addition, the *table of contents* regularly associated with these plans can provide unique and relevant information about various characteristics of the woodlands. Therefore, in contrast to the Roy map, estate plans provide a level of detail that can help reconstructing past woodland cover in order to better describe quantitative and qualitative changes in woodland since the eighteenth century.

While a large number of estate plans are needed for research projects that aim at investigating past changes at the landscape scale, many of these plans still belong to private owners. Their limited access certainly accounts for the paucity of UK studies that focus on estate plans. In order to address this issue, this project was undertaken in close collaboration with the community-led *Dumfries Archival Mapping Project* (DAMP). DAMP facilitated access to hundreds of privately-owned pre-OS estate plans that had been previously unavailable to researchers. These plans cover mostly the region of Nithsdale and Annandale in Dumfries and Galloway (South West Scotland).

As well as enhancing our understanding of Scottish woodland history, estate plans can contribute to strengthening the connections between ecology and landscape history. In so doing, these plans can relate the present-day characteristics of woodlands to the dynamic interactions with human actions that have shaped them through time.

1.2 Woodland's current context and the concept of 'ancient woodland'

In 1900, an estimated 5% of Scotland's land area was covered by woodland (Hopkins and Kirby, 2007); by 2006 this cover had increased to about 18% and current government policy aims to reach 25% by 2050 (Forestry Commission, 2009a; Thomas et al., 2015; Wilson et al., 2015). After centuries of decline – it is believed that between 50 and 60% of Scotland was once covered with woodland (Smout et al., 2005) – this change is mainly the result of commercial plantations of non-native conifers (Hopkins and Kirby, 2007). The total area of native woodland, where native species compose at least half of the canopy cover, remains low and is estimated to be just 4% (Forestry Commission Scotland, 2014). These fragmented woodlands also face several threats including clear-felling, excessive grazing, lack of management, exposure to edge effects, pests, invasion of exotic species such as *Rhododendron ponticum,* and climate change (Forestry Commission Scotland, 2009a; Wilson, 2015). Therefore, the preservation of extant fragments of native woodland and its expansion represent a priority for conservation planning (Davies, 2011; Wilson, 2015).

Conservation emphasis has been placed particularly on woodland with long and uninterrupted existence, namely the 'ancient woodland' (Goldberg et al., 2007). Following the work of Oliver Rackham and George Peterken in England in the 1970s, the concept of ancient woodland has sparked a growing interest in the UK and in many European countries (Goldberg et al., 2007; Hermy and Verheyen, 2007). The threshold date for defining woodland as 'ancient' varies between countries depending on the historical sources available (Goldberg et al., 2007; Hermy and Verheyen, 2007). For Scotland, the threshold is based on the date of the Roy map (i.e. c.1750) (Kupiec, 1997) – in comparison, the date of 1600 A.D has been retained in England, Wales and

Northern Ireland (Goldberg et al., 2007). Ancient woodland sites have experienced the long-term influence of human activities and have been increasingly recognised for their ecological and cultural heritage value (Rackham, 1993; Rotherham, 2011). Woodland continuity has been regarded as a key element in woodland ecology after it has been shown that woodlands with long continuity are more likely to provide ecological habitats to species rarely found elsewhere (Peterken, 1974; Hermy and Verheyen, 2007; Nordén et al., 2014). In Europe and North America, several studies suggest that plant communities in ancient forests can be distinct from those of recent forests and point out the possibility of using certain plant species as indicators of 'ancientness' (Rose, 1999; Sciama et al., 2009; Schmidt et al., 2014). Other research has highlighted the importance of woodland continuity in providing suitable habitats for rare or threatened species across bryophytes (e.g. Mölder et al., 2015), lichens (e.g. Fritz et al., 2008; Whittet and Ellis, 2013), invertebrates (e.g. Buse, 2012; Cateau et al., 2018) or mammals (Bright et al., 1994). For conservation goals, ancient woodland can also represent potential nuclei for future expansion to new areas of species associated with native woodland (Peterken, 2000; Gkaraveli et al., 2004; Watts, 2006).

The term 'ancient woodland' refers to woodland continuity independently of the tree composition and structure (Kupiec, 1997) but the UK Ancient Woodland Inventories further categorise ancient woodland sites into two broad categories, namely the Ancient Semi-Natural Woodland Sites (ASNW) and the Plantations on Ancient Woodland Sites (PAWS). The ASNW are composed of a majority of native trees and shrub species that originated from natural regeneration (self-sown or stump regrowth). At present, the ASNW is recognised as the most important for conservation of native woodland (Forestry Commission, 2014) and many ASNW sites have been designated as Sites of Special Scientific Interest (SSSIs) (Goldberg et al., 2007). The PAWS refer to ancient woodlands that were planted with a majority of non-native tree species for forestry. Over recent years, efforts have been made to restore some of these sites to native woodlands (Forestry Commission, 2003; Wilson, 2015).

Although there is no statutory protection for ancient woodland, the integration of ancient woodland's value is encouraged for UK planning decisions (Houses of Parliament, 2014). However, the UK Ancient Woodland Inventories have several important limits. Some ancient woodland sites are believed to have been overlooked and little is known about both the history and true ecological value of most of the sites compiled in the inventories (Goldberg et al., 2007). Another concern is that only sites greater than 2 ha have initially been recorded, while smaller sites can also display valuable ancient woodland features (Goldberg et al., 2007). In Scotland, despite some doubts surrounding the reliability of the Roy map (Whittington and Gibson, 1986; Smout et al., 2005), it does not seem that a critical assessment of the Scottish Ancient Woodland Inventory has ever been made. Moreover, despite various supposed ecological benefits, the concept of ancient woodland remains controversial as recent research has questioned the recognition and definition of ancient woodland as a distinct ecological category (e.g. Nordén and Appelqvist, 2001; Rolstad et al., 2002; Rotherham, 2011; Stone and Williamson, 2013; Barnes and Williamson, 2015).

While providing a better understanding of ancient woodland's history (both ASNW and PAWS), estate plans can help in assessing the Scottish Ancient Woodland Inventory's accuracy and reliability and, therefore, the current method of compilation of ancient woodland sites. These plans can also assist with the identification of case study sites for field surveys that aim to test the importance of woodland continuity on woodland's ecological characteristics and value. Consequently, estate plans can help to critically assess the concept of ancient woodland and its applicability to woodland conservation in Scotland.

1.3 National inventories of woodland cover

The National Forest Inventory (NFI) and the Native Woodland Survey of Scotland (NWSS) are woodland inventories that are used in this thesis as modern references for investigating the history of present day woodland since the eighteenth century. Both inventories include woodland sites over 0.5 ha in area, 20 m width and with a minimum of 20% canopy cover – the NFI uses the terms 'woodland' and 'forest' interchangeably (Forestry Commission, 2011, 2013). The inventories are freely available online as shapefile data for GIS and can serve for comparison with georeferenced reconstructions of past woodland cover based on historical maps.

The NFI is based on aerial photographs, and satellite imagery, and was completed with a field survey of a sample of woodlands (Forestry Commission, 2011). The woodland data categories comprise broadleaved (i.e. at least 80% of broadleaved species), conifer (i.e. at least 80% of conifer species), mixed mainly broadleaved (i.e. between 50 and 80% of broadleaved species) and mixed conifer (i.e. between 50 and 80% of conifer species). In addition, the inventory includes sites with the potential to meet the criteria mentioned above for size, width and canopy cover. These sites include 'ground prepared for planting', 'felled', 'windthrow', 'young trees', and 'assumed woodland'. The latter compiles woodlands under grant schemes, known as having been planted, but not yet visible on aerial photography (Forestry Commission, 2011).

The NWSS is a prime source of information on the Scottish native woodlands. Native woodlands are categorised into different habitat types depending on their location and composition, namely upland birchwoods, native pinewoods, wet woodland, lowland mixed deciduous woodland, upland oakwood, and upland mixed ashwood (the details of each category are available in *Scotland's Native Woodlands*; Forestry Commission, 2014). Nearly-native woodlands (i.e. between 40% and 50% of native species compose the canopy) and PAWS are also included in the NWSS. All the sites listed in the NWSS – and thus all the ancient woodlands – were mapped and surveyed, thereby providing important information on their ecological characteristics, including dominant habitat, maturity of the woodland, level of grazing pressure, and presence of invasive species (Forestry Commission, 2014).

1.4 Thesis aims

Using estate plans and GIS, the first aim of this research is to reconstruct historical woodland cover in the study area at different time periods from the second half of the eighteenth century onwards. The second aim is to characterise the long-term changes in woodland and assess their legacy on the distribution and characteristics of present-day woodland. The third and final aim is to critically assess the criteria to define ancient woodland as a distinct ecological category and to discuss implications for conservation planning. While focusing mostly on Nithsdale and Annandale, it is expected that the method to study estate plans can be applied outside the study area and thus provides a new approach to investigating Scottish woodland history and the environmental legacy of past changes.

Specific objectives are to:

1. Develop a GIS-based methodology to reconstruct past woodland cover at different time periods using the spatial information of a large variety of estate plans;

2. Assess the uncertainties associated with the above process and their implications in the study of past woodland cover changes;

3. Characterise the spatio-temporal changes of the woodland cover, in particular between the mid-eighteenth and mid-nineteenth centuries, a period for which there is a paucity of information;

4. Assess the spatial imprint of changes over the last 200-250 years on present-day woodland cover;

5. Identify what processes, driving forces and ‘actors’ may have accounted for these past changes;

6. Assess the accuracy and overall reliability of the Scottish Ancient Woodland Inventory and, by extension, the Roy map and First Edition OS survey that were used for the compilation of ancient woodland sites; and

7. Test in the field the assumption that ancient woodland sites are more likely to have a higher ecological value and should form a distinct ecological category.

Several studies combining the use of historical maps and GIS helped to develop and to implement the various methodologies applied in this thesis. Presented in the relevant chapters, these examples involve: the assessment of historical maps' accuracy and reliability (e.g. Leyk et al., 2005; Kaim et al., 2014); the study of quantitative changes in past woodland cover (e.g. Wulf et al., 2010); the characterisation of the changes in the spatial patterns of woodland cover (e.g. De Keersmaeker et al., 2015); the mapping of historical trajectories of each woodland site (e.g. Swetnam, 2007; Käyhkö and Skånes, 2008); and the use of a modelling approach to identify past driving forces (e.g. Loran et al., 2017). Historical maps were used in conjunction with other data sources, including other written archives, Digital Elevation Models, aerial photographs and botanical data collected in the field for this study.

1.5 Introduction to the study area

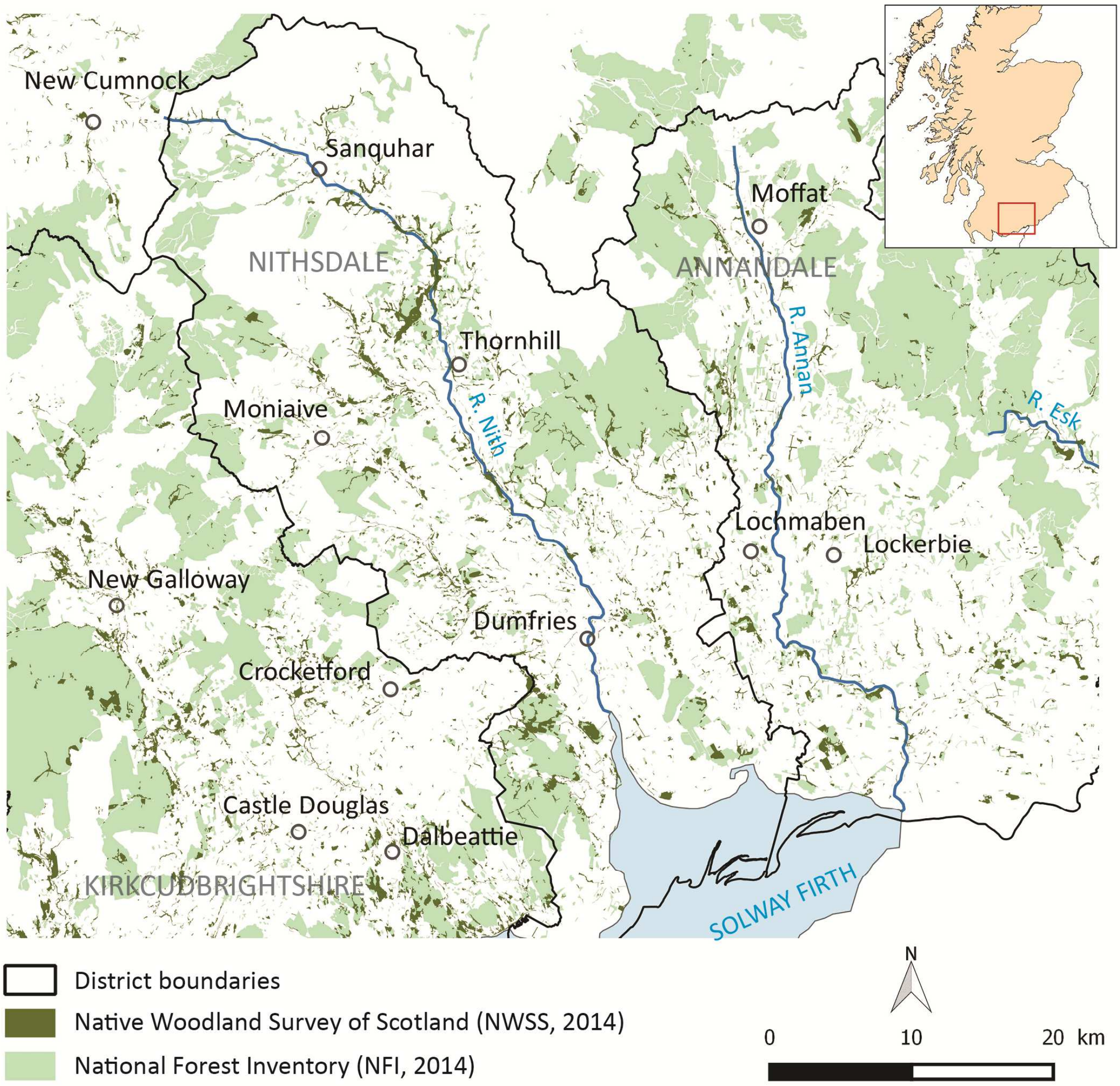


Figure 1.1 Location of the study area and woodland cover in 2014. See section 1.3 for the details of the woodland listed in the NWSS and NFI. Note that the exact boundaries and size of the study area are provided in Chapter 2 after the georeferencing of the estate plans. © Local Government Boundary Commission for Scotland. Contains Ordnance Survey data © Crown copyright and database rights 2013.

The opportunity to have access to a large collection of privately-owned estate plans, made possible by the Dumfries Archival Mapping Project (DAMP), has determined the location of the study area. Estate plans used for this study cover mostly Nithsdale and the west part of Annandale in South West Scotland, while a few plans also cover the east part of the historic county of Kirkcudbrightshire. Figure 1.1 shows the general location of the study area. Its exact boundaries are presented in Chapter 2 after the georeferencing of the estate plans that could be collated for this study. Nithsdale and Annandale are former districts of the county of Dumfriesshire and border the

Solway Firth to the south. The whole study area is now part of the council area of Dumfries and Galloway.

The River Nith, the River Annan and the River Esk form three major valleys that divide Dumfriesshire from north to south. At 821 m above sea level, the highest summit of the region is White Coomb, which is located about 10 miles north-east of Moffat. The bedrock geology is largely dominated by sedimentary Ordovician and Silurian formations (greywacke sandstones and siltstone). There are also Carboniferous rocks near Sanquhar, some large areas of Permian red sandstone around Dumfries, Thornhill, Lochmaben and Moffat, and a large Devonian granite intrusion around Dalbeattie. Glacial or marine sand and gravel, till - diamicton, alluvium and peat – form most of the superficial geology from the Quaternary period (British Geological Survey, 2018). In general, the soils are said to be low to moderately fertile with some shallow infertile areas associated with the granite intrusion (Wilson, 2015). Maps of soil and elevation for the study area are provided in Chapter 3.

The climate is temperate; the annual average minimum temperature is 4 – 6 °C and the annual average maximum temperature is 11 – 13 °C; the annual rainfall is 1121 – 1742 mm (Met Office, data from the climate stations of Dumfries and Eskdalemuir for the period 1981-2010). Dumfries and Galloway is windy and strong storms have been recorded in the region over the last 200 years (Davies, 1982).

Woodland covers about 31% of Dumfries and Galloway, which is one of the highest coverages in Scotland. As in the rest of the country, woodland cover in Dumfries and Galloway is dominated by non-native species including commercial plantations of conifers (Dumfries and Galloway Council, 2014). Native woodland represents 9.4% of the total woodland cover and 2.6% of the lands of the region (Forestry Commission, 2013). Wet woodland, upland birchwoods, and lowland mixed deciduous form the three main types of native woodland (Forestry Commission, 2013). It is noteworthy that, in contrast to northern Scotland, pinewoods are not native in southern Scotland (Wilson, 2015). The occurrence of Scots pines (*Pinus sylvestris*) in the study area is therefore an indication of plantation. Although regularly found in Scottish woodlands, beech (*Fagus sylvatica*), sycamore (*Acer pseudoplatanus*) and sweet chestnut (*Castanea sativa*), are broadleaved species that are also recognised as introduced (Wilson, 2015).

1.6 Thesis content

This thesis comprises three related pieces of research to address the objectives stated above (section 1.3).

Chapter 2 – Reconstructing past woodland cover from historical estate plans and First Edition Ordnance Survey maps

Historical plans of private estates, produced by contracted surveyors, provide rich but underutilised evidence of the long-term changes in woodland cover. Each one of these plans represents a small area but, put together, they offer a new insight into past management and changes in woodland distribution over time. The development of GIS tools has been a considerable improvement to collate and interrogate spatial information of historical maps. Chapter 2 presents a GIS-based methodology to reconstruct past woodland cover at different time periods using estate plans and First Edition Ordnance Survey maps. Three case studies serve to illustrate the results of the reconstruction: the Dukedom of Drumlanrig; Dalswinton estates; and Annandale estates. Inherent issues relating to the accuracy of estate plans are discussed as well as uncertainties resulting from the challenges of working on a large variety of plans drawn by different mapmakers.

Chapter 3 – Spatio-temporal woodland cover changes and their drivers since the mid-eighteenth century

Based on the reconstruction of past woodland-cover at different time periods (1740-1799, 1801-1833, and c.1860), this chapter aims to characterise the long-term spatial and temporal woodland cover changes in the study area. The analyses implemented for this chapter are as follows: 1) the landscape indices and change detection analysis are used to track past changes between each time series and to explore the progressive emergence of present-day woodland-cover patterns; 2) a trajectory analysis focusing on the broadleaved woodland sites of 2014 assesses the woodland continuity of these sites since the eighteenth century. This study also aims to provide further information about the planimetric accuracy of the woodland reconstruction; and 3) a series of spatially explicit models using logistic regression methods based on multiple data sources – DEM-derived variables, soil and water network maps, and archaeological data – investigate the processes and potential driving forces behind past woodland changes. The results are discussed in light of other historical sources: the first and second Statistical Accounts of Scotland (1791-1845) and the writings by other eighteenth and nineteenth century authors. These archives provide additional information on the historical tree composition of woodland, drivers responsible for the changes, and how the temporal resolution of the mapping reconstruction may underestimate the magnitude of past woodland changes.

Chapter 4 – Testing woodland continuity: A cartographic assessment of the Ancient Woodland Inventory and ecological implications

Woodland continuity has been recognised as determinant in woodland ecology. Ancient woodland sites are assumed to be of higher ecological and cultural value and have been the subject of provisional inventories in the UK since the 1980s. The Scottish Ancient Woodland Inventory is based on historical cartographic sources, namely the Roy map and the First Edition OS maps. Using past woodland cover reconstructions from estate plans, the first objective of this chapter is to provide a critical assessment of the Scottish Ancient Woodland Inventory's overall accuracy and reliability. By extension, this study assesses the potential of the Roy map to identify ancient woodland sites. The logistic regression models developed in Chapter 3 are also tested to determine whether these models can be used to identify errors in the inventory. Based on the plant surveys of 41 woodland sites in the study area, the second objective of this chapter is to test the assumption that ancient woodlands are more likely to have a higher ecological value and thereby should form a distinct ecological category. Ultimately, using the findings from the cartographic study and fieldwork, this chapter aims to critically assess the current criteria to define ancient woodland and to discuss implications of the results for woodland conservation planning.

Chapters 3 and 4 are based on the historical woodland cover reconstructions presented in Chapter 2, while Chapter 4 also makes use of the various findings discussed in Chapter 3. Chapter 5 summarises the findings of this PhD submission along with the propositions of avenues for future research.

Chapter 2

Reconstructing past woodland cover from historical estate plans and First Edition Ordnance Survey maps

2.1 Introduction

2.1.1 Surveying an estate and instrumentation

Bendall defines *estate* as an entity that belongs to a single owner and represents a continuous area of land or land in one parish (Bendall, 1992, p.28). In the context of the so-called ‘Scottish Agricultural Revolution’, during the eighteenth and nineteenth century, estates were more surveyed than ever before (Adams, 1971; Fleet et al., 2011). Contracted surveyors were commissioned primarily to produce plans of estates that the landowners could use for various purposes such as designing improved lands and enclosure, implementing new agricultural techniques and assisting with estate management (Adams, 1971). In that regard, Joseph Udny (ca 1770-1828), a surveyor who drew several plans studied for this research, wrote: ‘The chief benefit of a plan is to point out the defects and to enable one to remedy them’ (in Adams, 1971, p.27). As such, these plans were considered as valuable tools and it happened regularly that estates were mapped several times within a few decades, representing lands before and after major changes.

Other common reasons for a landowner to commission estate maps were renewal of leases and decisions on new rents after productivity improvement (Adams, 1971; O’Cionnaith, 2011), settlement changes, or lands to be exchanged, sold or inherited (Adams, 1971; Bendall, 1992). A plan could also be commissioned for its decorative value and to demonstrate the important social status and authority of its owner (Bendall, 1992). As Bendall (1992) has also noted, members of the aristocracy like Dukes and Earls, being landowners of considerably larger areas, doubtless had the most estate plans drawn. Occasionally, surveyors were also commissioned by the Court of Sessions to solve legal disputes – for instance, boundaries of ownership or water rights – and division of lands, notably in the case of commons (Bendall, 1992; Adams, 1971; Fleet et al., 2011).

Chains for measuring distances, the surveyor’s compass – also called circumferentor – to read horizontal angles, and plane tables to draw plans on level surface, composed the instrumentation of most of the eighteenth and early nineteenth century surveyors (O’Cionnaith, 2011; Macnair et al., 2016; Bendall, 1992). In addition, after significant improvement by Jonathan Sisson in 1737 and Jesse Ramsden later on, the theodolite was increasingly used throughout the eighteenth century (Ainslie, 1812; Macnair et al., 2016). One of the main advantages of the theodolite over the circumferentor lies in the fact that it is free from errors induced by magnetic variations (O'Cionnaith, 2011). Another asset was the possibility to measure simultaneously horizontal and vertical angles and, with triangulation, to calculate distances. This made the theodolite a more reliable and accurate instrument, which was of particular interest to survey large area (Ainslie, 1812; O'Cionnaith, 2011). Additionally to bringing considerable technical improvements, the theodolite had a significant advantage over the plane table when the weather conditions were too wet or too windy to lay paper sheets on a level table and draft the plan on site (Ainslie, 1812; Bendall, 1992; O'Cionnaith, 2011).

As the theodolite's accuracy improved, it seems that this instrument slowly but ultimately replaced circumferentor and plane table during the eighteenth and early nineteenth century (O'Cionnaith, 2011). Unfortunately, even though it might have influenced the spatial accuracy of the plans, it remains difficult to know how often the surveyors used a theodolite in the set of maps studied for this thesis. However, some evidence can occasionally be found. On a plan dated 1756 depicting mineshafts in the industrial landscape of Wanlockhead – about eight miles north-east from Sanquhar –, James Wells wrote:

> In surveying the several burns which run into Wanlock, the perpendicular Heights from Wanlock were taken each station by the sextant of the theodolite and are expressed in feet by the Numbers placed alongst the course of the said burns [Plan of Wanlockhead, 1756, RHP37555].

James Wells was one of the busiest surveyors operating in Nithsdale during the eighteenth century, suggesting that a model of the theodolite was already in use by 1756 in the region. It is therefore likely that other surveys by Wells and his contemporaries were undertaken with a theodolite.

2.1.2 Why use historical estate plans for landscape reconstruction

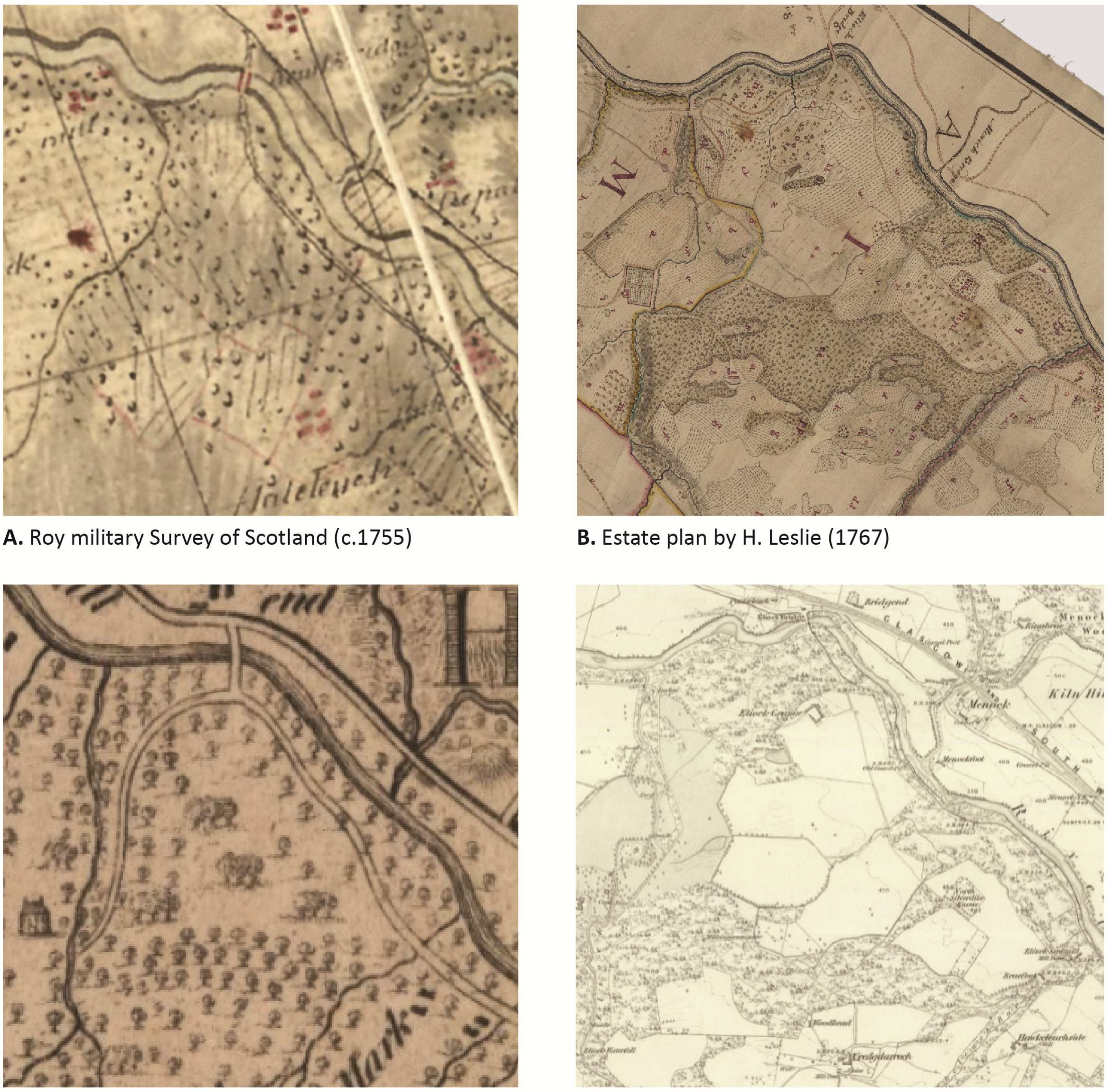
With the emergence of Geographic Information Systems (GIS), historical maps have been increasingly used for studying landscape change (e.g. Cousins, 2001; Petit and Lambin, 2002; Skaloš et al., 2011; Biro et al., 2013). However, there is a paucity of UK studies that focused on historical estate plans to investigate environmental changes at regional scale. Although underutilised, these plans appear unique for landscape reconstructions.

Firstly, in contrast with other pre-Ordnance-Survey maps covering large areas of Scotland – the Roy Military Survey of Scotland (1752-1755) and the Scottish county maps (see Chapter 1) – the relatively small portion of land covered by estate plans often represent a prime source of information in depicting past landscapes with a unique level of topographic detail (i.e. positioning of objects) and spatial accuracy (Figure 2.1). Farm buildings, houses, gardens, arable lands, moor, meadow, pasture, trees and woodland, rivers and streams were amongst the most commonly depicted features, and their boundaries were often finely delineated. Each plan can also provide further information related to the plan's commission, such as the location of mines and quarries.

Secondly, estate plans were usually produced with a *table of contents* that provide explanations of the symbols, acreage and tenurial conditions, as well as, most importantly for this research, additional information related to the land-use/land-cover (Fleet et al., 2011). Regarding woodlands, estate plans occasionally mention whether a wood is a plantation, sometimes the date it was planted, and they provide various evidence of past management such as coppicing – periodic cutting of trees to stump in order to encourage regrowth of poles, and wood pasture – often referring to open woodland with grazing livestock (Smout et al., 2005). For Dumfries and Galloway, as for most of the UK, this pre-Ordnance Survey cartographic information is exclusive to estate plans.

Thirdly, estate plans are often a unique cartographic source of information in depicting the same estate at different time periods. Therefore, they offer a valuable time-depth for the study of landscape change that occurred prior to the First Edition Ordnance Survey (OS).

Consequently, estate plans can give a rare insight into past woodland cover distribution and changes over time. Their level of detail and accuracy can also make them directly comparable with the First Edition OS maps. However, and it is certainly one of their main drawbacks, a large number of plans is needed for research projects that aim at investigating large scale landscape changes. Ready access to the plans must also be possible, a potential difficulty when plans are mostly privately owned – it is noteworthy that difficulties of access have been also reported in a study of Dutch estate plans (Heere, 2006). This issue might partly explain why estate plans are regularly overlooked in historical landscape studies. In that regard, close collaboration with the Dumfries Archival Mapping Project was essential to collate hundreds of plans that allowed coverage of an area over 1,000 km^2 in Dumfries and Galloway.



A. Roy military Survey of Scotland (c.1755)

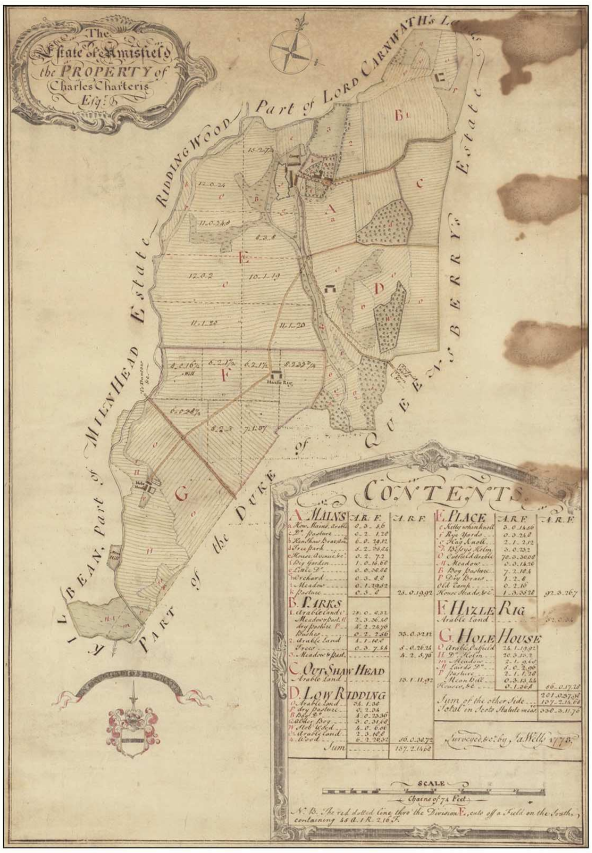
B. Estate plan by H. Leslie (1767)

C. County map by W. Crawford (c. 1804)

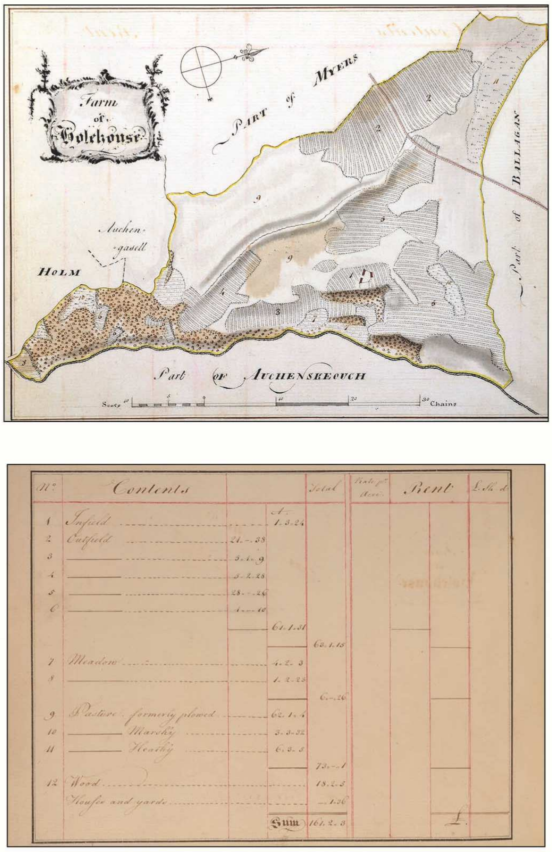
D. First Edition Ordnance Survey map (c.1860)

Figure 2.1 Historical maps covering part of Eliock estate near Sanquhar. While the estate plan by H. Leslie (**B.**) and First Edition Ordnance Survey maps (1:10,560) (**D.**) show detailed boundaries of the land-cover/land-use, such as woodland, the Roy military survey of Scotland (**A.**) and County map of Dumfriesshire (one inch to one mile) (**C.**) are more schematic and show less topographic detail. Courtesy of the National Library of Scotland for A., C. and D.

2.1.3 Initial considerations about the heterogeneity and comparability of estate plans



A.



B.

C.

Figure 2.2 Examples of the different forms of estate plans. (**A.**) The estate of Amisfield – The property of Charles Chateris Esqr, by James Wells, 1778 (c.68 x 47 cm, NLS); (**B.**) Farm of Holehouse and Table of contents - Book of plans of the barony of Drumlanrig, the property of Charles, Duke of Queensberry and Dover, Volume 1, by J. Leslie, 1772 (c.21 x 16 cm, RHP38134/15); (**C.**) Plan of farms belonging to the Duke of Buccleuch, by W. Crawford, 1820 (c.170 x 95 cm, RHP37668).

Like any map, historical maps show a certain perception of an infinite reality that result from a process of *conceptualisation* (Plewe, 2002; Leyk et al., 2005; Jenny and Hurni, 2011). As a result, each map represents only a selection of landscape features. For estate plans, land representation can vary according to the mapmaker, instructions by the people who commissioned the survey, and the survey's purpose, the three being related to some extent. A wide range of historical collections, as used for this research, means the bringing together of work by different surveyors, sometimes for different purposes, at various scales and time periods (Figure 2.2). Significant variations may therefore be expected regarding accuracy of the surveys, conceptualisation by the cartographer and subsequent cartographic reproduction. The latter involves the semantics related to symbols and language, also known as *convention*, and the level of topographic detail (Leyk et al. 2005).

However, does working on estate plans by different mapmakers mean working on strongly heterogeneous data? This critical question is necessary to assess the comparability of the information from the different plans. Integrating data from maps by various mapmakers is one of the most common issues that landscape historians have to face when the objective is to implement a consistent geospatial database (Petit and Lambin, 2002; Kaim et al., 2014). Different survey and drawing skills as well as instrumentation may have led to important variations between the plans. As such, some estate mapmakers were stylistically and in accuracy recognised by their contemporaries as better than others (Adams, 1971).

Nonetheless, it would be rather wrong to consider that the methods to survey an estate and depict the results on a plan are solely dependent upon the cartographer and, consequently, that each plan was absolutely distinct from every other. From the eighteenth century, surveying required important scientific knowledge in mathematics and geometry, as well as practical knowledge in the use of the surveying instruments (Bendall, 1992; O'Cionnaith, 2011). At that time, surveying texts, apprenticeships and schools were the three main ways that enabled a surveyor to develop their skills, with apprenticeships taking up to several years of training (Bendall, 1992; O'Cionnaith, 2011). For instance, O'Cionnaith (2011) reported that a seven year apprenticeship was common in Ireland. In sum, there was commonality of practice and purpose in the surveyors' work.

Likewise, in Dumfries and Galloway, most surveyors knew and were undoubtedly influenced by the work done by previous generations and contemporary colleagues, while many started their careers as assistant and were trained by the most experienced. Some examples of this are given by Adams (1971) concerning surveyors who mapped various estates in the study area, including John Leslie as assistant of William Cockburn, and John Gillon as apprentice of James and John Tait. These relationships might certainly explain similarities in conventions and aesthetic aspects between apprentice and master. In addition, the surveyors operating in the same regions shared regularly mutual acquaintance among their employers and it is likely that they occasionally knew each other (Adams, 1971). For example, James Wells, John Leslie, John and James Tait operated during the eighteenth century at similar time periods and regularly covered estates belonging to the same landowners.

Other relevant points tend to link the numerous estate plans that were used for this research. Several inscriptions by nineteenth century mapmakers refer to preceding plans of the same estate, confirming that previous maps and plans were regularly consulted. It is reasonable to conclude that such links would have had an influence on the subsequent production. The landowners also occasionally employed surveyors from the same family, sometimes over several generations. For example, in the eighteenth century, Charles Douglas, third Duke of Queensberry commissioned successively John and James Leslie (operating from the years 1750s to 1770s), while fathers and sons, John and Hamilton Leslie, and John and James Tait, mapped many estates and commonties in Annandale in the 1750s to 1780s (Adams, 1971). Interestingly but not surprising, the maps produced by members of the same family are stylistically very similar. All these observations support the assumption that mapmakers did not operate without the significant influence of their peers.

As a result, despite the challenge of working on plans from a large number of mapmakers, the strong similarities between their works indicates that their plans are often comparable in terms of style and content. It is also noteworthy that most landowners had preferred estate surveyors (O'Cionnaith, 2011), which explains why a restricted list of only eight surveyors from the eighteenth and early nineteenth century accounted for more than 80% of the maps used for this study. However, even if similarities are real, significant differences between plans and mapmakers still remain and they may cause a level of uncertainty that requires consideration and further discussion (see section 2.4).

2.1.4 Research objectives

The development of GIS tools has been a considerable improvement to collate and interrogate spatial information of historical maps. This chapter presents a GIS-based methodology to reconstruct past woodland cover at different time periods using estate plans and First Edition OS maps. Specifically, this research aims to investigate how a large set of estate plans can be combined and compared with the First Edition OS maps to provide a better understanding of changes in woodland cover since the second half of the eighteenth century. Several methodological issues are examined: How can we integrate the spatial information of a large variety of estate plans into a homogenous database to reconstruct past woodland cover? What types of uncertainties are associated with this process and how do they affect the reconstruction of woodland cover? How can the impact of these uncertainties on subsequent research goals be mitigated?

2.2 Methodology

2.2.1 Sources of historical maps

2.2.1.1 Pre-Ordnance Survey estate plans covering the study area

Access to private collections allowed the collation of approximately 340 maps, constituting the primary source of estate plans for this research. In addition, about 60 pre-OS estate plans were gathered from College, public and national archives, including the National Library of Scotland (NLS), the National Records of Scotland (NRS), the library of Hull University, the Ewart Library in Dumfries, and Dumfries Museum.

Among private collections, the most important is the well preserved archives of the Duke of Buccleuch and Queensberry at Drumlanrig castle, which provided 191 plans. These plans reflect the distinct periods of surveying that followed the lands' ownership history. In 1810, after the death of the fourth Duke of Queensberry, the Dukedom and Drumlanrig castle passed to the Scotts of Buccleuch with a collection of plans mostly dated from 1764 to 1772. Shortly afterwards, the estates of the new owners experienced a significant period of agricultural improvement when other surveyors were charged, in the 1820s, with remapping the lands of the Dukedom. This provides the opportunity today to appreciate the landscape changes in the Dukedom during the second half of the eighteenth century, before enclosure of the lands, and early nineteenth century, after major improvements.

Estate plans at Dalswinton and Maxwell houses in Nithsdale, as well as the collection belonging to the Earl of Annandale and Harfell in Annandale are other significant private sources of maps. Like the dukedom of Drumlanrig, many estates with mapping records experienced at least two major periods of surveying within a few decades, allowing once again a comparison between maps drawn during the eighteenth century and nineteenth century.

The estate plans collated for this research were produced under a wide range of forms, sizes and scales. A plan can cover a single farm or larger areas up to one or more parishes (Figure 2.2). In Drumlanrig, 163 plans showing pre-enclosed landscape were made in the years 1764-1766 and 1772, and bound into four volumes. Each volume covers one or two parishes and starts with a general arrangement plan showing the boundaries of the parish and the boundaries of each farm in the parish. The next pages of the volumes show individual farm plans with different symbols depicting the land-cover/land-use, followed by its related table of content (Figure 2.2B). The link between the plan and its counterpart table of content is made with numbers. In contrast, the maps made from surveys dated 1820-1825 on the same area can cover a much larger area of land, such as several parishes. For instance, in 1820, William and David Crawford surveyed and drew a map covering a maximum length of c. 23 km from West to East by c.13 km from North to South, corresponding to the parishes of Tynron, Penpont, and parts of the parishes of Durisdeer and Closeburn (scale c. 1:11,200, Figure 2.2C). Of all the maps that were collated, this covered the largest area in a single map.

To maintain a high level of detail, mapmakers had to draw plans of much larger size. Thus the Crawford and Crawford's map is c.170 cm by c.95 cm, while each farm plan of the volumes from the eighteenth century are of a relatively small size of c.21.5 cm by c.16.5 cm. Another example can be found in the collection of Dalswinton estates: a volume of 14 plans by William McCartney dated 1768 covers in detail Dalswinton estates whereas a large 1817 map drew by W. Crawford covers the same area in a single sheet. Regrettably, mapmakers who made the largest plans commonly listed the table of contents on a separate document that can rarely be found today. In that case, map's annotations, symbols and colours are the only evidence of past landscape.

In most cases, the estate plans studied for this research are hand-drawn, with a scale bar using the Scottish or English systems of measurements; a compass rose or north arrow showing either magnetic or geodetic 'true' north (i.e. also named on the plans 'line of the meridian'); a title cartouche of the estate and name of the land owner; information about the date of survey; name of surveyor and map drawer – also called 'delineator' – when the surveyor was not in charge of the drafting. Mapmakers also regularly drew decorative features to embellish the aesthetic aspect of the document with a vignette of the castle or landowner's house, heraldry, local scenes, or a particular area lying in the estate.

2.2.1.2 Selection of the final set of estate plans

Some private collections being very large and because of time constraints and restrictions to copying the maps at the owner's properties, two main criteria helped to prioritise the documents to copy:

1) Only maps of the areas surveyed before 1835 were selected. It was assumed that the changes occurring in the woodland cover between the years 1835-1860 could be characterised afterwards using the First Edition OS maps dated c.1860.

2) The maps showing the woodland cover depicted from field measures by the surveyors constituted the core of data for georeferencing. Inaccurate sketches were not used but were occasionally copied and studied when they provided supplementary information about the age of woodland or the type of management. A sketch can be mainly identified by its low levels of topographic detail, and spatial accuracy, as well as the absence of a scale, or by the title of the document that explicitly mentions its nature. It is however to be noted that a few plans defined as sketches in the title were perfectly accurate geographically. They were

perhaps described as such because they were a preliminary version of the final map or because the surveyor did not complete the map to the standards expected for a finished production.

Therefore, the selection of estate plans focused upon the maps with the potential to reconstruct woodland cover changes for two historical time series: the second half of the eighteenth century (1740-1799) and the early nineteenth century (1801-1835). The First Edition OS maps (c.1860) were the third and last historical time series of woodland cover reconstruction. The online NRS catalogue[1], along with meetings with map curators and archivists working for the different institutions, often followed by a viewing of the collections, helped to identify and locate the relevant archives.

The earliest estate plans were dated in the years 1740s, by E. Vernon. Most plans by Vernon were too inaccurate to be georeferenced but some depicted valuable information on past woodland cover and, consequently, were integrated into the study. It is to also to be noted that it was not possible to date accurately seven eighteenth century maps but the names of the surveyors provide a good approximate indication as to when they were made. The latest selected item was surveyed and drawn in 1833 by H. Stitt.

From the 400 digitised estate plans dated 1740-1833 covering Nithsdale and Annandale[2], 352 served for this study (Table 2.1). The full list of estate plans used for this PhD is provided in Appendix A. Most of the remaining maps, omitted from the study, appeared covering scattered areas outside the study area. They were ignored in order to keep consistency in the coverage and to avoid large gaps. This decision was to make the future interpretation of the results easier in working on a few large quasi-continuous and homogenous regions more likely to share similar land-cover/land-use changes history and landscape physical features. A few other plans, covering large areas, were also omitted because they seemed inaccurate. They were drawn at much smaller scales compared to the other items, and most of these plans did not show a good level of topographic detail.

[1] https://www.nrscotland.gov.uk/research/catalogues-and-indexes

[2] Many of these maps are now available online on the website of the National Library of Scotland (Dumfries-shire and Kirkcudbright-shire): http://maps.nls.uk/estates/index.html

Table 2.1 Sources of estate plans and material for digitising

Sources	Number of plans	Material to digitise the plans
National Records of Scotland (NRS)	27	Phase One IQ180MP Camera (DMF, 300 ppi)
National Library of Scotland (NLS)	13	Sheet-feed scanner Colortrac Gx+ 42 (400 dpi)
University of Hull Library	1	n.d
Drumlanrig Castle*	191	- Versascan 3650 Flatbed Scanner, 1270 x 915 mm (600 dpi) - Epson A3 Flatbed scanner (400 dpi) - Nikon D7000 - 55mm Micro f2.8 lens (DSLR, 300 ppi) - Custom-built camera using Phase One back and Schneider enlarging lens (DMF, min 400 ppi)
Annandale house*	59	
Maxwell house*	21	
Dalswinton house*	17	
Other private owners*	8	
Ewart Library (Dumfries)*	8	
Dumfries Museum*	7	
Total	352	

*estate plans copied in collaboration with DAMP; n.d = not determined.

2.2.1.3 Methods for digitising estate plans

Digitisation is the process that converts historical maps into numeric image files made of coloured pixels (Fleet, 2007). Only estate plans from the private collections, the Ewart Library and the Dumfries Museum were digitised in collaboration with DAMP; the other institutions – NRS and NLS – copied their own maps with a wide range of material and methods (Table 2.1). As a result, the control of the consistency of the digitising process between the collections proved difficult.

Most of the plans from private collections had to be copied at the owner's property due to the owner's concern about their archives being taken away from their house. Camera was easier to use on site and is recommended to prevent damage to the most fragile items (Fleet, 2007). A large format high resolution flatbed scanner was only used to copy a dozen of the largest maps at Drumlanrig castle with a resolution of 600 dots per inch (dpi). Another flatbed A3 scanner also served to copy about 20 of the smallest plans covering estates in Annandale (400 dpi).

Photographic sessions were organised by DAMP and the author of this thesis at the owner's properties. The pictures were taken with studio lights by professional photographers working for DAMP and the University of Glasgow, namely, Les Hill, graphic technician at the School of Geographical and Earth Sciences (University of Glasgow) and Lance Steward, independent photographer based in Thornhill who worked with DAMP at the beginning of the project.

Due to their size — sometimes more than 100 cm long — and to maintain a high resolution, the largest plans were photographed in small sections with a levelled camera: respectively c.15 x 10 cm with a Digital Medium Format (DMF) mounted on a horizontal rig for Lance Steward, and a maximum of c.50 x 75 cm with a Digital Single Lens Reflex (DSLR) on a vertical copy stand for

Les Hill. Les Hill's larger section size pictures helped to speed up the process while maintaining the image quality appropriate for this research.

The quality of the pictures had to be sufficient to read all the details depicted on the maps, particularly the writings and mapping symbols, and to reproduce sharp lines. Les Hill produced images under JPEG format with a minimum pixel array of 3000 x 3000 pixels and a resolution of 300 pixels per inch (ppi). Lance Steward used TIFF file format, approximately 20,000 x 14,000 pixels and a minimum resolution of 400 ppi. Like NRS and NLS, and as it is commonly the case for archival imaging (Fleet, 2007), both captured images with 24-bit colour depth. While the image quality produced by Lance Steward is much higher, the files proved to be very difficult to use into GIS software afterwards because of their very long opening times. The two photographers worked randomly on the private collections.

Regarding the NRS methods, items up to about A0 were copied with a glass plate to flatten the item and a DSLR camera. For larger maps, the NRS used a large format workstation, which has a DMF PhaseOne Camera mounted on a motorized column for both up and down arm movement and forward to back head movement. Cleaning and flattening of maps would be considered on a case by case basis by conservators. Magnets were used to hold maps and plans in place whilst being imaged (Rebecca Nielsen, Maps and Plans Archivist at NRS, pers comm).

The NLS also occasionally used an overhead DMF PhaseOne camera for digitising items too fragile to go through their sheet-feed scanner or to copy maps in a bound volume. A glass plate to flatten items as well as cleaning to prevent scan lines caused by dust were also used on a case-by-case basis (Chris Fleet, Map curator at the NLS, pers comm).

2.2.1.4 Limits of photographing historical maps

Photographing archives present several significant disadvantages: Firstly, the camera cannot cope with wrinkles on the maps nor the curve when they have been rolled up for years. When there was no risk of degradation, rules and weights placed at the edge of the photographed section helped to flatten the surface. Photographers occasionally shot items behind a glass plate. However, this shortcoming could still considerably affect the accuracy of the maps once embedded in a GIS and it had sometimes to be addressed again during the step of georeferencing, as explained later in this chapter (section 2.2.2).

Secondly, because of variation of the magnification across the lens, the camera may be responsible for a radial distortion that can slightly affect the proportions of the final image (Kingslake, 1992). These optical aberrations affect mostly the edges; they are called *Barrel* distortions when the lines tend to curve outwards and *Pincushion* when they curve inwards (Kingslake, 1992). In 2014, prior to this research project, Andrew Bates, University of Glasgow, MSc student, investigated the different possibilities for copying estate plans (Bates, 2014). The photography equipment was carefully chosen for maximum sharpness and minimum distortion, with Les Hill and Andrew Bates selecting a Nikon 55mm Micro f2.8 lens built on a sensor smaller than 35mm film (Bates, 2014). The same material was used by Les Hill to copy plans for this PhD. Lance Steward took images with a custom-built camera using PhaseOne back and Schneider enlarging lens after ensuring that it presented no significant distortion either (Lance Steward, pers comm).

2.2.1.5 Digitised First Edition Ordnance Survey maps (c.1860)

The First Edition OS maps are available on Edina Digimap website[3] which provides a wide array of maps and geospatial data for UK academia. They can be downloaded as black and white georeferenced Tiff raster files (GeoTIFF). The First Edition OS maps were drawn at two different scales: the 1:2,500 series (25-inch to the mile), are more detailed but cover only some parts of Scotland, while the 1:10,560 series (6-inch to the mile) cover the whole of Scotland (Oliver, 2013). The first was preferred for vectorising the woodlands in all areas covered by the '25-inch' series and the '6-inch' series helped to fill the gaps in the study area.

2.2.2 Georeferencing estate plans

The open-source QGIS v2.6.1 software (QGIS, 2015) allowed georeferencing of the maps, data acquisition as polygon shapefiles of woodland, the implementation of a consistent geospatial database, and the visualisation of the data on the historical maps in relation to other cartographic resources and aerial images.

2.2.2.1 Control points

Georeferencing is the process that assigns to historical maps a modern metric reference related to Earth coordinates or their corresponding map-projection (Balletti, 2006). To do so, it is necessary to choose points on the historical map, so called *control points*, at locations where it will be possible to determine accurate coordinates. Ideal objects to be used as control points (CPs) must have been stable over time, making them recognisable on both the historical map and the map or image layer(s) that serve as *reference* (Figure 2.3). For this research, the coordinates of the CPs were identified using as reference layers the *OS MasterMap Topography Layer* (scale 1:1 250), available on Digimap, and satellite images provided by Bing maps with the *Openlayers* plugin available in QGIS (QGIS, 2015). The set of CPs served to bring the estate map into coincidence with reference layers.

The great topographical detail depicted on estate plans helped to find CPs. The most obvious CPs were converging field boundaries: cross shapes, T junctions, and sharp corners (Bates, 2014).

[3] http://digimap.edina.ac.uk/

Roads and streams junctions, and the corners of building, such as bridges and old castles, were also carefully used after comparison with modern mapping or images, to ensure that shape, course or position had not been altered or changed over time. Furthermore, aerial photographs can help to find more CPs when they reveal other distinctive features on the ground that can be associated with previous land-uses or land-cover depicted on the historical maps (e.g. ruins or geometric variations in ground colour revealing past structures recognisable on estate plans).

Like any cartographic document, the number, quality and distribution across the map of the CPs are often a limiting factor for the accuracy of the georeferencing (Balletti, 2006). During the eighteenth and nineteenth centuries, the Enclosure movement associated with the agricultural improvement period led to major changes in the Scottish Landscape (Adams, 1971; Turnock, 2005; Fleet et al., 2011). The grid-like pattern of rectangular enclosed lands, still very familiar today, replaced the long-standing forms of landscape such as infield-outfield, runrig and commonty that had been inherited from medieval times (Adams, 1971; Turnock, 2005; Fleet et al., 2011). As a result, early plans covering pre-enclosure rural estates prove to be the most difficult to georeference as fewer CPs can be identified through comparison with modern references (Bendall, 1992). Likewise, plans of single farms (e.g. see Figure 2.2B) constitute another challenge to georeference as they cover small areas with sometimes too few distinctive features that are likely to be stable over time.

However, the use of other georeferenced historical maps and particularly the First Edition OS helped partly to overcome these issues. As they are dated c.1860, these maps share more common features with pre-OS plans than do modern-day mapping and images. Moreover, the georeferenced images of First Edition OS maps overlay on modern images with a spatial uncertainty of less than 5m from true (Winterbottom, 2000). As a result, the First Edition OS was used as reference to find more CPs than it would have been possible otherwise. Once these new CPs were determined, it was sometimes possible to adjust their position using the aerial images and OS Mastermap Topography layer. The latter served as much as possible as the main reference.

After being georeferenced, pre-OS maps that show acceptable positional accuracy — less than c.20m from true — could in turn be used as new references to find more CPs and georeference the earliest historical maps. For a given area, it is therefore most appropriate to georeference first the most recent estate maps using First Edition OS and modern data to decide on control points, and then, in a retrogressive manner, to georeference sequentially earlier maps (Figure 2.3).

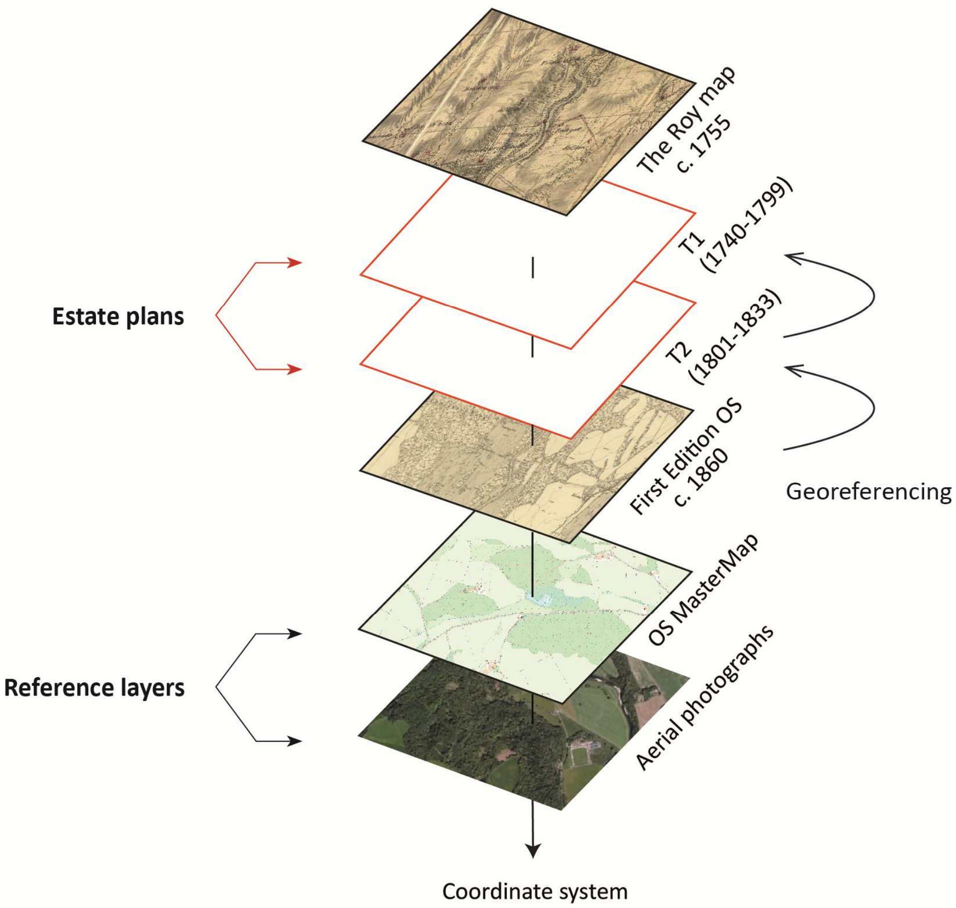


Figure 2.3 Reference layers to georeference estate plans under the same coordinate system. T1 and T2 are time series 1 and 2. First Editions OS maps and georeferenced estate plans can also serve in turn to georeference anterior estate plans. The Roy map was not georeferenced for this project but serve in Chapter 4 for comparison with estate plans.

2.2.2.2 Transformation methods

Once the control points are determined, the transformation process assigns each pixel of the historic map to real coordinates of the chosen coordinate system: WGS84/Pseudo Mercator. The *first order polynomial transformation*, also called *affine transformation*, has initially seemed to be the most appropriate transformation to georeference the maps. This five-parameter Euclidean transformation is determined by a least squares estimation (Jenny and Hurni, 2011). It allows scaling, translation, rotation and preserves collinearity (Jenny and Hurni, 2011; QGIS, 2015). As the new image produced with affine transformation represents the original more faithfully than with most other available methods, it appeared to be a good compromise between the accuracy of the georeferencing and the preservation of the raw data of the survey. For similar reasons, the NLS has used affine transformation for georeferencing their historical maps (Chris Fleet, map curator at NLS, pers comm).

Affine transformation can perform with as few as three CPs but more points are necessary to obtain higher accuracy (Balletti, 2006; QGIS, 2015). When too few CPs could be identified for this transformation to perform well, two different options were available:

1) Using as an intermediate step *Helmert transformation* — or four-parameter Euclidean transformation (Jenny and Hurny, 2011) — proved to be very appropriate. From two CPs, Helmert transformation allows simply a uniform scaling and rotation which does not distort the spatial geometry of the historical map (QGIS, 2015; Jenny and Hurny, 2011). After proceeding to Helmert transformation, the newly georeferenced image may help to uncover the less conspicuous CPs that can serve, in turn, to finally perform an affine transformation.

2) When there were still too few CPs available or the CPs were not evenly distributed across the map, Helmert transformation eventually offered the best results. Whereas affine transformation may be responsible for a strong unilateral distortion pattern along horizontal or vertical axis of the map (Jenny and Hurny, 2011), the more constrained, uniform scaling, Helmert transformation does not cause any change in the proportions of the map image. Consequently, this transformation could compensate for the lack of CPs while preserving better the raw data from original survey. However, it has to be noticed that insufficient CPs increased the uncertainty related to the positional accuracy of the georeferenced map (see 2.4.1.2).

Jenny and Hurny (2011) also recommend using in priority the more conservative Helmert transformation, while they suggest using affine transformation when one needs to compensate shearing or any unilateral alteration of the drawing support, like shrinking or stretching. Due to storage and time effect, these alterations happened regularly in the set of plans studied for this research. As a result, the choice of the best transformation depended on: 1) the number, quality and distribution of the CPs; and 2) the need to compensate any deformation of the drawing support. Consequently, the choice of the most appropriate transformation was flexible, on a case-by-case basis, after trying the different options described previously. A visual assessment of how well after each trial the georeferenced image overlaid on reference layers allowed selecting for individual plans the transformation that showed the best results. In the end, Helmert transformation was used for about 60% of the georeferencing cases and affine transformation helped for the remaining 40%.

Figure 2.4 shows an example of map boundaries unilateral distortion induced by affine transformation compared to the Helmert transformation. The maximum difference between these two transformations occurred at east of the farm of Kirbride for a shift between 20 to 30 m on the ground. As this may impact the positional accuracy of woodland in the reconstruction, the best transformation must be chosen carefully after comparison with reference layers.

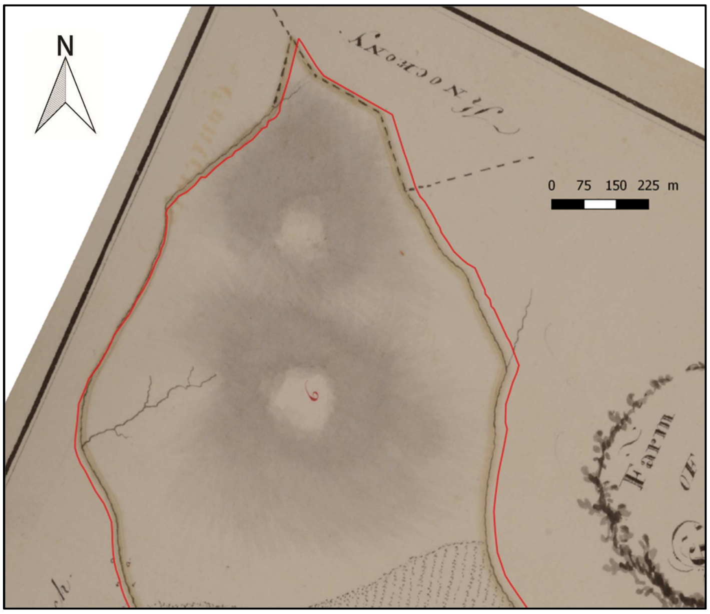


Figure 2.4 Subset of the georeferenced farm of Kirkbride (Leslie, 1772, RHP 38134/28): boundaries of the farm after affine transformation (red line) compared to original shape (Helmert transformation, background map).

2.2.2.3 Root Mean Square Error

After the transformation process, a residual error is returned by QGIS for each of the control points used to georeference the map (QGIS, 2015). Expressed in metric or pixel unit, it accounts for the coordinate difference, along X-axis and Y-axis, between the CP on the georeferenced historical map and its actual target location as specified before transformation of the map (Grosso, 2010). The residual for each CP is calculated as follows:

$$\text{Residual(i)} = \sqrt{(dXi^2 + dYi^2)}$$

The error values of each CP are also aggregated by QGIS into a single value called *mean error* or *Root Mean Square Error* (RMSE, Menke et al., 2016). The RMSE value is calculated as follows:

$$\text{RMSE} = \sqrt{\left(\frac{\sum_{i=1}^{n}(RD-HM)^2}{n}\right)}$$

Where RD = coordinate(s) of the CP as on the reference data (predicted value); HM = coordinate(s) on the historical map after transformation (observed value); n = number of observations. Note that in QGIS, n = number of CPs - minimum number of CPs to perform the transformation. The minimum number is 2 for Helmert transformation, and 3 for affine transformation.

RMSE is defined as a measure of the magnitude of error (Veregin, 1999). As such, this statistic can serve as an indicator of the quality of the transformation by quantifying the consistency and accuracy of the transformation (e.g. Bitelli et al., 2009; Lukas, 2014). However, the RMSE varies with the transformation type and should not be understood simply as an indicator of the overall positional accuracy of the map (Bitelli et al., 2009). For instance, more mathematically complex transformation methods allow important warping of the image, which tend to produce very low RMSE values even if large sections of maps poorly aligned on reference data. The RMSE value will also depends on the number, distribution and quality of the CPs (Tan et al., 2013), which is often a limiting factor for georeferencing historical maps. However, as Helmert and affine transformations allow little deformation of the image, CPs with the highest residual error can often be explained by positional errors during the survey, mistakes in attributing wrong CPs on the historical image, or inaccuracy due to located alteration of the drawing support. Consequently, removing carefully some of the CPs presenting the highest residual errors helped to improve the alignment of the georeferenced map over reference layer(s) and then increased its positional accuracy. This had to be done while bearing in mind that a very low number of CPs (2,3 or sometimes 4) can in turn also lead to a very low RMSE even if large sections of the map do not overlay properly on reference layers. Therefore, a trade-off had to be found between the number of CPs and their quality. The variation of RMSE according to CPs number, distribution and quality will be discussed further in the section related to planimetric accuracy of estate plans (section 2.4.1.2).

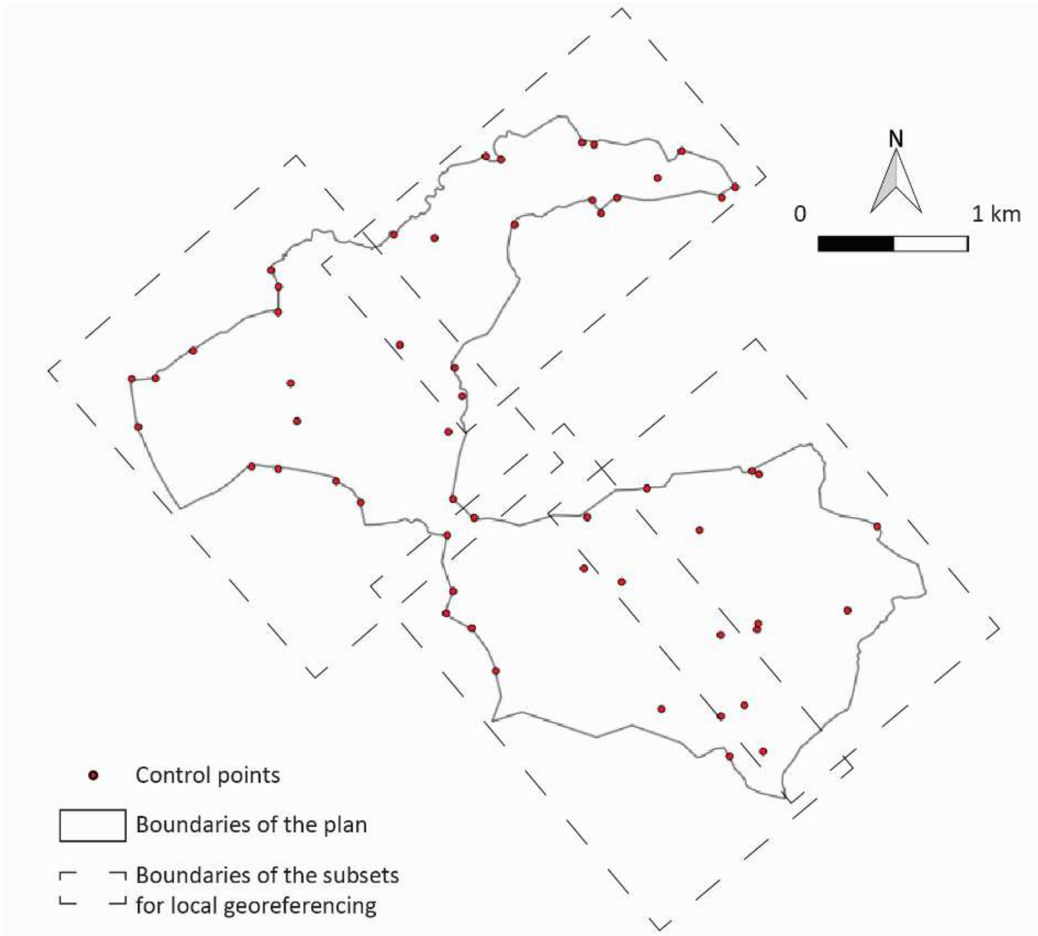
2.2.2.4 Local georeferencing

Identifying a high number of CPs was also important as it increased the possibility of undertaking on the same map several local georeferencing. In preventing georeferencing errors to accumulate across the maps, this step proved to be essential to improve the spatial accuracy of georeferenced maps. Local georeferencing was therefore particularly valuable to georeference documents covering the largest areas, for which surveying inaccuracies can propagate and accumulate towards the edge of the plan or from the first to the last points recorded by the surveyors in the field. In this regard, such maps were often divided in several sections that were georeferenced separately. For instance, the map by Crawford and Crawford (1825, see Figure 2.2C) covering an area of c.24 km x c.13 km was divided and georeferenced in six separate sections, and the plan of the Barony of Lochrutton by James Wells (1774-1755), covering 1,437 ha, was divided in four sections (Figure 2.5A). Such local georeferencing used, as in the other georeferencing, Helmert or affine transformations.

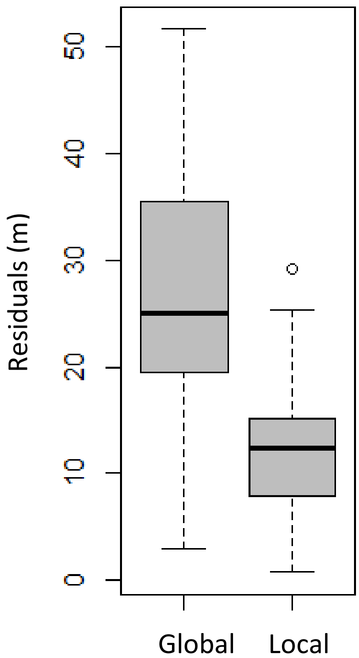
To illustrate further the improvement allowed by local georeferencing over global georeferencing, Figure 2.5B and Table 2.2 show a comparison between the two methods for the plan by J. Wells.

The boxplots presented in Figure 2.5B are based on the residual values of the CPs calculated after Helmert transformation. A boxplot shows the spread and centre of the distribution of a dataset using quartiles. The lowest 25% of the data range from the lowest value (i.e. end of the lower 'whisker') to the bottom of the box (i.e. first quartile); the median (i.e. second quartile) corresponds to the black line in the middle of the grey box; the highest 25% of the data range from the top of the box (i.e. third quartile) to the highest value (i.e. top of the upper 'whisker'). As a result, the grey box represents the middle 50% of data. The circles indicate the outliers.

The same set of 55 CPs served to georeference the plan for both methods. The comparison shows that the set of residual values decreased significantly with local georeferencing (Mann–Whitney U test, $p < 0.001$). The decrease of the range of residual values, as well the median— from 25.1 m to 12.4 m— and RMSE — from 29.4 m to 10.4-16.6 m according to the section of the plan — reflect the transformation's more consistent and accurate results (Table 2.2).



A.



B.

Figure 2.5 Example of local georeferencing: 'A Plan of the Barony of Lochrutton' by J. Wells (1774-1775). (**A.**) Boundaries of the plan and subsets for local georeferencing; (**B.**) Boxplot of residual values of control points after global and local georeferencing. For both methods, the same set of 55 control points was used to enable the comparison.

Table 2.2 Summary data of RMSE, residuals and median of residuals for the two methods used to georeference 'A Plan of the Barony of Lochrutton' by J. Wells (1774-1775).

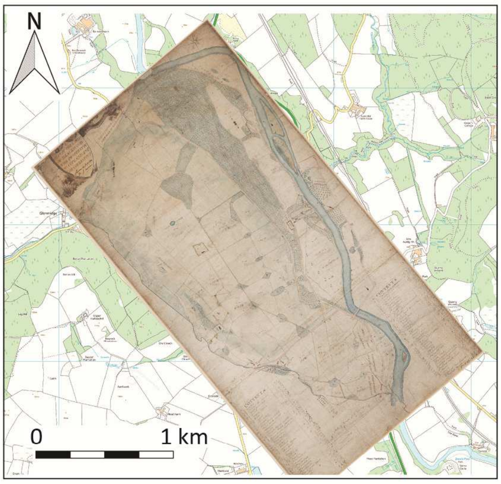
	Global georeferencing	Local georeferencing
RMSE (m)	29.4	10.9 – 16.6
Residuals (m)	2.9 – 51.7	0.7 – 29.2
Median of residuals (m)	25.1	12.4

In preventing the accumulation of georeferencing errors across the map, local georeferencing can also help to mitigate the inaccuracy of items that have experienced physical degradation, such as shrinkage or creases with which digitising methods failed to cope. As a result, the number and size of the sections used for local georeferencing varied following three criteria: 1) True ground size of the area covered by the map — the larger the area covered by the map is, the more sections might be necessary; 2) Spatial accuracy of the digitised map — the less accurate maps can be subject to more local georeferencing; and 3) Number of CPs available — a sufficient number of points for each section is needed for the transformation step to perform well. Several trials were necessary before obtaining the local georeferencing that provided the best outcome. Results of each trial were assessed through visual assessment and using the RMSE values. Reasons for differences in accuracy between the plans are discussed further in this chapter (see 2.4.1).

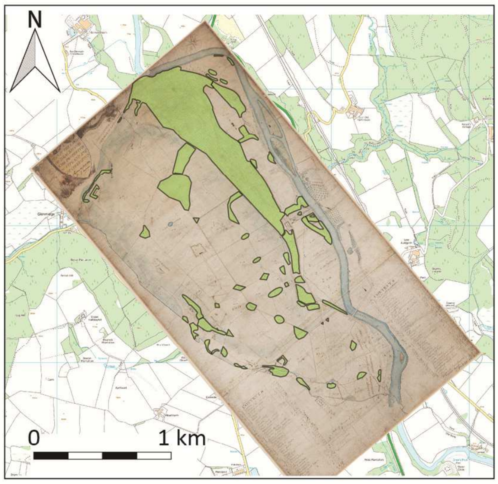
2.2.3 Data acquisition and integration into a geospatial database

2.2.3.1 Vectorisation of the woodland cover

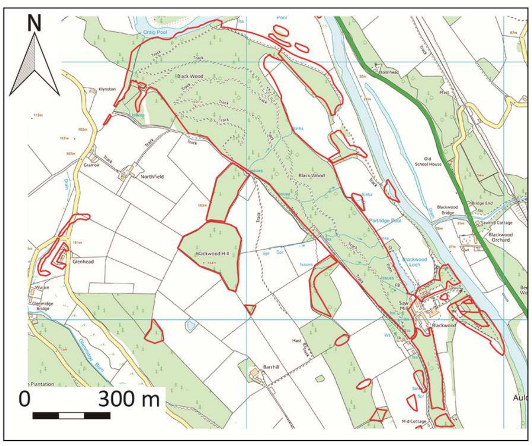
1. Control points (in red) on reference map (Ordnance Survey) and the estate plan to georeference (Land of Blackwood by Morrison, 1804)



2. After Helmert transformation (rotation and rescaling)



3. Vectorisation of the woodland depicted on the estate plan



4. Vector layer of woodland cover in 1804 (red outline) overlaid on modern reference map

Figure 2.6 Georeferencing estate plans and vectorisation of woodland: example of the estate plan of Blackwood by J. Morrison, 1804.

The woodlands depicted on the historical maps were captured manually as polygon shapefiles and using the *National grid OSGB 1936*[4] projection, which is commonly used for spatial studies in the UK (OS, 2015) (Figure 2.6). This step of data capture is called *vectorisation*. A database (i.e. Attribute table) linked each georeferenced woodland polygon to the name of the estate, the parish, the date of the survey, as well as the name of surveyor. For the First Edition OS maps, the surveyor was tagged only as 'OS' (Table 2.3).

Unless later additions are mentioned, it is assumed that the maps selected for this research showed the land cover at the year indicated on the map, notwithstanding that a survey could perhaps be spread over more than one year. This might have particularly concerned the surveys of very large areas such as the three volumes of plans by James Leslie covering the Dukedom of Drumlanrig. Only the year 1772 was mentioned but, considering the extent of the area covered, Leslie may have started his survey, months or year(s) before. Dates that corresponded to the earliest archival evidence of a woodland site were also recorded, when available, along with their historical source (i.e. 'Earliest Record' in the attribute table). For instance, a map might not be able to be georeferenced but it demonstrated the previous existence of the same woodland or, as it happened regularly, maps mentioned the exact — anterior — date of a woodland plantation.

In many instances, the 'table of contents' associated with the maps brought miscellaneous information about the land-cover/land-use, sometimes providing evidence of particular types of woodland management (e.g. coppice, wood pasture, plantation, etc.). On rare occasions, they also provide some relevant information on the type of vegetation that composed the different woodland sites (e.g. 'oak wood', 'alder bog', 'fir plantation', or 'brushwood' and 'bushy woods'). This raw information as well as other evidence available from non-georeferenced historical maps was recorded into the GIS geospatial database for each polygon and categorised afterwards (see section 2.2.3.3 about categorisation).

[4] Ordnance Survey Great Britain 1936 is based on the Airy 1830 ellipsoid and serves as the basis of the national OS mapping (OS, 2015)

Table 2.3 Historical woodland Inventory - Attribute table. See further detail in Table 2.4 regarding the different categories for 'Class_Code' and Table 2.5 for 'Management'.

List of Woodland features	Explanation
Site_Name*	Farm name or any other relevant geographic indication of the woodland site location
Parish*	Parish where the woodland site is located
Map_Origin*	Surveyor/mapmaker's name when estate plans; 'OS' when Ordnance Survey plans
Date*	Date of the map or survey as provided on the map
Map_Description	Description as written on the map or in the map's *table of content*. E.g. 'Copsee', 'Brushwood', 'Oak wood', 'Young planting'
Class_Code	Woodland class category. E.g. 1 = 'Woodland'; 2 = 'Low woodland'; 3 = 'Bushes'; 4 = 'Open woodland'
Management	Evidence of management: 'Grazed', 'Plantation', 'Orchard or Garden', 'Coppicing' and 'Pollarding'
Earliest_Record	Date that corresponds to the earliest archival evidence of the existence of a woodland site
Source_Earliest_Record	Name of the archive providing the 'Earliest record' date
Notes*	It can refer to an uncertainty or any observation of interest. E.g. 'Poor accuracy of the georeferencing'; 'Data partly erased'; 'Later addition in 1812 by J. Jardine'.

* The same information is also provided in the Attribute table related to the polygons from the vectorisation of each estate plans' boundaries (table 2.4, section 2.2.3.4)

2.2.3.2 Limitations on defining past woodland cover

Defining areas of woodland on historical maps is not as straightforward as it may seem. While assessing the potential of historical maps to identify ancient woodland sites, Glaves et al. (2009a) reported that symbols on estate plans are not always consistent and can be misleading. The principal issues regarding the visual interpretation of woodland for this research were as follows: 1) most, but not all, mapmakers drew a thin line to delineate woodland boundaries. Skaloš et al. (2012) reported the same issue in a study of the First Military Surveys map in the Czech Republic (1780); 2) mapmakers occasionally drew on the same map different symbols to distinguish various woody vegetation cover, with a meaning that is unclear today. This was particularly an issue when the table of contents was missing; and 3) the exact definitions of some objects such as 'bushy wood' or 'natural woodland' occurring in a few eighteenth and nineteenth century table of content's maps are ambiguous and therefore problematic.

Delimiting woodland boundaries from historical maps can have an element of subjectivity and some crucial questions had to be asked: How should one draw the limits when they are not clearly delineated by a line (e.g. open woodland sites, riparian vegetation)? And should wood pastures, open woodlands, orchards or objects with ambiguous meanings like 'bushy woods' be included? To complicate matters further, 29 different pre-OS surveyors over a period of 80 years have been identified, each with their own conventions for representing woodlands and with variations in language to define them. These variations may depend on several factors such as when the mapmakers operated, their geographic origins, or their knowledge of woodland vegetation and management. The uncertainties listed below can therefore occasionally lead to a misinterpretation of the original mapmaker's intentions:

- The distinction between thin woodland plantings along field boundaries and hedgerow trees was not always clear. Likewise, it was possible to observe – comparing different historical maps – that a line of trees can be a hedge when depicted along the fields, and thin but dense woodlands, when lying along the rivers. Only a few mapmakers used different tree symbols to make these distinctions.

- Wood pastures are not always mentioned and described as such. This was particularly problematic on the First Edition OS map. As they are not delineated by a thin line, identifying the physical limits of open woodlands, which can be wood pastures, is often challenging. This issue was also reported by Kaim et al. (2014) while reconstructing forest cover changes from topographic maps in the Polish Carpathians and Swiss Alps.

- Tree symbols on historical maps being occasionally superior to 15 m lengths on the ground, it was sometimes uncertain whether a small group of trees on a plan represented the true existing number of trees, or proper woodland. Similarly, estate plans rarely allow a clear understanding of density of growth.

- Orchards may not be recorded separately or drawn differently from other woodlands

Comparison between maps covering the same area proved to be the best method to understand the mapmaker's representations and facilitate the decisions with regard to what might be considered as woodland or not. This process of familiarising with the individual mapmaker's conventions was possible thanks to the large collection collated for this study. It is also to be noted that a small group of eight mapmakers drew most of the estate plans that served for this research (about 295 out of 352 plans). This provided plenty of opportunities for comparisons that helped to familiarise with the work of each. In general, woodland was considered in a broader perspective, including landscape elements such as 'bushy wood', 'brushwood' and open woodland. To address further some of the shortcomings listed above:

- Lines of trees were not included in the database when they were drawn along field boundaries as they were likely to depict hedgerows. They were included when they lie along rivers and streams as this more likely represented denser riparian vegetation. It was assumed that hedgerows did not represent a real interest with regards to the scope of this study, contrary to riparian woodlands.

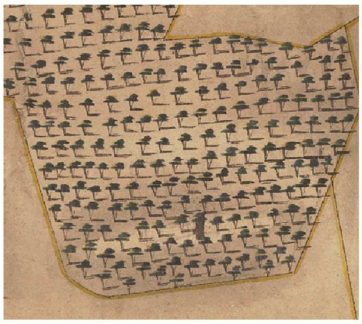
- A vegetation class named 'Open woodland' served to classify all areas depicted with scattered trees symbols covering an area between 40% and 70% within the boundaries of a geometric area delimited by the most external trees (e.g. in Figure 2.7). This class concerns woodland sites for which there was no evidence of grazing activities. As a result, one should bear in mind that open woodlands may have been grazed.

- All the orchards and wood pastures mentioned as such on the maps were recorded and assigned to appropriate categories (see section 2.2.3.3 about categorisation of woodland type and past management evidence).

- Whether a group of trees should be recorded as woodland or not was decided based on cartographic comparisons with maps covering the same area at different time periods and with a good understanding of the convention used by the mapmaker.

- All the areas described as ‘bushy woods’ in the maps’ tables of contents were also recorded. Even if the exact meaning in terms of vegetation structure or management remained unclear, these sites may have become mature woods today and, as a result, can be considered at least as the early stage of future woodland. In general, the terminology applied in the historical maps was considered with caution.

a. ‘Woodland’ [19]
J. Wells (1787)

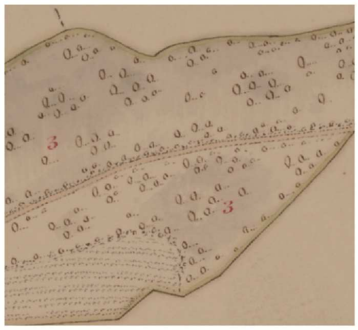


b. ‘Plantation’
J. Jardine (1807)

c. Woodland
W. Crawford (1820)

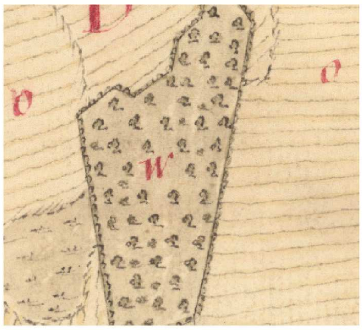
d. ‘Shaw wood’ [33]
S. Cowan (1814)

e. ‘Pasture and Brushwood’ [63]
S. Cowan (1814)



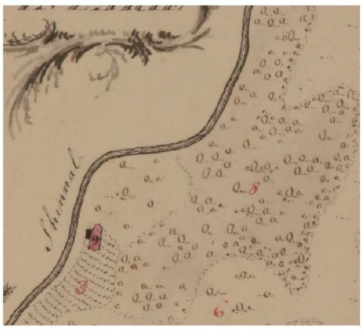
f. ‘Brush wood’ [3]
J. Leslie (1772)

g. ‘Wood and scroggs’ [3]
J. Lewars (1814)



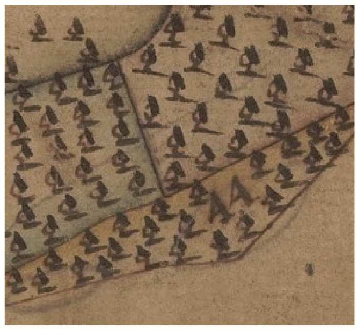
h. ‘Stob Wood’ [and hedgerow trees] - Wells (1778)

i. ‘Stab Wood’
Unknown (1829)



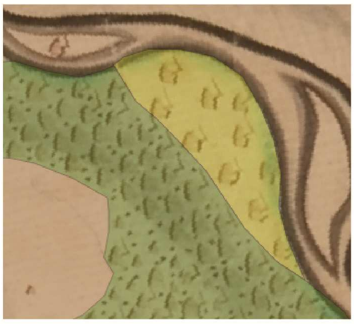
j. ‘Pasture with bushes’ [6]
‘Wood’ [8] - J. Leslie (1772)

k. ‘Bushy bogue’ [20]
W. McCartney (1783)

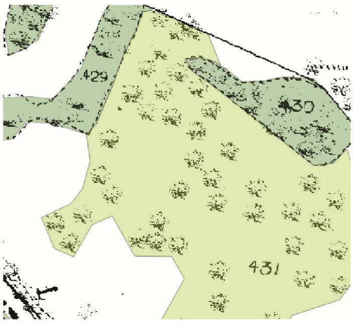


l. ‘Bushes’ [44]
W. McCartney (1783)

Figure 2.7 Vignettes of trees and woodland from historical estate plans.

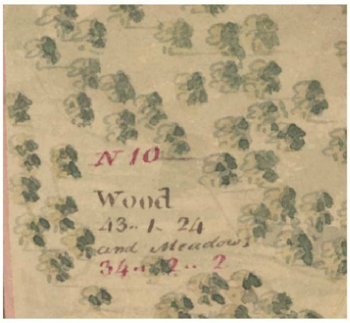


m. Wood [Dark green] - Open Wood [Light green] - J. Udny (1793)



n. Wood [Dg] - Open Wood [Lg] First Edition OS 1:2,500 (c. 1860)

o. Wood [Dg] - Open Wood [Lg] First Edition OS 1:10,560 (c. 1860)



p. 'Wood and Meadows' [10] W. Crawford (1820)

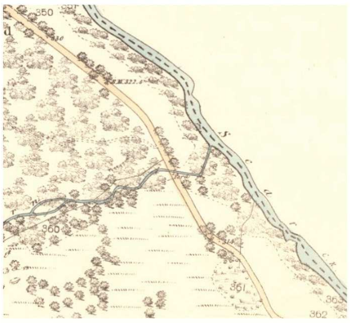
q. Transition from Woodland to Open Woodland? - W. Crawford (1820)

r. Wood and Wood pasture W. Crawford (1820)

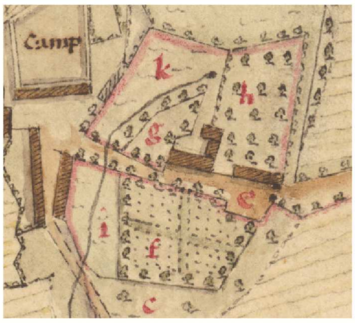
s. Wood and hedgerow trees J. Tait (1782)

t. Wood along stream J. Wells (1763)

u. Wood along stream W. Crawford (1820)



v. Wood along stream First Edition OS 1:2,500 (c. 1860)



w. 'Garden' [f] and 'Orchard' [h] J. Wells (1778)

x. 'Orchard' J. Tait (1782)

Figure 2.7 /continued Vignettes of trees and woodland from historical estate plans.

Figure 2.7 shows the various symbols to depict trees, woodland and related land-cover/land-use on historical estate plans. The vignettes illustrate different conventions depending on the surveyor and type of woodland, as well as the reasoning to understand mapmakers' depictions. The following observations can be made:

- Vignettes **a**, **b** and **c** show tree symbols vectorised as 'Woodland'. These sites were delineated by a thin line on **a** and **b** (probably enclosed), but not on **c**.
- On the same map, S. Cowan used different symbols to differentiate 'woodland' (**d**) from 'brushwood' (**e**). In contrast, J. Leslie seems to use similar symbols for both (**f** and **j**) but he depicted 'bushes' differently (**j**).
- While the table of contents says 'Wood and Scroggs alongst burn', the scarce symbols used by J. Lewars on **g** makes unclear whether the mapmaker intended to show proper woodland or isolated elements only. This was also perhaps to leave space for the writing of the number.
- Vignettes **h** and **I** show 'stob' and 'stab' for which the meaning will be discussed later. Tree symbols used by Wells to show this wood is not different from the ones to show any other woodland (see **a**)**.**
- While W. McCartney depicted 'bushy bogue' (**k**) slightly differently with scarce symbols, there was no difference on the same map to represent 'bushes' from other woodland (**l**).
- Different ways of depicting open woodland and/or wood pasture are presented from **m** to **r**. On vignettes **m**, **n** and **o**, shades of green were added to illustrate how differences were made between 'open woodland' from 'woodland' during the vectorisation process (see section 2.2.3.3 about categorisation). While **p** and **r**, by W. Crawford, clearly show that the woods were probably more open – a comparison can be made on vignette **r** with a woodland site on the upper left corner – **q** may be understood as a transition towards open woodland from lower to left to upper right corners. This assumption was supported by comparison with other historical maps and particularly the First Edition OS maps covering this area.
- Hedgerows as in **s** were not recorded, as opposed to riparian vegetation in **t**, **u** and **v**. Even though separated by forty years, a comparison between **u** and **v** – covering the same area – tends to confirm that Crawford might have used single tree lines to show proper woodland along the stream.
- Vignettes **w** and **x** are two examples of gardens and orchards on estate plans.

2.2.3.3 Categorisation of woodland type and past management evidence

Based on map symbols and designation as on the table of reference, each woodland polygon was categorised in two distinct manners: i) *Vegetation class*: Woodland; Low woodland; Bushes; Open woodland; Orchard and Garden; and Unknown; and ii) *Management type*: Plantation; Grazed; Coppice; Pollard; Orchard or Garden; and Unknown. For each category, the list of the various corresponding written or symbol designations on estate plans is listed respectively in Table 2.4 and Table 2.5.

Table 2.4 Vegetation classes and several corresponding designations on estate plans.

Vegetation class	Object designation (from written description on the map and/or symbols)
Woodland (1)	'Wood' 'Woody' 'Shaw wood' 'Banks wood' 'Natural wood' 'Plantation' 'Planting' 'Clump of firs'
Low woodland (2)	'Brush wood' 'Low brush' 'Coppice' 'Copsee' 'Stubs' 'Stob wood'
Bushes (3)	'Thorns and hollies' 'Scroggs' 'Bushes' 'Pasture bushy' 'Pasture [marchy] with bushes' 'Meadow with bushes' 'Bushy and Meadow pasture' 'Bushy bogue'
Open woodland (4)	Open woodland (scattered tree symbols covering > 40% of the area) 'Wood and bushes' 'Wood pasture' 'Pasture and wood' 'Tree park' 'Pasture intermixed with trees' 'Pasture overgrown with wood and bramble' 'Pasture covered with brush-wood' 'Meadow intermixed with brushwood' 'Pasture covered with brush-wood and stubs'
Orchard/Garden (5)	'Orchard' 'Garden'
Unknown/Unclassified (6)	'Pasture Wett' (with – undetermined – wood or bushes depicted) 'Alder bogue' 'Bogue with trees' 'Bushy and planted lines' 'Meadow' (with – undetermined – wood or bushes depicted)

Table 2.5 Management types and corresponding designations on estate plans. The other forms of terminology listed in Table 2.4 that are not present here were left out due to insufficient evidence of management.

Management type	**Object names as on the map**
Plantation	'Plantation' 'Planting' 'Clump of firs'
Coppice	'Brushwood' 'Coppiced' 'Copsee'
Grazing	'Pasture bushy' 'Pasture with bushes' 'Meadow with bushes' 'Bushy and Meadow pasture' 'Wood pasture' 'Pasture and wood' 'Tree park' 'Pasture overgrown with wood and bramble' 'Pasture covered with brush-wood' 'Pasture intermixed with trees' 'Meadow intermixed with brushwood' 'Pasture Wett' (with wood or bushes depicted) 'Meadow' (with wood or bushes depicted)
Grazing , Pollard and Coppice	'Pasture covered with brush-wood and stubs'
Pollard	'Stob' 'Stubs'
Orchard/Garden	'Orchard' 'Garden'

Tables 2.4 and 2.5 illustrate the wide array of terminology used by mapmakers to define woodland or related types of land-cover cover. The categorisation of old terminology such as 'shaw wood', 'stob' and 'stubs' is mostly based on the online "Dictionary of the Scots language" (DSL, 2017), but also on the "Glossary associated with woodland management in South Yorkshire" published by Jones in 2013. The former provides definition and examples based on the different uses of words in historical writings. Although written for Yorkshire, the latter provides definitions similar to those in the DSL and helped to complete it with further information.

'Shaw' can be defined as small farm woodland (Jones, 2013; DSL 2017), while 'stub' – and variant spelling 'stob' – may refer to a low-cut pollard (Jones, 2013) or stump of a tree (DSL, 2017). The nature of 'brushwood' is sometimes explicitly defined on maps as in the farm of Birkhill surveyed by Leslie (1772, RHP38136/38): 'Low brush wood mostly birch'. Brushwood may also refer to hawthorn (*Crataegus monogyna*), hazel (*Corylus avellana*), rowan (*Sorbus aucuparia*), alder (*Alnus glutinosa*) and 'almost all irregular growing and stinted trees, naturally appearing in a state of neglect' (Singers, 1829, p.137), including also ash (*Fraxinus excelsior*), oak (*Quercus* sp.) and elm (*Ulmus* sp.). According to Singers (1829), the branches and twigs of these trees could be used as fuelwood. Tree height and use suggest, therefore, that 'brushwood' and 'coppice' can be categorised together. Brushwood may also refer to the product of coppice itself (Peterken, 1993). Likewise, the DSL also defines 'scrogg' as similar to brushwood (DSL, 2017). A few eighteenth century plans by W. McCartney also mention 'natural wood' and one of these woods was 'to be planted'. Notwithstanding that this usage might imply coppice woodland according to the use referred to by Monteath in his 'Forester's Guide and Profitable Planter' (1824), there was no further evidence of it on the historical maps. It is also to be noted that in the New Statistical Account of Scotland covering the study area (i.e. Vol. IV, 1845), the term 'natural woods' was used several times to distinguish sites that were not of plantation origin (e.g. p. 202, 261, 344, 464). This usage suggests perhaps a drift of the meaning of this terminology over time or different uses proper to surveyors or writers. In all cases, it is likely that these woods as reported on the historical plans were all composed of broadleaved trees. Further to the categorisation:

- **Vegetation class**: Classes are based on assumption of vegetation height and density according to the map symbols and written evidence. The ambiguous nature of the terminology used by the different mapmakers prevented the creation of consistent sub-classes of the vegetation units. Moreover, the rare evidence for most classes makes them of little use for investigating woodland cover changes over time. As a result, only the broader vegetation classes presented in Table 2.4 were retained.

  This categorisation is still not without some issues as significant 'permeability' might still exist between classes. Firstly, 'Woodland' (class 1) refers here to sites that might present denser woodland vegetation and more closed canopy compared to the other classes. However, some of these sites could also be coppice, or coppice-with-standards, which made use of the lower storey as coppice and the upper storey as mature trees cut on a longer rotation for timber production (Peterken, 1993). These coppice woods may have been simply described by some mapmakers as ‘Wood’ and therefore placed in class 1 rather than class 2 (‘Low woodland’). Likewise, ‘Alder bogue’, unclassified here, could have been used as coppice (class 2), for instance, to product gunpowder charcoal (Smout et al. 2005), or as woodland pasture (class 4, ‘Open woodland’) (Wilson, 2015). As already noted, ‘natural woodland’ could also be coppice. Secondly, while it seems that special care was taken by many mapmakers to make the distinction between woodland (class 1), brushwood (class 2) and bushes (class 3) – all three can occur distinctly on the same map – there is no guarantee that all mapmakers used the same definition criteria for these classes and the distinction may not always be clear in the field (in other words, these are *fuzzy classes*). Thirdly, it was not always possible to understand a symbol so as to assign each polygon a vegetation class. Symbols sometimes simply fail to differentiate the different classes on the map, or information provided in the table of reference could not be clearly located on the plan.

- **Management type**: likewise, several issues raised with regards to the management type assigned to woodland polygons. This concerns particularly plans without a table of reference. The principal problem was the lack of management evidence for the many woodland sites described only as ‘Wood’ on the plans. Without any physical barrier to prevent grazing, it is also likely that some open woodland sites were used as wood pasture even though there is no explicit mention of this use. In these two cases, it was not possible to assign any management type to the polygons. As noted for vegetation classes, some ‘permeability’ certainly also exists between management types, and a single woodland site can occasionally be assigned to two types. For example, ‘plantation’ can refer to conifers plantation for timber product, as happened increasingly during the eighteenth and nineteenth century (see Chapter 3), but it may also refer to plantations used as coppice, such as planted oak coppice (Monteath, 1824). As mentioned previously, ‘Alder bogue’, not classified here, could be coppice and/or wood pasture (Wilson, 2015). As a result, one should keep in mind that management types are based on evidence provided by the maps only. However, in reality, a woodland site could cover more than one management type as the types are not necessarily incompatible or mutually exclusive.

2.2.3.4 Vectorisation of the estate plans' boundaries

Besides the woodland cover, the total area covered by each estate plan was also vectorised after georeferencing (using the National grid 'OSGB 1936'). This was necessary to know the coverage of each historical plan and therefore to identify the area that was not wooded. It is noteworthy that some mapmakers clearly exaggerated the width of watercourses, such as the River Nith, when the latter marked the physical boundaries of the mapped area – perhaps to emphasise the boundaries of the lands and for aesthetic reasons. As vectorising the whole watercourse could create an important bias regarding what was wooded or not, only a small watercourse width was vectorised.

2.2.3.5 Spatial aggregation and post-processing

After vectorisation of estate plans' boundaries and woodland, a global assemblage was undertaken by merging all the polygon layers of all georeferenced plans in separate files according to their two categories – woodland or plan boundaries – and the time series to which they belong. This allowed reconstruction of the woodland cover across the study area and at three different time periods: the mid- to late eighteenth century (1740-1799), early nineteenth century (1801-1833) and c.1860 (First Edition OS maps). Although the two earliest time series do not overlap everywhere (see Figure 2.8) it will be always possible to compare one of them against the woodland cover in c.1860.

The challenge of aggregating plans' boundaries or woodland polygons from hundreds of different maps to create geospatial databases led to some post-processing adjustments. Choices and implementation involved were based on the projected use of the databases. Indeed, while producing the coverage map presented in Figure 2.8, misalignment could occur during the global assemblage of the different plan's boundaries. This happened due to positional inaccuracy and more particularly when the boundaries of adjacent plans were separated by a stream, the depiction of which appearing not particularly accurate on the historical estate plans used for this PhD – the smaller watercourses, for instance, were often depicted as simple snake-like lines. Watercourses could also change through time causing a mismatch between the plans' boundaries of lands lying on either bank. Two types of data inconsistency may then occur: 1) narrow 'no data' gaps between polygons, also called *slivers*; and 2) overlap of different data — related to the different maps — at the same location. As the slivers could not be responsible for major issues during subsequent analysis, they were not corrected. However, to keep the database consistent, overlaps had to be suppressed in a post-processing step which consisted of keeping only one of the two overlapping polygons. The choice of the polygon to keep was arbitrary as it had no impact for future analysis.

The same issues also occurred when aggregating adjacent woodlands polygons from different maps. When two or more polygons were separated by a stream, the slivers remained untouched (i.e.

without filling). This was to keep separate woodland sites on both sides of the stream, the latter having a potential importance during future analysis as an ecological barrier and for the study of woodland metrics in Chapter 3. However, misalignment slivers could be filled for adjacent woodland polygons separated by a fence or a wall when it was obvious that it resulted from slight positional differences due to the georeferencing process or the accuracy of the plan. As for plans' boundaries, woodland polygon overlaps at the edge of different plans were removed in an unbiased way with the data of only one of the overlapping polygons being retained.

In addition, plans of the same time series occasionally covered the same area twice within a few years. An example of this is the land of Airds mapped in 1791 by J. Wells, only nine years after a survey by W. McCartney. While the plan by Wells was drawn along with other plans belonging to the same landowner and commissioned by him, the earlier map by McCartney was actually commissioned by the Court of Session to solve a property dispute. Another example concerned lands belonging to the third Duke of Queensberry near Drumlanrig castle. It appeared that in the 1760s, J. Wells was employed by the Duke to survey part of his lands, while the plans by J. Leslie (1772) were part of a larger project that aimed to survey all the lands belonging to the Dukedom. The little dissimilarity between the plans of the two surveyors suggests that Leslie made a new survey of the lands rather than copying Wells. In the cases where the same area was covered by at least two plans of the same time series, the data of the first plan of the overlapping woodland polygons were aggregated, in order to work with the earliest cartographic evidence for each woodland site.

2.3 Results

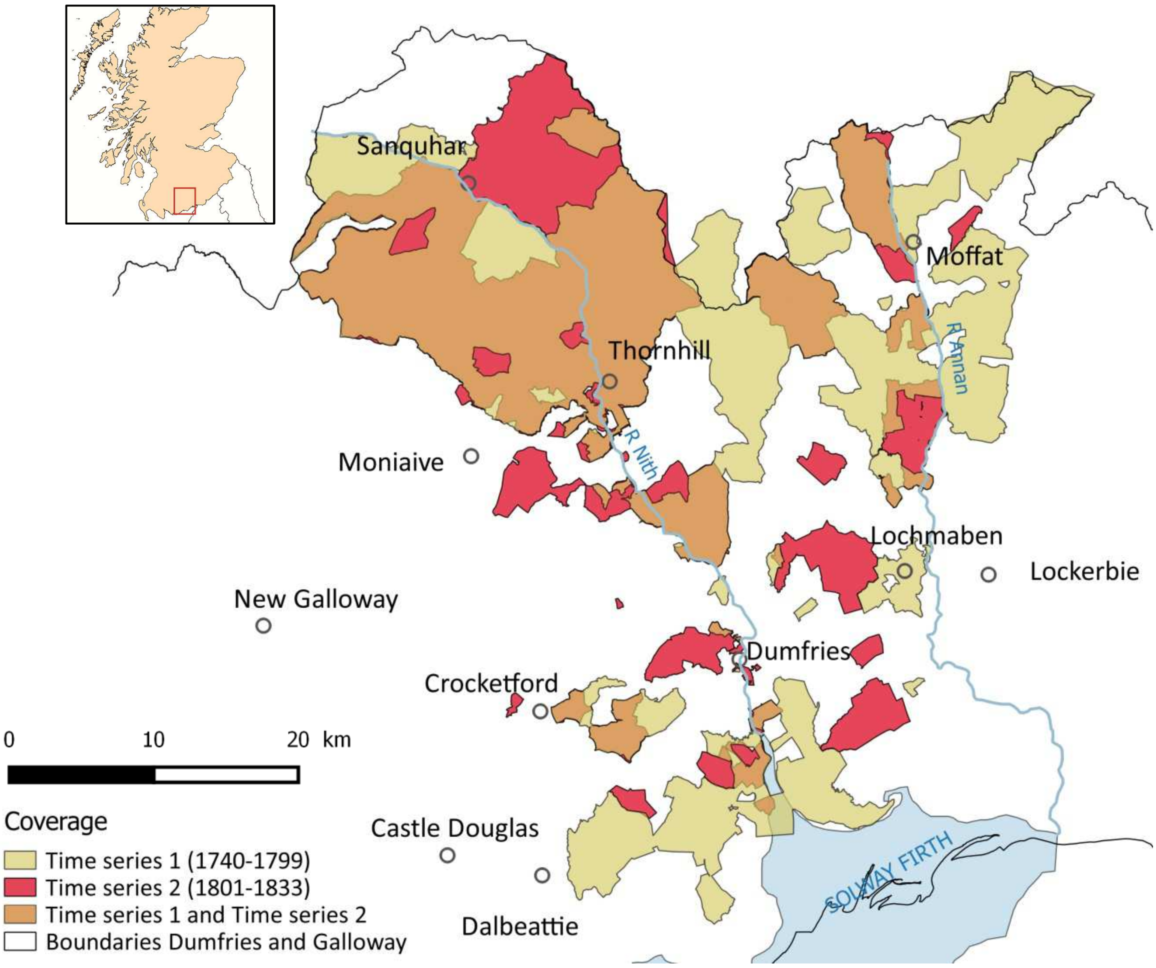


Figure 2.8 Coverage in Nithsdale and Annandale with 352 estate plans dated 1740 to 1833.

Table 2.6 Area covered by estate plans

Time series	Area (ha)
Time series 1 (T1)	86,526
Time series 2 (T2)	63,098
Total covered by T1 and T2	41,984
Total covered by T1 and/or T2	107,698

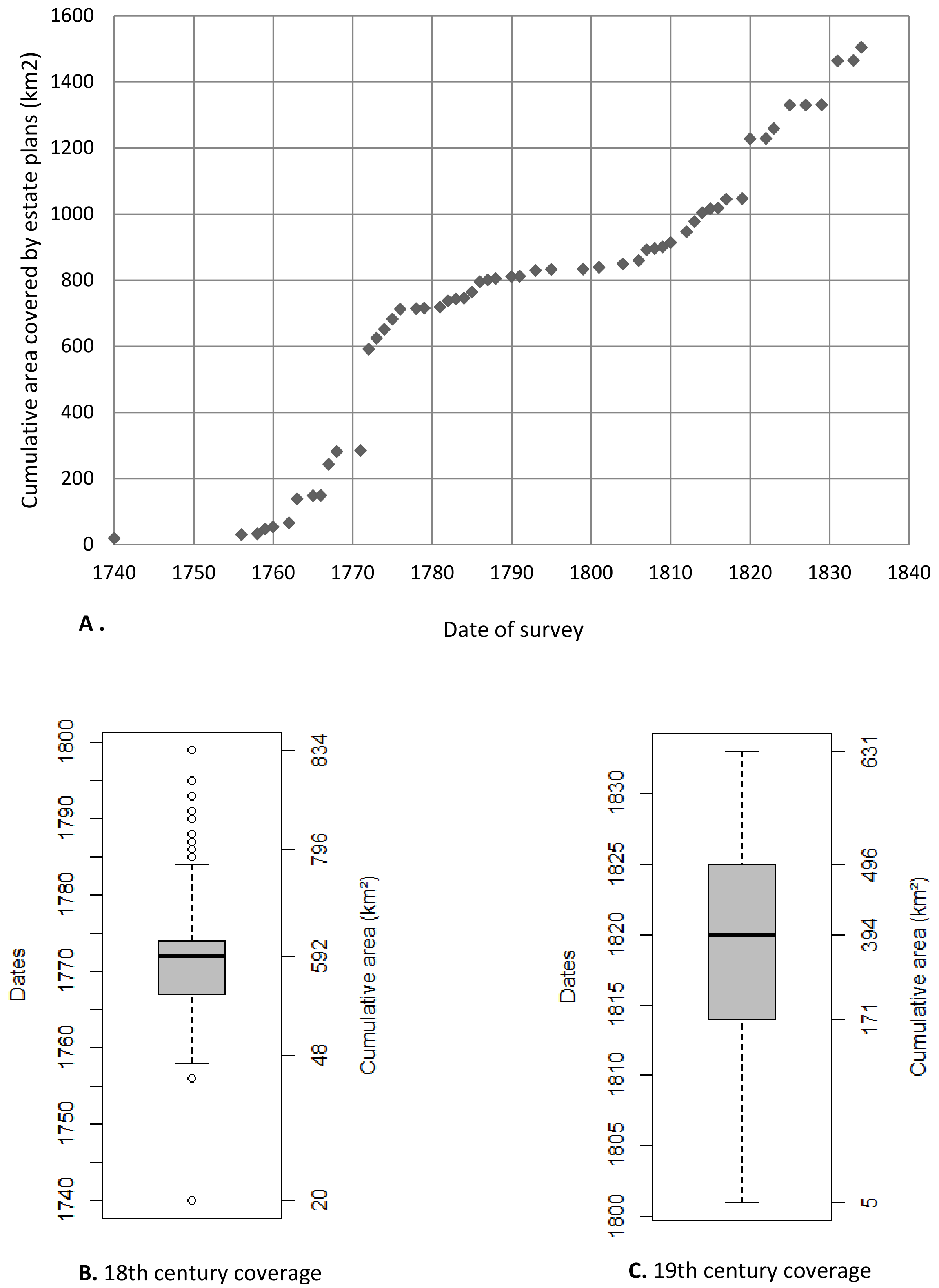


Figure 2.9 (**A.**) **Cumulative area covered by estate plans from 1740 to 1833;** (**B.**) **Distribution of the coverage according to the dates of the plans that were drawn during the eighteenth century; (C.) Distribution of the coverage with maps drawn during the nineteenth century.** For **B.** and **C.**, as an indicative basis, the right vertical axis show the equivalent cumulative area covered with maps though the eighteenth and nineteenth century.

2.3.1 Coverage in Nithsdale and Annandale

Figure 2.8 shows the spatial coverage achieved for each time series after assembling the boundaries of all georeferenced historical plans. Altogether, the estate plans cover a total area of about 107,700 ha while the two time series cover a common area of 41,980 ha. The first time series (T1, 1740-1799) covers about 86,520 ha and the second time series (T2, 1801-1833) covers 63,100 ha. Woodland reconstructions in T1 and T2 will be therefore not systematically comparable everywhere. However, comparisons with the First Edition OS – 25 or 6 inch to the mile series – will be possible on the whole study area.

The selection of estate plans aimed to keep some form of continuity in the coverage but large gaps inevitably occurred. Many plans used for this study were commissioned by large landowners and many of the cutting and gaps in coverage correspond to the boundaries of their lands. However, national archives, public collections and DAMP helped to collate also plans commissioned by smaller landowners. These plans particularly enabled coverage of the area south and west of Dumfries, as well as lands around Lochmaben.

Since the summer of 2016, after the end of data collection for this project, DAMP has copied more estate plans. While some of them could partly fill these gaps, and more are expected to be found in the future, it is also certain that gaps will remain. Many plans might have been lost or destroyed over time, making full coverage of Nithsdale and Annandale nearly impossible. However, for the scope of this study, the area covered by estate plans was already considered as sufficient to uncover significant changes in past woodland cover in the study area.

2.3.2 Dates of survey per time series

Aggregating separately eighteenth century from early nineteenth century data from estate plans could, at first sight, appear arbitrary. However, this separation is not only due to the common convention of historians to discuss events of eighteenth versus nineteenth centuries. With regards to the periods of estate surveys, Figure 2.9 shows contrasted trends in our set of maps between the two time series. The curve in Figure 2.9A reflects the cumulative area covered by estate plans through time. There was a steep increase of about 664 km^2 of land surveyed between 1760 and 1780, with an acceleration that led to more than 300 km^2 surveyed in 1772 when J. Leslie finished his plans of Drumlanrig estates. Surveys at the end of the eighteenth century seem less regular, with only a slow increase of 115 km^2 mapped between 1780 and 1799. Between 1804 and 1833, the curve shows once again a steeper and steady increase in coverage to reach the cumulative area of about 625 km^2.

Figures 2.9B and 2.9C offer an alternative to visualise the changes in coverage over time. Figure 2.9B shows that 75% of the area surveyed in the eighteenth century was surveyed between 1758 and 1774, 50% within six years (1768-1774 – see grey box). Regarding the second time series (Figure 2.9C), the distribution is more spread but dominated by maps drawn between 1815 and 1825 (50% of the area). These two periods may then correspond to periods of more intense estate mapping activity. As a result, we can expect that future work on this collection of estate plans will see the results dominated by data from the years 1768-1774, for the first time series, while the weight of the years 1815 to 1825 will dominate the estimates made from nineteenth century plans. Therefore, the choice of separating the maps into two groups, according to the century they belonged to, appeared obvious and meaningful here. In addition, this separation is supported in the data by the fact that most estates for which two pre-OS plans existed were surveyed in the eighteenth century and, many decades later, in the nineteenth century.

2.3.3 Woodland cover reconstruction: three case studies

2.3.3.1 Maps of woodland cover reconstruction

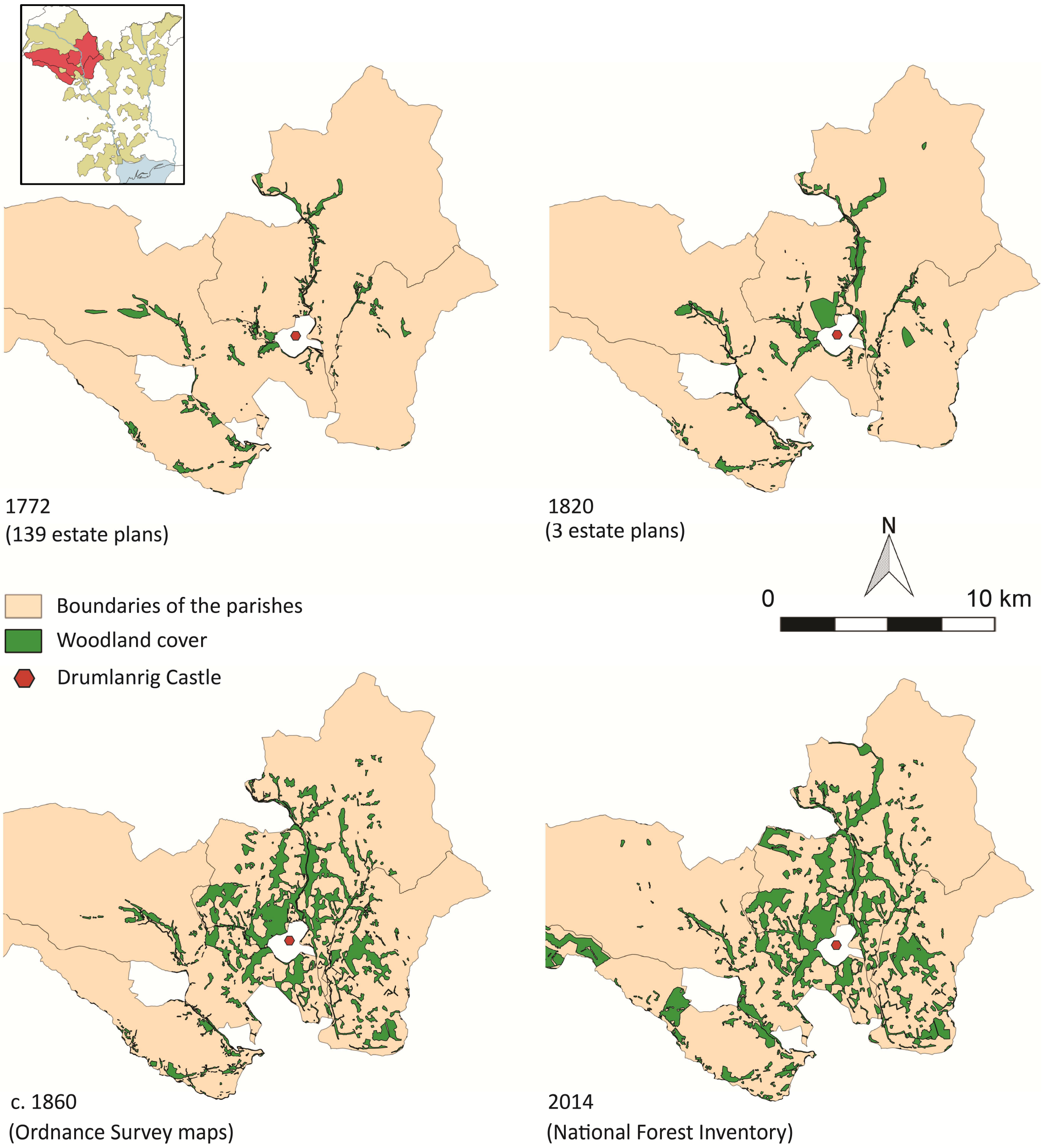


Figure 2.10 Extract of the woodland cover reconstruction for 1772, 1820, c. 1860 and 2014 in the parishes of Morton, Durisdeer, part of Penpont and Tynron near Drumlanrig Castle. The coverage corresponds to part of the area surveyed in 1772 by James Leslie and 1820 by William and David Crawford. Data for 2014 are extracted from the National Forest Inventory (NFI, 2014). Polygons for which Category was 'Non-Woodland' in the NFI geodatabase were left out. The number of estate plans used to make the reconstruction is indicated for the years 1772 and 1820.

Table 2.7 Area covered with woodland in part of the parishes of Morton, Durisdeer, Penpont and Tynron. Percentages are expressed relative to the total area covered (22,546 ha).

Date	Area covered with Woodland (ha)
1772	661 (2.9%)
1820	966 (4.3%)
c. 1860	2,296 (10.2%)
2014	4,248 (18.8%)

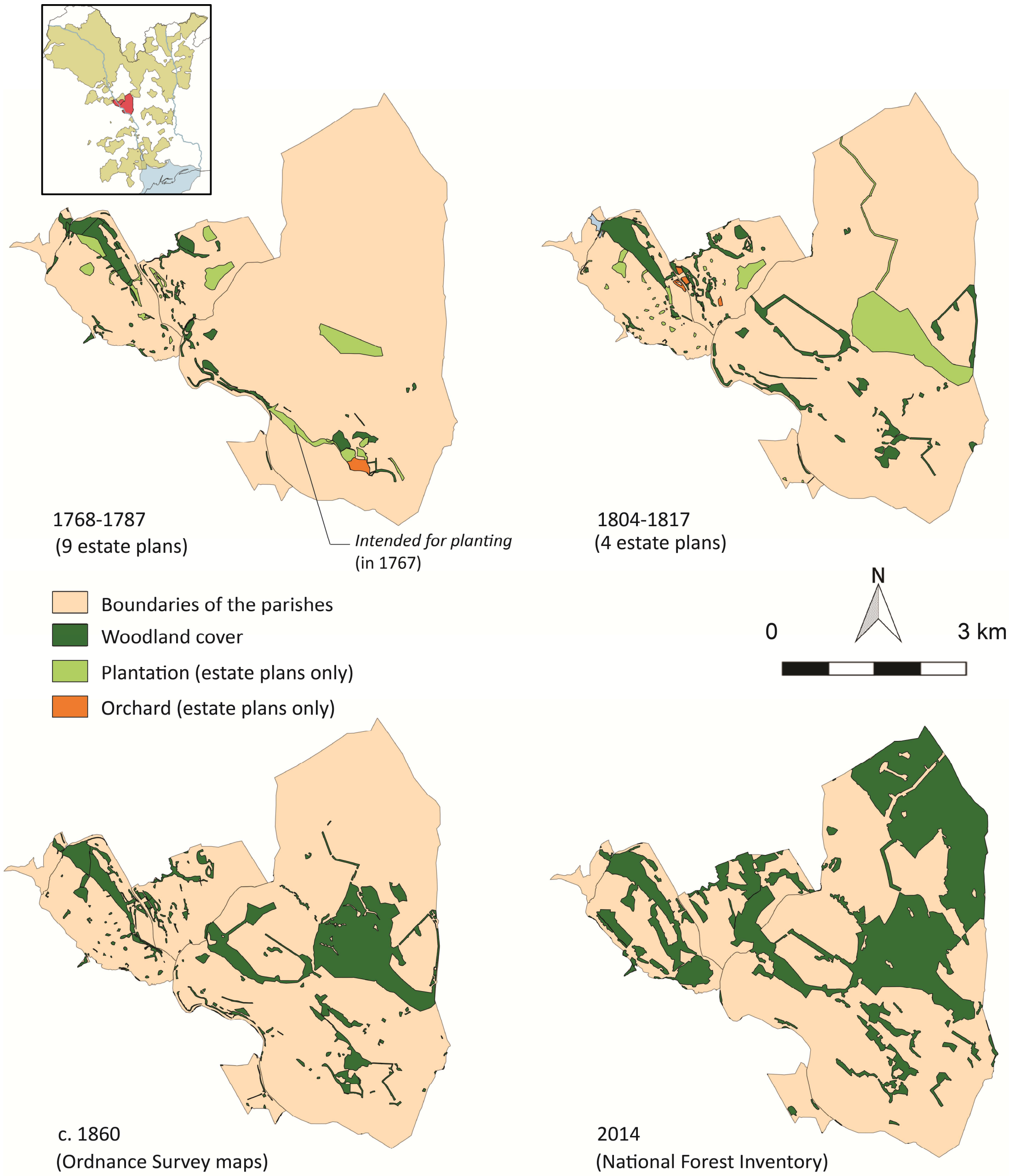


Figure 2.11 Woodland cover reconstruction for 1767-1787, 1804-1817, c. 1860 and 2014 in part of the parishes of Closeburn, Keir, Kirkmahoe and Dunscore (Dalswinton estates and surrounding area). Areas as 'plantation' and 'orchard' were deducted from estate plans indications by the surveyors only and do not mean to be exhaustive.

Table 2.8 Area covered with woodland in part of the parishes of Closeburn, Keir, Kirkmahoe and Dunscore. Percentages are expressed relative to the total area covered (2,744 ha).

Date	Area covered with Woodland (ha)
1767-1787	180 (6.6%)
1804-1817	332 (12.1%)
c. 1860	411 (15.0%)
2014	941 (34.3%)

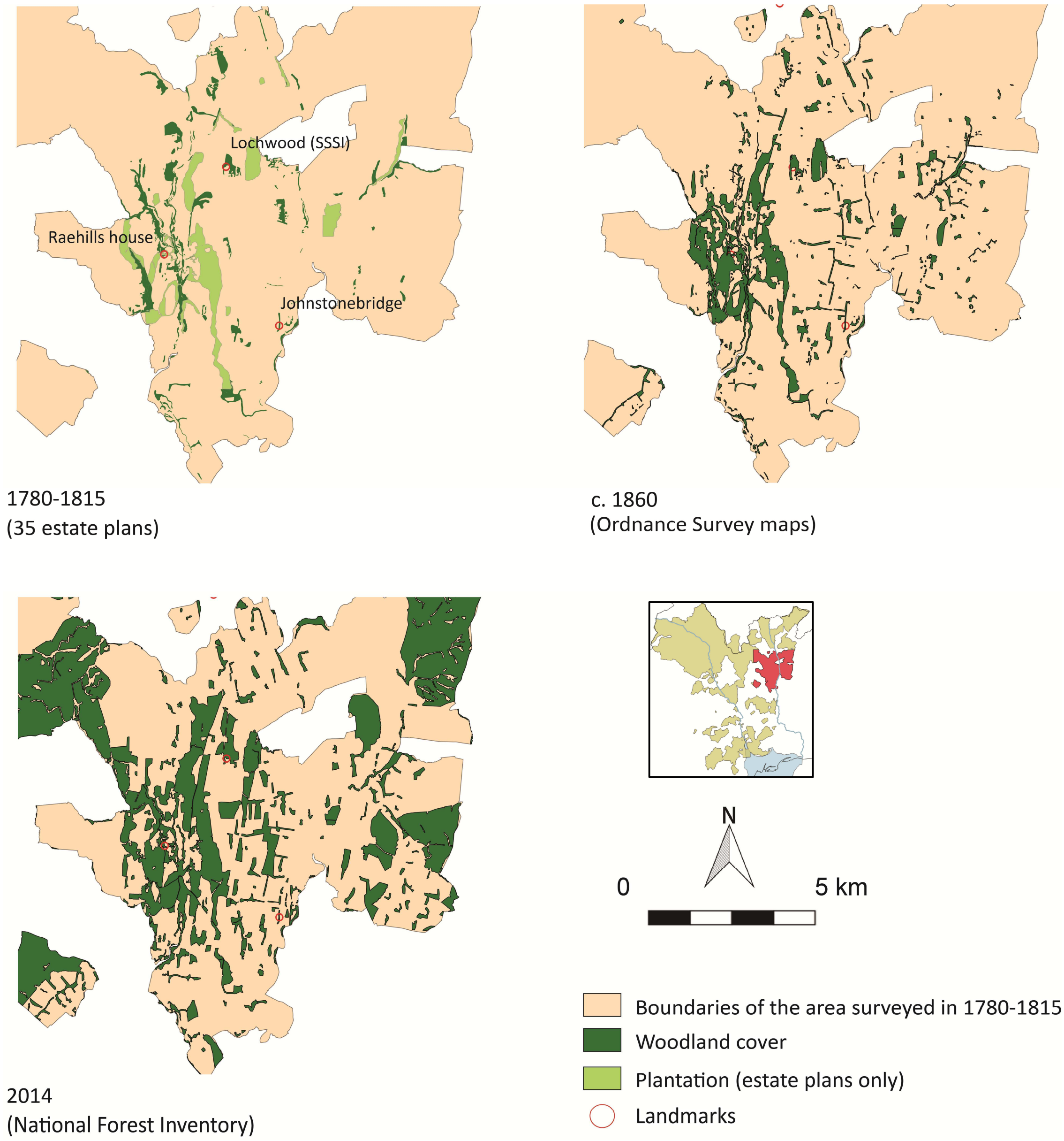


Figure 2.12 Woodland cover reconstruction for 1780-1815, c. 1860 and 2014 in part of the parishes of Johnstone, Kirkpatrick-Juxta and Wamphray (Annandale estates). Area as 'plantation' was deducted from estate plans indications by the surveyors only and does not mean to be exhaustive.

Table 2.9 Area covered with woodland in part of the parishes of Johnstone, Kirkpatrick-Juxta and Wamphray. Percentages are expressed relative to the total area covered (12,954 ha). The area covered with plantations in 1780-1815 is a minimum estimate only.

Date	Area covered with Woodland (ha)
1780-1815 total	940 (7.3%)
- 1780-1786 plantation	299 (2.3%)
- 1786-1815 plantation	187 (1.4%)
- 1780-1815 total plantation	466 (3.7%)
c. 1860	1,147 (8.8%)
2014	4,029 (31.1%)

Figures 2.10, 2.11 and 2.12 show three cases of detailed woodland cover reconstructions for respectively, Drumlanrig, Dalswinton and Annandale estates. These examples illustrate various outcomes from the reconstruction process depending on the source of data and location.

For the three case studies, the coverage includes all types of woodland cover as presented in Table 2.4. In the case of Drumlanrig estates (Figure 2.10), classes 'Woodland', 'Low woodland', 'Bushes', and 'Open woodland' could be precisely determined from James Leslie's table of contents and accounted for respectively 70%, 10%, 11% and 6% of the vectorised woodland vegetation. The remaining 3% could not be categorised because of uncertainties due to unclear depiction or explanation (i.e. '*Pasture wett*' or '*Meadow*' on which were depicted round symbols representing either trees or bushes; areas that seem wooded on the plans but for which the description is missing). Due to the scale and for the sake of clarity, watercourses were not represented on the reconstruction maps but most woodland cover depicted by Leslie lay along watercourses.

As these eighteenth century plans were from the same surveyor, the categorisation of the woodland into vegetation classes was easier for Drumlanrig estates and certainly more consistent than elsewhere in the study area. However, these vegetation classes cannot be systematically compared with the classes identified from the plans drew in 1820-1825 by William and David Crawford which cover the same area. Unlike Leslie, Crawford and Crawford did not distinguish the vegetation by annotations or symbols to distinguish woodland from bushes and brushwood. In general, the lack of comparability between time-series regarding vegetation classes is an important limitation of using estate plans to understand intrinsic woodland changes. Nevertheless, Crawford and Crawford mentioned other relevant information regarding the vegetation classes and woodland management. Many sites are indicated as 'plantation' and the surveyors identified various kinds of open woodland sites such as 'pasture with wood' and 'wood and meadows'.

Regarding Dalswinton estates (Figure 2.11), it is interesting to note that estate surveyors named as 'plantation' on the plans only some of the sites planted with woodland. Indeed, comparisons between the two earliest time series clearly suggest that there was more plantation than was indicated by mapmakers on early nineteenth century plans — natural regeneration being unlikely to have happened on such a large extent. Moreover, some woodland sites identified as "plantation" on eighteenth century plans were only described as "wood" on nineteenth century plans. Perhaps, the most recent plantations only were considered as such, or the largest planted sites. In any case, this issue confirms that the surveyors' indications were insufficient to identify all planted sites on the area covered by estate plans. As a result, estimates of area planted with woodland should be understood as a minimum only.

Unlike for the Drumlanrig and Dalswinton estates, woodland cover reconstruction on Annandale estates (Figure 2.12) did not allow a systematic comparison between T1 and T2 because of their very small overlap (see Figure 2.8). As many of these plans emphasised the woodland plantation and they often provided the exact dates for each, data from plans dated 1780-1815 were merged here into the same time series. In this manner, the reconstruction from estate plans can be compared afterwards against other time periods (i.e. c.1860 and 2014 data). The reconstructions also become more informative showing the large extent plantations with regards to the area wooded in 1780-1815, while it was also possible to estimate the minimum woodland area planted for the periods 1780-1786 and 1786-1815. Although the part of the reconstruction for the estates located towards the south of the study area is not discussed here, an extract is provided in Appendix B.

2.3.3.2 Woodland cover estimates

For all case studies, the woodland cover increased considerably between each time series: from 2.9% to 10.2% between T1 and c.1860 in Drumlanrig estates (Tables 2.7) and 6.6% to 15.0% for Dalswinton (Tables 2.8). In Annandale, this can be seen through the large area of plantations in the study area: a minimum of 466 ha of woodland was planted between 1780 and 1815 corresponding to almost a half of the total area under woods estimated during that time period (940 ha). The same trend of increase can be observed in most of the study area, as is shown in Chapter 3. However, it must be noted that the examples of Drumlanrig, Dalswinton and Annandale were purposely selected to show how woodland cover changes can be revealed by spatial reconstructions using many estate plans. Therefore, to visualise the changes better, these examples focused on estates with a lot of woodland compared to the rest of the study area. Consequently, the estimates provided in Tables 2.7, 2.8 and 2.9 do not reflect the proportion of woodland at larger scales, which is much lower when one integrates all areas not wooded in the past. Estimates of the woodland cover at the scale of the whole study area are considered further in Chapter 3.

Finally, changes of woodland cover in the study area happened progressively and irregularly depending on location. The increase of the woodland cover we observed previously in Figures 2.10, 2.11 and 2.12 occurred across the whole study area but at different paces. Therefore, the resulting composite images produced for each time series – because estate plans were made in different years – do not reflect accurately the woodland cover at a single point in time. The purpose of these reconstructions was mostly to uncover trends at different location to understand better changes that happened before the time of the First Edition OS mapping. As a result, calculations behind the quantitative assessment of woodland cover at each time series as provided in Tables 2.7, 2.8 and 2.9 were approximations that aimed primarily to reflect the overall extent of the changes, rather than estimating the exact amount of woodland changes between specific years.

2.4 Discussion on the uncertainties in the woodland cover reconstruction

'Uncertainty' can be defined as doubt about information provided by a map at a specific location (Fisher, 2003). Linked to data quality, several sources of uncertainty are likely to occur when working on estate plans. An assessment of uncertainties and limitations of using estate plans is required before proceeding to further studies. This assessment can help to decide whether the geospatial database specificities meet the needs of future application (or, in other words, are fit for purpose – Veregin 1999, Leyk et al. 2005). Uncertainties can be integrated into the three domains defined by Leyk et al. (2005) in their conceptual framework of uncertainty investigation*: Production-oriented uncertainty*, *Transformation-oriented uncertainty* and *Application-oriented uncertainty*. In drawing on this conceptual framework, this discussion explores in a chronological manner the uncertainty arisen from the historical estate plans production to their practical use for research on woodland cover changes.

2.4.1 Production-oriented uncertainty

The uncertainties arising from field survey (observation and measurements), conceptualisation by the mapmaker (discretising, abstraction and generalisation) and map production constitute what Leyk et al. (2005) defined the *production-oriented uncertainty*. This domain of uncertainty is closely linked to the data quality of the plans and, therefore, inherent to historical data. Two aspects of the topographical information are now assessed, namely, 1) *reliability*, defined as how true and comprehensive the information was (Bendall, 1992), and 2) *positional accuracy*. In studies that make use of historical maps, positional accuracy usually refers *to planimetric accuracy* and *geodetic accuracy* (Bendall, 1992). The former evaluates how the distances and bearings between two objects on the map match their true values, and the second refers to the position of a map in a coordinate system (Bendall, 1992, Jenny and Hurni, 2011). As estate maps cover small distances, the latter is considered as not relevant for this study (Bendall, 1992, Jenny and Hurni, 2011) and planimetric accuracy only is discussed. Although not treated by Leyk et al. (2005), a third issue that refers to later amendments of some of the estate plans is also considered.

2.4.1.1 Reliability of the information

Regarding woodland evidence on estate plans, the main critical question is how reliable and comprehensive is the woodland record on historical estate plans. For example, Glaves et al. (2009a) noted that woodland sites were sometimes omitted when it did not suit the purpose of the map, and that hachuring to represent the slope can obscure the symbols for woodland. While it was perhaps more often the case for earlier, sketchier, estate plans – such as seventeenth and early eighteenth century documents – the omission of woodland to show physical characteristics of the landscape could only be evidenced on Crawford's county map of Dumfriesshire dated c.1804.

Concerning the estate plans used for this study, the information they provide tends to suggest that woodland was unlikely to be intentionally overlooked. Firstly, all tables of reference refer to measurement estimates of the woodland cover within each estate, or part of the estate. This suggests an interest from the landowner to know how much of his land was wooded. In the context of agricultural improvement and at a time when plantations were thriving almost everywhere in the study area, one can imagine that having an accurate depiction of the woodland cover on commissioned estate plans was indeed in the interest of landowners.

Secondly, as mentioned previously, it has occasionally been possible to compare plans of the same area made close to each other in time (i.e. within a very few years'). These comparisons helped to assess the *consistency*, defined by Veregin as 'the absence of apparent contradictions in a database' (Veregin, 1999, p.182). For instance, the part of the parish of Durisdeer lying east of the River Nith near Drumlanrig castle was mapped by J. Wells in 1763 and by J. Leslie in 1772. While quite different in style, Wells drawing showing slightly more topographical information, the two plans show very similar woodland cover. Likewise, almost identical woodland cover is shown for the farm of Airds in the parish of Troqueer surveyed in 1786 by W. McCartney and in 1791 by J. Wells. More differences exist for the Dalswinton estates mapped in a Volume of 14 farm plans by W. McCartney in 1768, and J. Wells in 1786. However, this difference seems to be real and related to the ongoing trend of increasing plantation cover that occurred in this estate until at least c.1860 (see Figure 2.10). Notably though, a large 12.3 ha woodland site mapped by McCartney in 1768 was not depicted by Wells in 1786 while the trend in this area suggests increasing woodland planting with time rather than felling. In the relevant table of reference, McCartney noted about this site: "intended for plantation" (Figure 2.10). The fact that neither Wells nor anyone else afterwards depicted this woodland certainly means that this plantation never occurred and that McCartney had mapped as planted an area that was intended to be planted but never was. This conclusion should prompt caution when the table of reference associated with an estate map is missing. Although difficult to know how often it happened, this matter should be borne in mind in the critical assessment of the woodland changes deduced from estate plans.

Nonetheless, the great detail with which the mapmakers often drew the woodland boundaries and the degree to which their shapes were consistent over time allowed little doubt on the reliability of the woodland depiction. The consistent changes observed after comparison between the time series did not point to either any woodland that may have been overlooked or ignored in the past. This second issue is slightly more complicated to detect, however, as it implies that a record for each of the three historical time series exist for the same area, which was not case for the whole study area (see Figure 2.8). Signs that should signal caution about woodland depiction include when a woodland site is depicted on time series 1, disappears on time series 2 and is depicted again on time series 3. In a similar way, Kaim et al. (2014) investigated reliability in the analysis of changes in forest with a *trajectory analysis* which records absence or presence of a forest site for each of their four time series. This analysis allowed quantification of less realistic trajectories. A trajectory analysis is undertaken in Chapter 3. While there was no data to support this hypothesis in this study, it is also possible that certain forms of management, such as recent coppicing, may have caused the surveyor unintentionally to overlook some woodland sites and consider them instead as open lands (Glaves et al., 2009a; Kaim et al. 2014).

The issue of understanding the tree symbols and the wide range of written description referring to woodland in the tables of reference constitutes the most significant production-oriented uncertainty affecting data quality. In that regard, Plew (2002) and Leyk et al. (2005) defined as *vagueness* the issue of categorising an object into ill-defined or fuzzy classes, resulting from overlapping definitions; and they defined as *ambiguity* the confusion arising when a concept has several meanings or weak definitions. Although the latter can occasionally be clarified after further investigation of semantic consistency – for instance by comparison of maps or by using other types of archives – it is still essential to bear in mind that vagueness and ambiguity will influence whether one considers an object as woodland and how it will be categorised at a certain location. As a result, using evidence from historical maps to categorise woodland sites into vegetation class and management types appeared problematic and not always consistent: some records such as ‘bushy wood’ or ‘natural woodland’ are ambiguous as they permit of multiple interpretations, which may also change over time. In the meantime woodland-related categories were defined based on vague evidence and fuzzy classes. These matters led to the impossible challenge of differentiating ‘woodland’ from ‘bushes’ and ‘brushwood’ in a systematic and consistent way across all the maps. In addition, due to a lack of evidence or to varying degrees of vegetation description level between the plans, many woodland sites could not be categorised.

However, as we see below in Chapter 3, categories can still provide a relevant insight into past woodland cover and management activities under the condition that they are used with great care. Along with the possibility provided by GIS software to select part of the geo-database with a combination of queries, categories provide more flexibility for defining woodland in future analysis. Indeed, the use of GIS helps to adapt the treatment of data to the aim of the research, and explore alternative options more easily. This is particularly useful to add or remove some categories when one tries to estimate the area covered by different types of woodland. For example, the total area used as wood pasture can be assessed taking into account only woodland sites with explicit mentions of pasture or in integrating all open woodland sites. This helps to place the estimate area of wood pasture into a range of values. Likewise, vegetation studies of modern woodland sites with historical records may want to integrate or leave out sites recorded as 'bushes' or 'brushwood' during the eighteenth or nineteenth century. The use of categories should therefore vary according to the project goals and it should be done while bearing in mind the shortcomings behind the process of categorisation.

2.4.1.2 Planimetric accuracy

The varying purposes of historical maps meant that they did not all need to be planimetrically accurate (Bendall, 1992; Jenny and Hurni, 2011). The planimetric accuracy of historical estate plans was nonetheless likely to be the object of a particular care. This is, for instance, suggested by the table of contents associated with plans that provide acreage of the different types of land-cover/land-use such as infield, outfield, meadow, pasture and woodlands. Measurements undoubtedly served as a tool with regards to the way the landowners would manage their estates and run their businesses (improvement, price for renting, etc. – Adams, 1971). Adams (1971) also reported complaints of landowners not satisfied by the accuracy of their surveyors.

Surveying instruments, surveyor's skills and scale of the plans are all relevant in considering plans' accuracy when they were made. Some lands were certainly more challenging to survey than others, including steep areas or lands with higher elevation hills. In addition, errors may have occurred at each stage of the map production: from field measures to data compilation, sketch drawing, and fair copies production (Jenny, 2006). Errors were also likely to propagate if the survey covered larger areas. This could be mitigated by the use of theodolite and triangulation methods, rapidly considered as more appropriate to survey large portions of lands and recommended by John Ainslie, a well-known Scottish surveyor (Macnair et al., 2015), in his 1812 treatise on land surveying :

> (…) a theodolite, which is now the most common instrument that is made use of by experienced practical surveyors, and has many advantages over all surveying instruments, particularly for taking the surveys of large estate. (p.82)

After georeferencing, the alignment of historical maps with reference data and the calculation of the RMSE can partly help to assess the planimetric accuracy of these maps. However, how well a map aligns with reference data after georeferencing does not only reflect the quality of the mapping by the surveyors. Digitising methods, preservation of the drawing support, and size of the subsets of plans for local georeferencing can altogether strongly affect the planimetric accuracy of the georeferenced maps. The systematic reasons why some plans are more accurate than others was, therefore, not assessed further. This challenging task could be the object itself of another research project.

Contrary to the approach by Leyk et al. (2005), it does not seem relevant here to use the RMSE measure as an assessment of the transformation-oriented uncertainty only (i.e. uncertainty related to data processing, see section 4.2), when RMSE also partly reflects the varying planimetric accuracy of the plans and therefore the production-oriented uncertainty. Therefore, Figure 2.13, which is indicative of the degree of positional error that affects georeferenced plans, can be understood as the result of the combined effect of these two domains of uncertainties.

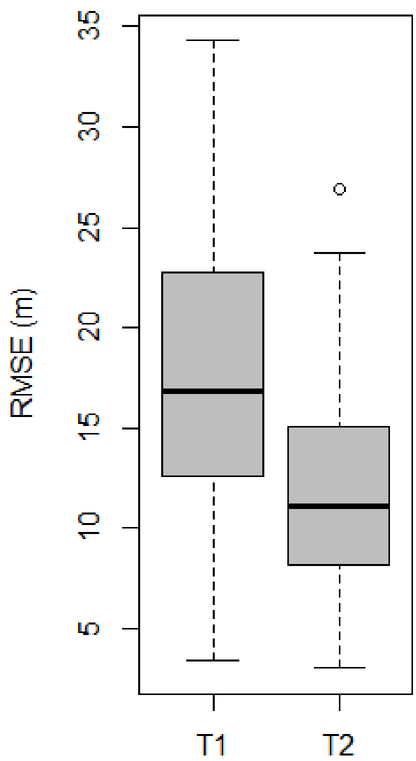


Figure 2.13 Boxplot of RMSE values for T1 (time series 1) and T2 (time series 2). RMSE values were calculated from respectively 143 (T1) and 81 (T2) georeferenced map images on which at least one woodland site was depicted.

Figure 2.13 shows boxplots of RMSE values for georeferenced map images categorised in the two earlier time series. The images correspond to the whole maps or subsets of it in the case of local georeferencing. The medians are respectively 16.8 m and 11.1 m for T1 and T2. The difference being statistically significant (Mann–Whitney U test, $p < 0.001$), the transformation process for georeferencing seems more consistent and accurate when applied on maps drawn in the nineteenth century than in the eighteenth century.

It is likely that the significant differences observed between T1 and T2 reflect partly the better quality of surveys associated with the improvement of instrumental accuracy and particularly the development of the theodolite. However, as already mentioned, various factors can also affect the

RMSE, in particular the number and quality of control points, type of transformation, and map storage responsible sometimes for wrinkles and curves of the drawing support.

For instance, in T1, 27 maps have a RMSE value above 24 m. Amongst them, 23 items are farms plans by James Leslie, bound in four different Volumes (1764-1766 and 1772, see example in Figure 2.2B). Besides the early dates of the maps, different reasons may explain a higher RMSE: 1) a fewer number of CPs could be found on individual farm plans of pre-enclosure landscape and uncertainties often occurred regarding the quality of these CPs as the position of objects may have moved over time in the context of a highly changing landscape; 2) some of the plans were drawn at smaller scales — 1:15,000 and less — compared to most other estate plans used for this study; 3) the area covered by the survey present a wide variety of landforms, particularly hills and steep river banks, making the survey more challenging. This may explain why some georeferenced plans from surveys undertaken on flat lands, by the same surveyor, presented a considerably lower RMSE (e.g. below 15 m for the surveys in the parish of Keir); and 4) the availability of plans under the form of volumes did not permit the making of copies as flat as would be preferred. Notably, the median of the RMSE values for T1 would decrease from 16.8 to 13.8 m if omitting the RMSE values calculated from georeferenced Leslie's farm plans of Drumlanrig estates. It would also decrease for T2 after removing survey of these estates during the nineteenth century, which may support further the assumption that Drumlanrig estates were more challenging to survey.

By extension, the RMSE of georeferenced maps can also serve to assess the planimetric accuracy of the woodland cover reconstruction. However, as for any statistical metrics, a good understanding of RMSE properties, and related uncertainties, is required. In squaring the residual errors before averaging, RMSE penalises larger errors associated with CPs (Chai and Draxler, 2014). As Chai and Draxler (2014) also noted, because RMSE is more sensitive to higher error values, it will vary with the range of error magnitudes and so all CPs will not have the same weight in RMSE calculation. As it is common to observe larger residual values for isolated CPs at the edge of the plans (e.g. Leslie's farm plans in Drumlanrig), this sensitivity of the RMSE may particularly affect its use to assess the accuracy of georeferenced historical maps. In practice, the least accurate parts of a plan (i.e. with highest CP's residual errors) will have more weight on the RMSE value than any other CPs.

This point is particularly important when one aims to assess the planimetric accuracy of woodland depiction on historical plans and the subsequent woodland cover reconstruction: the number of CPs was maximised in areas with woodland in order to make the georeferencing more accurate at these specific locations. However, this was done sometimes at the expense of the accuracy of other sections of the map, for which CPs ultimately had larger residuals and, in turn, increased the RMSE. As a result, georeferenced plans presenting high planimetric accuracy where the woodland was depicted, may have a high RMSE because other parts of the plan, without woodland, are less accurate. The RMSE values of these georeferenced plans — and associated woodland reconstruction — can therefore be considered as an upper estimate of the error, or planimetric uncertainty, of woodland depiction and reconstruction. In contrast, low RMSE values will not be representative enough of the planimetric accuracy of the whole item, and the woodland reconstruction, if 1) residual errors are calculated from a too little number of CPs; and 2) the CPs are unevenly distributed across the map. As a result, some georeferenced maps, for which control points were difficult to find, had a very low RMSE values whereas large sections – wooded or not – did not overlay properly on reference layers.

In addition, the RMSE value may also suffer bias as calculated based on chosen rather than independent CPs. As pointed out by Bendall (1992), these points are selected because they are more easily identifiable and, for a similar reason, they may have also served in the past to carry out the survey. As these points would not reflect the whole map but the maximum accuracy, this would have in effect decrease the RMSE.

These different cases show how variations in the RMSE values do not necessarily reflect directly the accuracy of a map. The RMSE can thus sometimes be a misleading indicator of the woodland cover reconstruction accuracy. In all cases, a single number to summarise many error values will always lead to a significant loss of information (Chai and Draxler, 2014). In combination with RMSE, other statistical metrics could be considered in the future to better assess the planimetric accuracy of woodland reconstruction: for examples, the mean absolute error (MAE) that gives a similar weight to each CP's residual error (Chai and Draxler, 2014); and a metric that would give higher weights to errors near any area of particular interest like woodland, and that will penalize georeferencing with few, or unevenly distributed, CPs.

2.4.1.3 Post-production changes

While not mentioned by Leyk et al. (2005), post map-production changes are also likely to occur and bear with further uncertainties. Many archives suffered time damages. For instance, the writings can fade away, which lead to a loss of information. It affected particularly the plans' table of contents. Some maps were also voluntarily amended in the following years to reflect future plans or recent changes. This last point was never an apparent problem for this research though as the observed changes did not mask the original content. Furthermore, it seems that the people responsible for these changes regularly mentioned the years of additions on the maps, and it is believed that amendments were easily identified by the use of different colours and symbols.

2.4.2 Transformation-oriented uncertainty

The successive steps of integrating data from historical maps into a GIS to produce the final geospatial database (i.e. digitisation of the maps, georeferencing the images, vectorisation and spatial aggregation of the woodland data) may be responsible for further uncertainties that may particularly lead to positional errors. The processing error (Kaim et al., 2014) is called *Transformation-oriented uncertainty* (Leyk et al., 2005). One way recommended by Leyk et al. (2005) to assess this domain of uncertainty is the calculation of RMSE values as presented in Figure 2.13.

The use of *second order polynomial*, which allows partial curvature of the map content (QGIS, 2015), or more mathematically complex *third-order polynomial* and *rubber-sheet* transformation methods would have helped to better align the historical map with the reference data and would have decreased the RMSE. These solutions have been particularly used on maps covering large areas like county maps (e.g. Macnair et al., 2016). To some extent, warping the image could also be used as a correction of the maps for which the drawing support suffered shrinkage or other physical alteration over time (Jenny and Hurny, 2011). These transformation methods would, however, give a false impression of accuracy and they would necessarily increase the transformation-oriented uncertainty in modifying dramatically the spatial data. The modification of the spatial content of the map would in turn alter to an unknown extent the original shape and size of the woodland as initially drawn by the mapmaker. For this reason, more constrained Helmert or affine transformation appeared preferable.

Petit and Lambin's (2002) concerns about the quality of the processed data being compromised by the resolution of the smallest scale map are not particularly relevant here given that estate plans generally cover only small areas and, in any event, are all drawn to a small range of scales. Likewise, the fact that the resolution of GIS software is almost without limit and, as such, far better than any digitised map (Petit and Lambin, 2002) is less an issue for estate plans than for maps drawn at smaller scales. For the latter, the vectorisation can be exaggeratedly accurate (e.g. woodland boundaries vectorised with a resolution below one meter) and thus be misleading considering the low resolution of the original maps. In the present study, most farm plans have a scale between c.1:6,000 and c.1:15,000, whereas other research studies used an array of historical maps with a wider range of scales (e.g. 1:25,000 to 1:100,000 for Kaim et al., 2014). Moreover, it is noteworthy that the estate plans with smallest scales were conveniently used to cover large portions of lands at high elevation where no woodland was growing. Only a few eighteenth century farm plans of smaller scales (c.1:35,000) and depicting woodland were georeferenced ('Reduction plans' by Josef Udny, see Appendix A). These plans cover the parishes of Moffat and Wamphray and they were retained as they provide also comprehensive information about past management, including plantations, wood pasture, coppice, and sometimes information on tree species. It might be relevant in the future to add the scale of the maps that were vectorised in the woodlands' attribute table, which was not possible for this study – the size of the plans was not systematically communicated by the organisations who copied them.

Finally, putting altogether a wide variety of plans made at different dates lead to a composite reconstruction that does not allow a snapshot of the woodland cover at a single point in time. Moreover, using the transition from one century to another as a threshold to separate the two earlier time series is not without influencing the woodland cover reconstruction and, therefore, woodland estimates calculated for each time series. A different date to separate the two earlier time series would necessarily affect the reconstruction and would lead to an increase of the woodland estimates for one time series at the expense of the other. As a result, the influence of the threshold contributes further to the transformation-oriented uncertainty.

2.4.3 Application-oriented uncertainty

Misinterpretation or discrepancy existing between the original purpose of the map and its intended application define the last type of uncertainty named *Application-oriented uncertainty*. According to Plewe (2002), misinterpretation can be the result of a lack of knowledge by the interpreter as well as variations in language and concepts between recorder and interpreter. This can be illustrated in the definition of various objects of study such as open woodland and wood pasture as we understand it today against mapmakers' conceptualisation and depiction. Ambiguous evidence (Plewe, 2002; Leyk et al., 2005) could strongly contribute to this domain of uncertainty as a wrong understanding by the interpreter may subsequently lead to a misuse of the data.

In addition, the risk of some bias resulting from the partial coverage of Nithsdale and Annandale cannot be completely avoided. Most maps used for this study were commissioned by large private landowners with, in fact, the financial capacities to undertake woodland plantations and major improvements on their estates. One can assume that changes occurred more rapidly, or more widely, on their lands than on the ones belonging to smaller landowners. This should be considered as a possible bias when quantifying and characterising past woodland cover changes at a regional scale. The database might not be absolutely representative of the whole study area but biased due to an over-representation of the lands belonging to larger, wealthier, landowners. This quality of the database is referred to by Veregin (1999) as *model completeness*. It defines the relationship between the "objects in the database" and "[their] desired degree of abstraction and generalisation" for a practical use (p. 183). Nonetheless, the study of plans from national institutions and the collection of small landowner farm plans by DAMP certainly helped to mitigate this possible bias.

Finally, as pointed out by De Keersmaeker et al. (2015) in their analysis of forest changes in Flanders since 1775, temporary events affecting woodland sites — such as temporary wood clearance — may have happened between two time series and remain undetected due to a lower *temporal resolution* (Veregin, 1999) of the woodland cover reconstruction. It must be taken into account when one tries to assess woodland continuity over time (De Keersmaeker et al., 2015). Examples of this issue are discussed further in Chapter 3 and illustrated in Muller and Carruthers (2017) (Appendix D). Chapter 3 and Chapter 4 analyse in detail the woodland database for specific research goals, and examples of application-oriented uncertainty will be further illustrated, as well as various practical solutions to cope with it.

2.5 Conclusion

This chapter details how data from 352 historical estate maps were collated in a GIS to reconstruct Nithsdale and Annandale past woodland cover with detailed boundaries. This was possible for two different time periods: the second half of the eighteenth century (1740-1799) and early nineteenth century (1801-1833). Over an area of about 1,077 km^2, this reconstruction provides an accurate and realistic depiction of past woodland cover distribution that can be directly compared with woodland cover extracted from the mid-nineteenth century First Edition OS maps (c.1860) and current woodland cover. Estate plans are also valuable in that they offer additional information on past management and shed further light on different kinds of woodland vegetation. More generally, this methodology demonstrates that the potential of estate plans is not restricted to local studies only. It highlights the considerable value of estate plans for studies of historical landscape that aim to reconstruct and investigate past landscape and regional changes at periods when cartographic evidence was scarce or considerably less detailed.

Although many uncertainties are associated with this methodology, the approach used here helped to mitigate some of their detrimental effect on the reliability and accuracy of the reconstruction. Using two transformation types faithful to the original survey — Helmert and affine transformation — is a pragmatic approach that both acknowledged the physical characteristics of the plans (e.g. wrinkles, shears) and subsequent spatial accuracy of the digital copy and allowed the georeferencing of map images with a spatial accuracy suitable for future research goals. This approach may compensate or mitigate deformations or inaccuracies at several stages of the process, including survey, map production, storage and digitisation of the plans. This methodology was enhanced further with local georeferencing of subsets of the largest size maps, or the ones covering the largest areas. Finally, although not always consistent, categorisation of the semantic elements related to woodland cover may offer more flexibility for future treatment of the data.

However, an assessment of the production, transformation and application-oriented uncertainties shows that significant forms of uncertainties can remain. These uncertainties are inherent to the challenge of working on a large number of plans varying in form, dates of production, and woodland data quality. While it highlighted some of the limitations of the geospatial database, this assessment helps to decide how its characteristics can meet the needs of future applications. In that regard, some uncertainties concerning the reliability and accuracy of historical maps, and derived woodland cover reconstruction, are analysed further in the two next chapters. These chapters are based on the woodland reconstruction at each time series to characterise qualitatively and quantitatively woodland cover changes (Chapter 3), to assess the reliability of the Scottish Ancient Woodland Inventory, and to identify specific sites for testing the ecological importance of woodland continuity (Chapter 4).

Chapter 3

Spatiotemporal woodland cover changes and their drivers since the mid-eighteenth century

3.1 Introduction

3.1.1 The importance of understanding past woodland cover changes

The long-term history (>100 years) of land-cover/land-use changes has strong implications on species and habitats distribution, diversity and abundance, thereby influencing present-day structures and functions of ecosystems (Foster, 1992; Foster et al., 2003). A better understanding of this long history has been increasingly regarded as essential to identify, conserve or restore habitats of higher ecological and cultural value (e.g. Cousins, 2001; Käyhkö and Skånes, 2006; Gimmi et al., 2011; Biro et al., 2013).

For Europe's woodlands, past management practices, such as coppicing regimes, grazing, plantation of non-native tree species, are likely to have had long-lasting effects on the biophysical characteristics of present-day woodland sites (Hermy and Verheyen, 2007; Hermy, 2015). Research has notably investigated the legacy of past practices and relatively recent changes on soil properties, seed bank, above-ground vegetation, invertebrate fauna, and lichens (Kirby et al., 1995; Holl and Smith, 2007; Van Calster et al., 2008; Chauchard et al., 2013; Fortuny et al., 2014; Munteanu et al., 2015). At the landscape scale, past management has contributed to shape the spatial configuration of the woodland cover and tree species abundance patterns (e.g. Käyhkö and Skånes, 2008; Rochel, 2015). It seems therefore fundamental to assess, at multiple levels, changing woodland management practices over time in order to understand their implications for present-day woodland ecosystems.

The continuity (i.e. uninterrupted presence) of woodland habitats is regarded as another key element in woodland ecology (Flinn and Vellend, 2005; Hermy and Verheyen, 2007; Nordén et al., 2014; Watts et al., 2016). In the UK, the most studied examples to investigate the effect of continuity on woodland ecosystems are certainly the so-called 'indicator species of ancient woodland' (Rose, 1999; Crawford, 2009) while ancient woodlands – established since at least 1750 in Scotland and 1600 in the rest of the UK – are considered as areas of higher biological value (see Chapters 1 and 4). Indeed, the areas continuously wooded for centuries are likely to be occupied by a larger diversity of slow coloniser' organisms that require environmental stability (Hermy and Verheyen, 2007). In addition, the regular higher structural heterogeneity of these woodlands – shaped by the interplay of continuity and management history – can provide a wider array of micro-habitats suitable for niche specialists (Hermy and Verheyen, 2007). Likewise, veteran trees, in open or dense woodlands, have been recognised as essential to preserve specialised saproxylic insect species, rarer lichens, and to maintain populations of bats and birds associated with these trees (Kirby et al., 1995; Siitonen and Ranius, 2015). As a result, ancient woodlands and old trees are commonly considered as habitats of major importance for conservation strategies in the UK (Goldberg et al., 2007).

The ecological properties of relatively more recent woodland that have grown on areas once used for other agricultural purposes are also strongly rooted into the past. For instance, it has been demonstrated that former land-use, such as arable lands, can exert a long-lasting influence on woodland soil properties – including carbon and nitrogen cycling, pH, phosphorus availability, microbial community –, seed banks, and vegetation composition (Fraterrigo et al, 2006; Hermy and Verheyen, 2007; Plue et al. 2008; Sciama et al, 2009; Fichtner et al., 2014; Hermy, 2015). In north-eastern France, Dupouey et al. (2002a) pointed out how former Gallo-Roman agricultural activities have influenced the present-day soil and flora characteristics of woodlands. Likewise, in the Carpathian region, Munteanu et al. (2015) assumed that contemporary woodland disturbance patterns (pest, pollution, wind throws, etc.) is rooted in the last 150 years of past land-use, with odds of disturbance estimated 50% higher in post-1860 plantations. As a result, understanding the ecological qualities of more recent woodland requires a good knowledge of past land-use and constitutes another reason for improved assessment of land-use/land-cover changes on a long-term basis.

On a broader scale, the rearrangement of the woodland spatial connectivity affects the mobility of many organisms via changes in the distances between woodland patches (Peterken, 2000; Humphrey et al., 2015; De Keersmaeker et al., 2015). Fragmentation of woodland cover can increase spatial isolation of individuals and lead to local extinctions of species (Watts, 2006: Humphrey et al., 2015). In parallel, changes in size and shape of woodland sites over time can modify local conditions affecting the viability of populations (De Keersmaeker et al., 2015). For example, woodland sites with a low perimeter-area ratio (i.e. long and thin shape) are more exposed to the *edge effect*, which is known to affect woodland biodiversity and ecosystem functions through modification of biotic and abiotic conditions such as light intensity, wind, air moisture, air temperature and nitrogen deposition (Murcia, 1995; McDonald and Urban, 2006). Landscape and patch indices have often been used to characterise woodland size and shape, spatial distribution patterns, and *in fine* to understand species diversity (Humphrey et al., 2015). These analyses have also been applied to vectorised woodland cover depicted on historical maps (De Keersmaeker et al., 2015).

3.1.2 Investigating past woodland cover changes using historical maps and other archives

With the improvement of GIS tools, new methods to analyse the spatial content of historical maps have been developed over recent decades (e.g. Cousins, 2001; Käyhkö and Skånes, 2006; De Keersmaeker et al., 2015). These methods have been occasionally applied to study the long-term woodland cover changes and to investigate the long-lasting effects on present-day woodland ecosystems (e.g. Wulf et al., 2010; Skaloš et al., 2012; Kaim et al., 2014).

To study the landscape changes from historical maps, two main approaches are regularly considered (Biro et al., 2013): 1) *change detection analysis*, which is based on the comparison of land-cover/land-use configuration between two time-series and which infers transition matrices (e.g. Cousins, 2001); and 2) categorisation of the landscape into *trajectories* of historical changes (e.g. Swetnam, 2007; Käyhkö and Skånes, 2008). This last approach is considered to be more qualitative (Biro et al., 2013) as it focuses on present-day landscape to highlight the long-time dynamics that generated its properties (Käyhkö and Skånes, 2006; Biro et al., 2013). The study of trajectories was also used to assess the overall reliability and accuracy of the woodland cover reconstructions from historical maps (Kaim et al., 2014). Both approaches are used in this chapter for their complementary aspects.

Furthermore, the value of historical maps can be enhanced when they are used in combination with other historical source types. For example, Wulf et al. (2017) used archival documents, books, and other elements of the 'grey' literature to complement historical maps and to investigate tree species composition changes since 1780 in north-eastern Germany. Written archives can also help to uncover the underlying historical driving forces and actors that operated in the area covered by the maps (e.g. Wulf et al., 2010; Bürgi et al., 2015). Driving forces are defined by Bürgi et al. (2004) as the forces responsible for the changes observed in the landscape and they can be biophysical ('natural'), socioeconomic, political, cultural, and technological. Regarding woodland management, placing the different trends in practices into their historical contexts (economy, politics, etc.) may help to better apprehend the long-lasting consequences of these changes on present-day woodland. In addition, Bürgi and Schuler (2003) have argued that the study of long-term driving forces can help to provide better forecasts of future development via more reliable projection scenarios of change.

Finally, spatial models that combine the analysis of historical maps with various biophysical parameters, and historical and archaeological data, can offer more opportunities to improve our understanding of past woodland cover changes. For example, Loran et al. (2017) used generalised additive models to investigate biophysical controls (e.g. climate, slope) and socioeconomic factors (e.g. population and farm census) that may have driven the forest gain in Switzerland during the years 1850-2000. Although not based on historical maps but on data derived from written archives, Müllerová et al. (2014) and Szabó et al. (2015) have also used spatial models such as maximum entropy methods to examine past coppicing management patterns since the Middle-Ages.

3.1.3 Aims and approaches

In parts of Nithsdale and Annandale, the eighteenth and early nineteenth century estate plans and First Edition OS maps are valuable sources of information to reconstruct past woodland cover with a unique level of spatial resolution for three historical time-slices, namely 1740-1799, 1801-1833 and c.1860 (see Chapter 2). These depictions cover times of great transformations of the Lowlands Scottish rural landscape, and for which direct evidence of woodland extent and management is usually scarce and incomplete. Through the study of the long-term woodland dynamics, this dataset has the potential to enhance our understandings of woodland history in the study area and the link between woodland cover changes and their present-day ecological implications.

However, historical maps are not sufficient on their own to understand the dynamics of past woodland cover across centuries and historical driving forces and actors. Estate plans offer little evidence of tree species composition of the woodland they depicted; by nature, they could not show the physical context of the woodland sites (e.g. elevation, steepness); and the temporality of the changes is sometimes unclear due to long intervals between time slices and the combination of plans drawn at different years within each time series. Regarding woodland vegetation classes and management types, Chapter 2 highlighted the challenges in thematically harmonising the evidence from estate plans.

In an effort to overcome these limitations, it seemed essential to adopt an integrative approach that combined multiple data to ascertain and complete the woodland cover reconstruction from historical mapping sources. Historical archives, archaeological data, DEM-derived data and other environmental data, such as soil and watercourses maps, provide background information that can add a new dimension to the woodland reconstruction. This information can also help to address some of the uncertainties introduced in Chapter 2, such as the uncertainty related to planimetric accuracy and the reliability of historical data (production and transformation-oriented uncertainties).

Drawing upon this integrative approach, this chapter aims to fill gaps regarding the following questions: 1) how has the woodland cover changed over time, in particular between the mid-eighteenth and mid-nineteenth centuries, for which there is a paucity of information?; 2) to what extent does the present-day broadleaved woodland cover bear the spatial imprint of at least 250 years of changes?; and 3) what processes, driving forces and actors may have accounted for these changes? In parallel, this chapter continues further exploration of some of the production, transformation and application-oriented uncertainties inherent to the use of historical maps (see Chapter 2).

3.2 Methods

3.2.1 Woodland datasets

To perform these analysis, we consider three time series at which the historical woodland cover was reconstructed from estate plans and First Edition OS maps: T1 (years 1740-1799), T2 (1801-1833) and T3 (c.1860) (see coverage of each time series, Figure 2.8). We also consider as T4, the time series for the woodland cover in 2014.

T4 is based on the georeferenced vector format database provided by the National Forest Inventory (NFI, 2014) and the Native Woodland Survey of Scotland (NWSS, 2014). The latter provides only information on the native and nearly native woodland habitats (e.g. ‘Wet woodland’, ‘Upland oakwood’, ‘Lowland mixed deciduous’, etc. see Chapter 1). An initial comparison showed that the NFI overlooked some woodland sites listed in the NWSS, which might have resulted from the different methodologies used to compile these two inventories (see Chapter 1). Conversely, some sites categorised as ‘Broadleaved’ in the NFI were not included in the NWSS. These sites may have been overlooked during the NWSS – any survey of this extent is likely have uncertainties – unless they were woodlands dominated by broadleaved tree species considered as non-native species, such as beech, sycamore and sweet chestnut (Wilson, 2015). It was therefore not possible to make a systematic distinction between non-native broadleaved and native broadleaved woodland sites in the study area. Considering this limitation and according to the goals of the spatial analyses undertaken in this chapter, the two vector format inventories provided by the NFI and NWSS were merged in a unique database as follows:

1) The NFI was first cleaned of the woodland polygons categorised ‘Non Woodland’, ‘Assumed woodland’, ‘Shrub’, ‘Ground prep’, ‘Felled’, ‘Windthrow’ and ‘Young trees’. It was uncertain for many of these sites, particularly ‘Assumed woodland’, if they were actually woodlands and extant in 2014. In addition, it was not possible to identify the woodland dominated by coniferous from broadleaved trees, which would have also limited the consistency of the analysis.

2) The NFI woodland categories named 'mixed mainly broadleaved' and 'mixed mainly conifer' were respectively re-categorised as 'broadleaved' and 'conifer'. This aimed to reduce considerably the number of analyses while a higher level of accuracy on woodland cover types would have not permitted a considerably more detailed interpretation of the data. As a result, the woodland categories 'broadleaved' and 'conifer' for this study were defined according to the dominant type of trees in the canopy.

3) The categories 'broadleaved' and 'mixed mainly broadleaved' from the NFI were merged with all 'native' and 'nearly-native' woodland sites from the NWSS and overlooked in the NFI. This was done with the objective to produce a comprehensive list of sites for which the canopy is dominated by broadleaved trees. By so doing, and with the subsequent intention to use this database to select sites for the field survey (see Chapter 4), it is assumed that all the broadleaved woodland sites with long-time history were recorded. It is noteworthy that some vector polygons from the NFI that were left out in the first step could be re-introduced when these polygons were categorised as 'native' or 'nearly-native woodland' in the NWSS.

3.2.2 Division of the study area

Put together, the estate plans covered a total surface of 107,698 ha (Figure 2.8 and Table 2.6). However, only an area of 41,980 ha was covered by estate plans of both T1 and T2. This area represents 48.5% of the coverage by T1 and 66.0% of the coverage by T2. Given the heterogeneous nature of the whole study area (e.g. hilly and flat lands, areas dominated by the river Nith estuary and Solway coast, see Chapter 1), the coverage by T1 and T2 may include lands with different physical characteristics. In view of increasing the comparability of the data between all the time series for the spatial analyses, the study area was broken down into three different sub-study areas, as follows (Figure 3.1):

- **Area 1** for the area covered by all the time series, namely T1, T2, T3 and T4 (41,980 ha)

- **Area 2** for the area covered by T1, T3 and T4 (86,526 ha)

- **Area 3** for the area covered by T2, T3 and T4 (63,098 ha)

It is noteworthy that these three sub-study areas are not spatially independent as they obviously overlap partially with each other. Additionally, **'Area 4'** is the whole study area of 107,698 ha covered by T1 and/or T2, T3 and T4, which serves for the comparison between T3 and T4 (Figure 3.1).

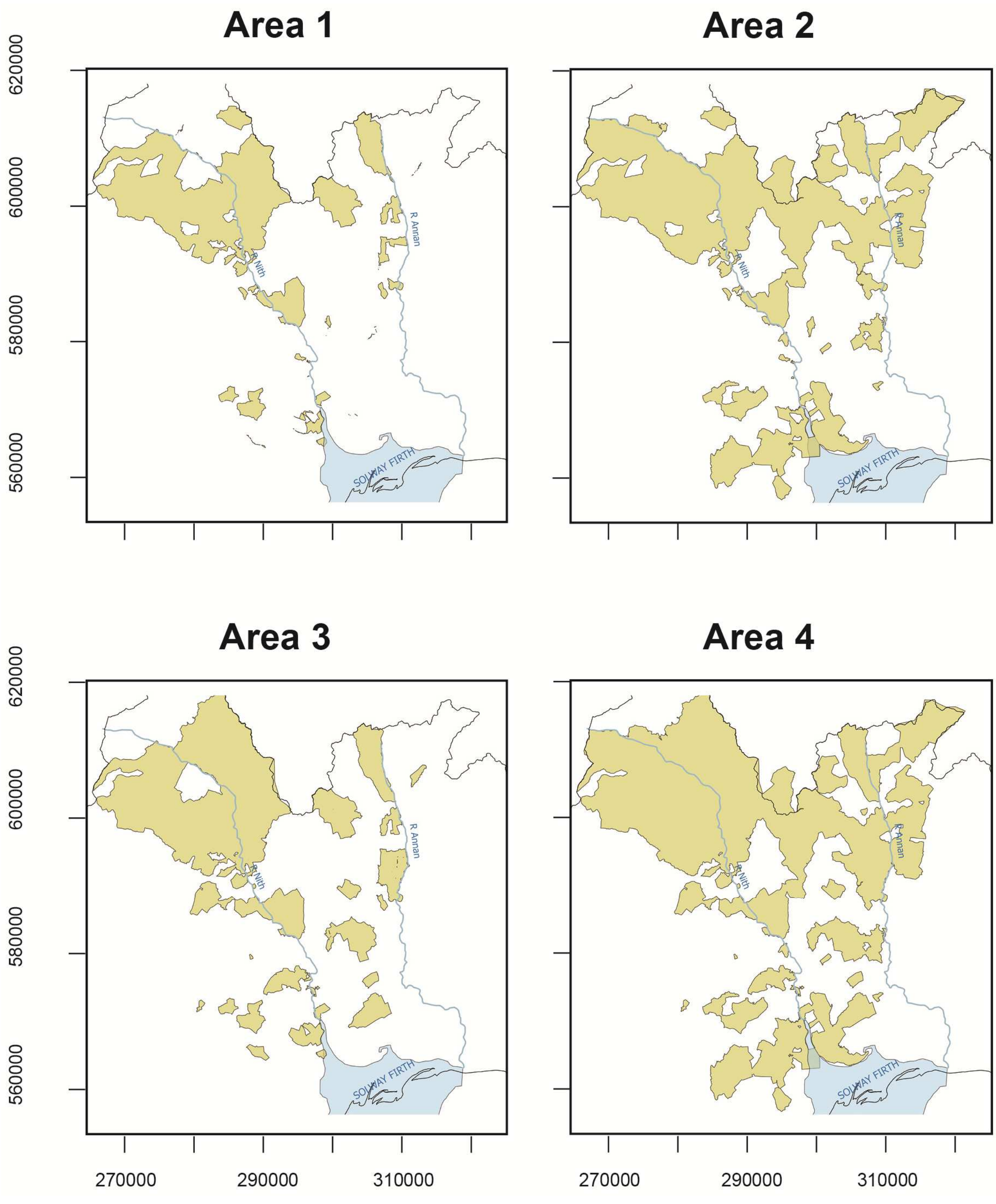


Figure 3.1 Division of the study area following the coverage with estate plans in T1 and T2.

3.2.3 Data conversion

Prior to the analyses, the shapefiles – woodland polygons captured from georeferenced estate plans – were transformed into georeferenced raster binary images with each grid cell covering an area of 5x5 m (25 m^2). The cells could therefore only take two values: '1' for cells with woodland and '0' for absence of woodland. Despite a slight loss of resolution, the raster format was an easier format than vector format for manipulating the woodland data from the different datasets (i.e. combining woodland maps and categorising woodland into historical trajectories), while affording a reasonable calculating time. Furthermore, the size of the grid cells permitted a spatial accuracy both faithful to the initial data acquisition under polygons format and sufficient in regard to the objectives of the spatial analyses. The rasterisation process also had a minor effect on the quantitative estimates of woodland coverage – the values are very similar to those calculated from the shapefiles – and did not impact the minimum woodland size that can be used for spatial analyses. Finally, a sensitivity analysis conducted by Swetnam (2007) on a series of maps with scales between 1:10,000 and 1:25,000 – similar to most of the estate plans used for this PhD project (see Chapter 2) – showed that coarser resolutions than 5x5 m could mask the rarer trajectories of changes. Consequently, Swetnam (2007) found this resolution most appropriate to study landscape changes.

At this stage, all vegetation classes (i.e. 'Woodland', 'Low woodland', 'Bushes', 'Open woodland', 'Orchard' and 'Unclassified', see Table 2.4) had been rasterised and considered indistinctly as 'woodland'. The GDAL plugin in the processing toolbox of the open-source QGIS v2.6.1 software (QGIS, 2015) allowed the rasterisation of the woodland cover reconstructions.

3.2.4 Woodland metrics

This analysis was done on woodland patches, a *patch* being defined as a group of adjacent cells sharing the same categorical value (i.e. '1') and following an 8-cell rule. According to this rule, the 4 diagonal and the 4 orthogonal cells adjacent to a focal cell belong to the same woodland patch (McGarigal et al., 2012).

The calculation of landscape metrics aimed to characterise the changes over time in woodland sites geometrical characteristics and, at the landscape scale, changes in the extent and configuration of the woodland cover. This study drew upon the calculation of simple indices for each time series, namely the total area covered by woodland, number of patches, and statistical distributions of patch size, including the Euclidean nearest neighbour distance and the shape index. The Euclidean nearest neighbour distance measures the shortest straight-line – edge to edge – distance between a focal woodland patch and the nearest woodland, while the shape index aimed to reflect the complexity of a patch compared to a compact square shape of the same size (McGarigal et al., 2012). As woodland patches presented a wide range of sizes, the shape index was found more appropriate for comparison between time series than the more straightforward *perimeter-area ratio*, which changes according to the size of the patch (McGarigal et al., 2012). These metrics can reflect changes in the woodland spatial configuration that are determinant for the movement of species and the viability of populations (De Keersmaeker et al., 2015). Developed by Martin Jung for QGIS (Jung, 2016), the python plugin *LecoS – Landscape ecology Statistics* – served to perform the analyses using the same calculation methods of metrics as those developed by McGarigal et al. (2012) in the widely-used software *Fragstats* (Jung, 2016).

It is noteworthy that a pre-processing step was undertaken first to remove artefact patches – isolated cells or small group of cells – produced after rasterisation of the woodland polygons, and the process of clipping the woodland cover according to the boundaries of the three sub-study areas. If these artefacts were considered as separated patches, they could affect the results of the landscape metrics analysis. The *sieved* GDAL function available in the QGIS processing toolbox enabled removing all artefact patches below 5 cells, which correspond approximately to the minimum woodland size vectorised from historical maps (see Chapter 2). In Area 1, the sieving step decreased the number of woodland patches from 450 to 408 for T1 and 1080 to 1002 for T3. Even though this revealed to have had a minor impact on the subsequent calculations of metrics, the results were thought to be more accurate.

3.2.5 Change detection analyses

These analyses were based on the production of *transition maps*, which indicated where the woodland is new, lost or extant between two time series. Quantitative data could subsequently be extracted. While the woodland metrics analysis accounts for net woodland cover changes only, this technique serves also to quantify gross changes (i.e. the total extent of woodland that undergone changes). Ultimately, the pairwise comparison of successive time series helped to reconstruct gradually the progressive changes in the extent of the woodland cover over time (Figure 3.2a). GDAL and the *Raster calculator* function in QGIS allowed the combination of raster files to categorise the woodland cover as 'new', 'lost' or 'extant' between two time series. *LecoS* (Jung, 2016) served to extract quantitative data.

The 'vegetation classes' and 'management types' categorised from evidence provided by estate plans (see Chapter 2) were also studied in an effort to glean information on how these categories evolved with time, despite the limitations discussed in Chapter 2. Indeed the ambiguity and vagueness of the terminology employed by the different mapmakers for these categories limit the consistency of any study undertaken over time and space. Moreover, in many instances, there was no evidence available from the historical maps. This issue concerned particularly the woodland in T2 (1801-1833) where the classes 'Low woodland' and 'Bushes' covered less than 2 ha each, which is unlikely to provide an accurate estimate of their true extent in the historical landscapes. However, it remained possible for each category (i.e. 'vegetation classes' and 'management types') to assess how much was cleared or wooded in T3 and T4. As a simple sampling would do, the results based on the few sites with mapping evidence of past vegetation may reflect some historical trends that occurred at a larger scale. This assessment was undertaken independently of the changes in vegetation characteristics that may have occurred over time. For example, even if a 'Low woodland' or 'Open woodland' in T1 had become high and dense woodland in T3, the analysis will only record that the area had remained wooded between T1 and T3.

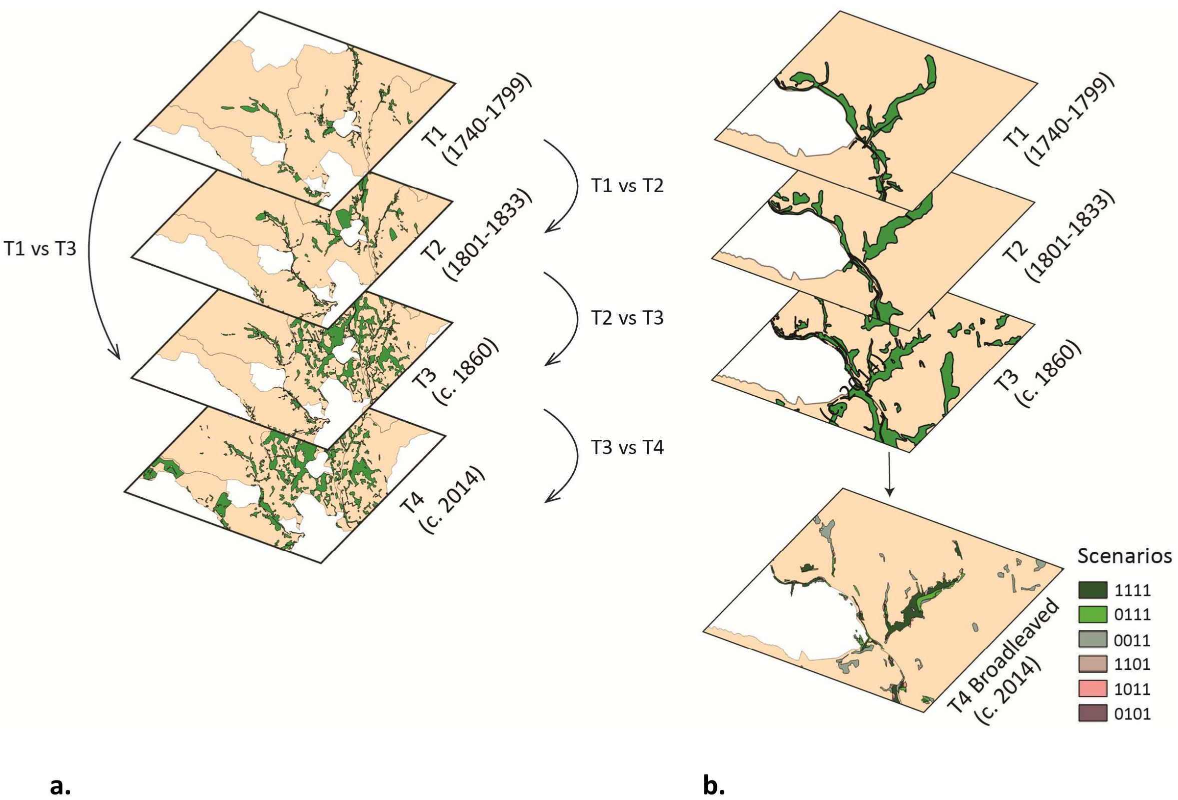


Figure 3.2 Methodology: Change detection analyses (a.) and Trajectory analysis (b.)

3.2.6 Trajectory analysis

This analysis focused on woodland sites in which broadleaved trees were the dominant habitat (>50% of the canopy cover) in 2014. While the change detection analysis was based on pairwise comparisons of two time series, this analysis combined the data of all the historical time series to categorise the present-day woodland cover into *historical trajectories* (Figure 3.2b). In assessing the stability of the broadleaved woodland sites over time, this work identified the areas that have been continuously wooded for a longer period of time such as 'ancient' woodlands. Thereafter, this categorisation can be used to investigate how the broadleaved woodland cover may bear the imprint of historical changes that have occurred since at least the mid-eighteenth century (see Chapter 4). As the coniferous woodlands result from plantations of trees which are not natives of the Scottish Lowlands (Wilson, 2015, p.18), they were ruled out of this analysis. With the exception of the orchards and gardens, which were also beyond the scope of this study, all other historical woodland categories vectorised from historical maps were broadly considered as woodland.

The categorisation of the woodland cover trajectories drew upon the presence ('1') or absence ('0') of woodland at each 5x5 m cell and for each time series. The GIS overlay of the different datasets – woodland cover for each time series – allowed the categorising of each cell into trajectories defined by a succession of 4-digit characters taking the values '1' and '0' where the area of study is covered by all the time series (e.g. category '1-0-0-1' for a cell found as 'woodland' in T1, 'non-woodland' in T2 and T3, 'woodland' in T4) (Figure 3.2b). Each one of these categories is called a *trajectory*. In addition, this categorisation of trajectories integrated the fact that many woodland sites were not covered by estate plans from T1 or T2. The missing time series had therefore to be included in the categorisation using 'X' as 'no data'. For example, in Area 3, the trajectory 'X-1-1-1' indicates a cell has been wooded since the early nineteenth century but may be of more ancient origins, 'X' symbolising 'no data' for T1. In Area 2, the trajectory '1-X-1-1' means that the woodland has been present from at least T1 until 2014 but there is no historical mapping evidence that the area was wooded in T2.

The final result of this categorisation is a combined map showing the long-term history and various trajectories of all broadleaved woodland sites that were present in 2014 in the study area. This *stability map* (terminology that follows Swetnam, 2007) permitted subsequent extraction of quantitative data about the extent covered by the different trajectories. Similarly to the change detection analyses, GDAL and the *raster calculator* in QGIS were used for the categorisation process.

In addition, following Kaim et al. (2014), this analysis enabled the assessment of the uncertainty related to the planimetric accuracy and reliability of the woodland cover reconstructions from historical maps. Because of the variations in the woodland sites' shape and positional accuracy (see Chapter 2), a propagation of this uncertainty was expected when overlaying three or four different historical time series (Leyk et al., 2005; De Clercq et al., 2009); some woodland cells could therefore be allocated false trajectories (Skaloš et al., 2012). A quantification of the trajectories that seemed less realistic – showing several periods of deforestation and re-growth within a short time – was used as an overall indicator of this uncertainty (Kaim et al., 2014; Loran et al., 2016).

Furthermore, the *perimeter-area ratio* (PAR) – where the perimeter is expressed in 'm' and area in 'm^2' – of each woodland trajectory patch was calculated and used as an additional indicator of the reliability of the different trajectories. In the present study, it is assumed that uncertain trajectory patches can be identified through their long linear shape. Small patches with large perimeters – or *slivers* – are likely to result from variations in accuracy of the overlaid GIS layers (De Clercq et al., 2009; De Keersmaeker et al., 2015). Therefore, identifying the patches with the highest PAR can pinpoint areas for which the woodland trajectories are most uncertain, being results of either variations in the planimetric accuracy of the datasets or real changes in woodland boundaries (De Keersmaeker et al., 2015).

3.2.7 Logistic regression models of past woodland distribution and changes

3.2.7.1 Binomial logistic regression: aim and principle

Logistic regression methods have been widely used to investigate land-use/land-cover patterns of changes and related driving forces (e.g. Serneels and Lambin, 2001; Xie et al., 2005; Gellrich et al., 2007; Matsuura and Suzuki, 2013; Kim et al., 2014; Bavaghar, 2015). In the present study, binomial logistic regressions examine the explanatory power of influential variables that may partially account for past woodland-cover distribution in T1, and the distribution of newly afforested areas in T2 and T3.

In this study, binomial logistic regressions (LR) explore the relationship between a set of environmental and historical variables, namely *explanatory variables* (Table 3.1, Figures 3.3 and 3.4), in relation to the distribution of past woodland cover in the study area (i.e. presence or absence of woodland, namely *response variable*). More specifically, LR is based on maximum likelihood estimation to estimate the probability of each cell to be ‘1’ (presence of woodland) as a function of a set of explanatory variables.

The choice of using binomial LR is justified by the categorical and binomial character of the response variable (i.e. presence/absence of woodland). Moreover, LR is said to be flexible as it makes very little assumption on the distribution of the explanatory data: these variables can be continuous or categorical and do not need to follow a normal distribution (Xie et al., 2005; Bavaghar, 2015). The form of the logistic function is given by the equations below (Xie et al., 2005; Bavaghar, 2015):

$$P = \frac{e^y}{1 + e^y} \qquad (1)$$

$$y = \log_e\left(\frac{P}{1-P}\right) = \log it(P) \qquad (2)$$

$$y = (\beta_0 + \beta_1 X_1 + \beta_2 X_2 + _{\dots} + \beta_n X_n) \qquad (3)$$

where P denotes the probability of woodland occurrence in each 5x5 m cell (i.e. response variable is '1'); $X_1, X_2, \ldots, X_n$ are the explanatory variables; β_0 is the constant; $\beta_1, \beta_2, \ldots, \beta_n$ are the coefficients to be estimated through a maximum likelihood iterative procedure; y is the $\log_e$ of the odds (i.e. the likelihood ratio that the response variable is '1'). The odds ratios (OR) associated with each explanatory variables were calculated as $\exp(\beta_n)$. As the regression coefficient indicates the contribution of each explanatory variable to the probability P, a positive sign implies that the explanatory variable increases the probability of a cell to be 1 (OR > 1), while a negative sign implies otherwise (OR < 1) (Xie et al., 2005).

To produce the models, the study area was divided into three regions of comparable size, according to the ownership of the lands, namely 'Drumlanrig' (for Drumlanrig estates), 'Annandale' (for Annandale estates) and 'Other' (for the rest of the study area) (Figure 3.4). This division helped to examine if different spatial trends could be identified regarding the distribution of past woodland cover in T1, newly afforested areas in T2 and T3, and if this may reflect distinct management practices between land-owners. Furthermore, the division of the study area into three regions of considerably smaller size may mitigate *non-stationarity*. The latter can influence the models when the explanatory power of the variables differs strongly across the study area (Wagner and Fortin, 2005). Contrasted topographic characteristics and human factors, such as distinct management practices between estates, can lead to major issues related to non-stationarity and, therefore, affect the quality of the models.

Due to the limited number of explanatory variables available, it is noteworthy that this series of LR did not aim to model accurately past woodland cover and changes over time, which might require extensive information about driving forces such as historical estimates of population and farms, local needs in wood, etc. In the present study, the LR analyses were undertaken to explore the explanatory power of the variables listed in Table 3.1 and represented in Figures 3.3 and 3.4. Some of these explanatory variables, such as slope, elevation and aspect, are widely used to investigate woodland distribution (e.g. Rutherford et al. 2008; Bavaghar, 2015; Tagil, 2015) and it is hypothesised in the present study that they can represent some of the driving forces that account for past changes. As such these analyses aim, first of all, to be exploratory to identify how much understanding of the spatio-temporal changes can be gained by using this set of explanatory variables.

Finally, spatially explicit (i.e. georeferenced) maps were produced as output to show, according to the different models, what areas were most likely to be wooded in T1 or recently wooded in T2 and T3. The difference between woodland reconstructions and these maps can feed a discussion regarding the historical and environmental reasons why the models may fit better in some portions of the study area than others.

3.2.7.2 Explanatory variables (Table 3.1 and Figures 3.3. and 3.4)

The environmental explanatory variables are terrain variables derived from a 5 m Digital Elevation Model (DEM, OS Terrain 5 Contours); Euclidean distance variables – calculated from a series of buffers – derived from the watercourse network and distribution of anterior woodland cover (for studies on T2 and T3); and soil data from the 1:250K National Soil Map (1984). The soil data from the more detailed 1:25k survey could not be used because the digital version does not cover a large part of the study area. Following Rutherford et al. (2008), aspect was derived from the DEM and transformed to cosine and sine to obtain continuous values ranging from -1 to 1 for 'eastness' and 'northness', respectively.

For the study of the woodland cover in T1, the only variable that used archaeological data is the Euclidean distance to the nearest castle or tower houses with known medieval or post-medieval occupation. The list and position of these sites are based on georeferenced archaeological data of the region as provided by the Dumfries and Galloway Council Planning and Environment. The choice to include this variable followed an initial observation that several woodlands in T1 were located in the vicinity of ancient castles and tower houses. The underlying assumption was that these sites may have been preserved at some point in the past to provide wood for their occupiers. Likewise, a dataset of the wood-demanding historical industrial sites was initially considered. Unfortunately, this dataset, also provided by the council, could not distinguish accurately the sites used during the time frame of this study from earlier or later sites, precluding a consistent analysis on the role of past industries. The explanatory variables were prepared using QGIS 2.6.1 (QGIS, 2015) with GDAL and GRASS plugins.

Table 3.1 The explanatory variables used for the logistic regressions

Explanatory variable	Description	Unit	Data source
Elevation	Digital elevation model (DEM), 5 m resolution	m	DEM - OS Terrain 5 (Edina Digimap)
Slope	Slope calculated in degrees	°	Derived from DEM
Eastness	Cosine conversion of aspect	-1 to +1	Derived from DEM
Northness	Sine conversion of aspect	-1 to +1	Derived from DEM
D_castle	Euclidean distance to nearest castle or tower house	m	Calculated from Dumfries and Galloway Council Planning and Environment data
D_watercourse	Eucidean distance to nearest watercourse	m	Calculated from OS Open Rivers (SHAPE geospatial data), Scale 1:25,000, Tiles: GB, Updated: 13 March 2015 (Edina Digimap)
Soil	Major soil group of the first named soil (MSG84_1, see soil classification in Soil Survey of Scotland, 1984)	Categorical: brown earths, podzols, ground-water gleys, peats, surface-water gleys, alluvial soils and rankers	1:250,000 National Soil Map of Scotland (The James Hutton Institute)
D_woodlandT1 D_woodlandT2	Euclidean distance to the nearest woodland in T1 (or T2)	m	Calculated from the woodland reconstruction in T1 (or T2)

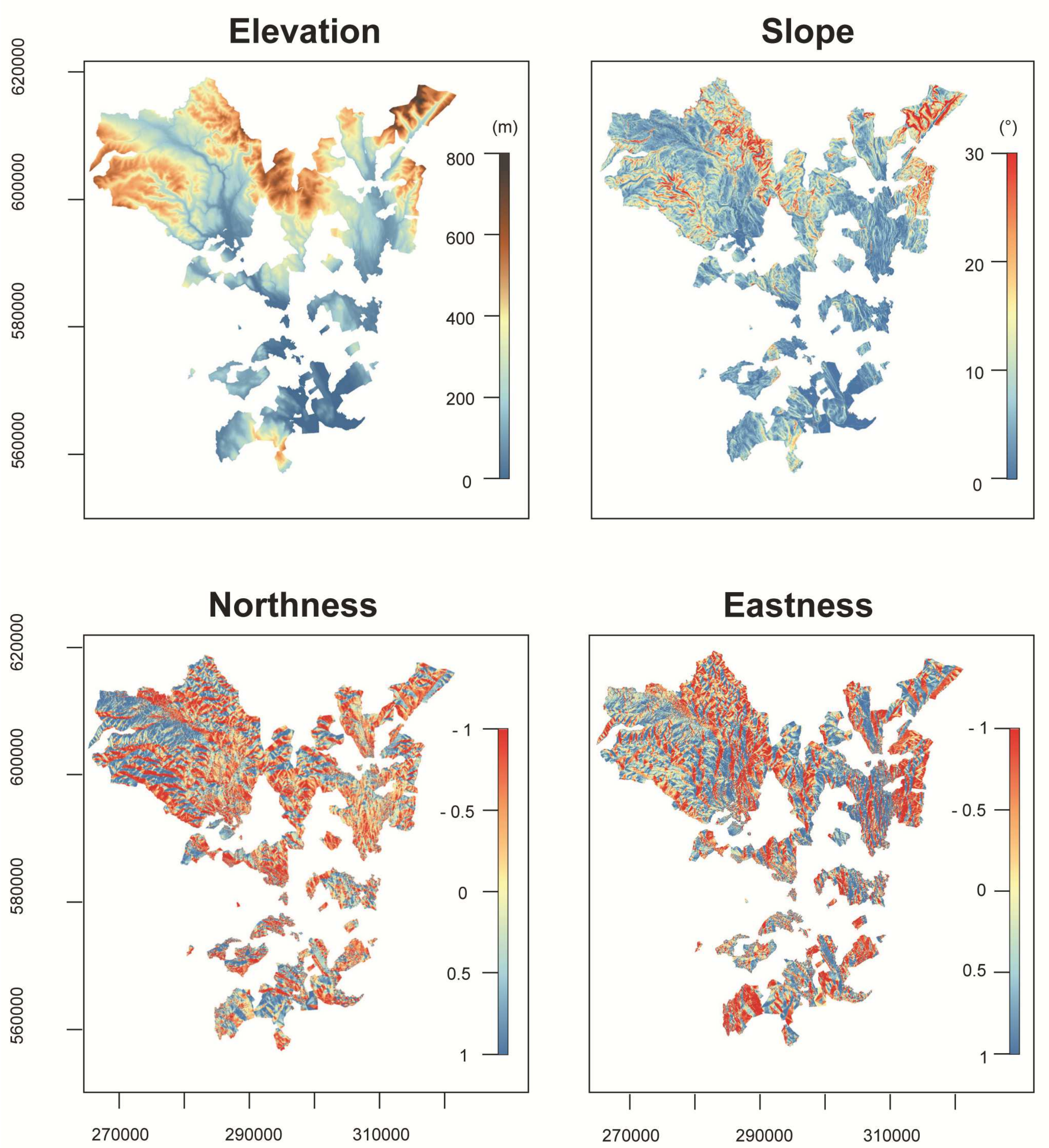


Figure 3.3 Explanatory variables used for the logistic regressions (elevation, slope, northness and eastness)

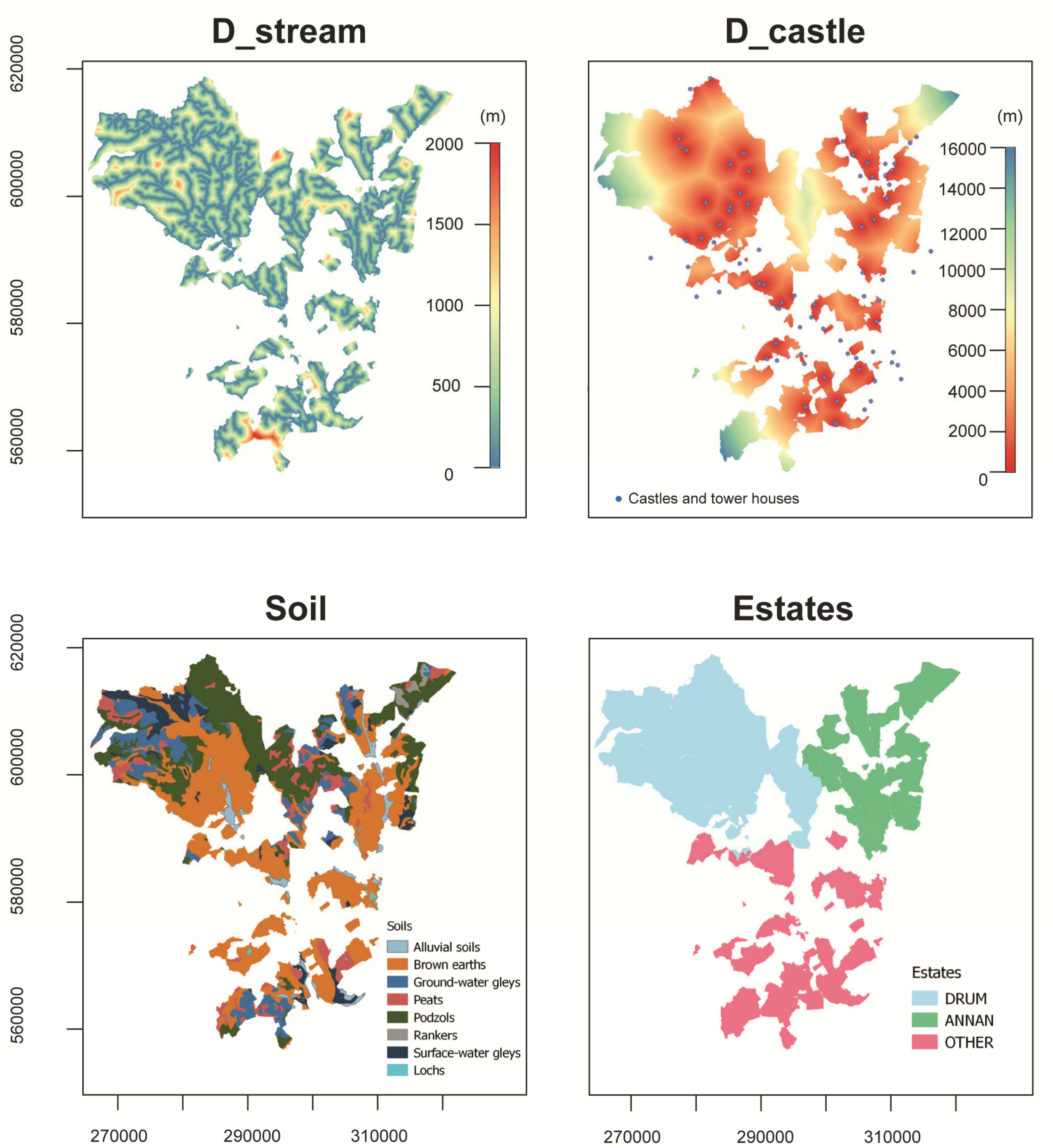


Figure 3.4 Explanatory variables used for the logistic regressions (distance to the nearest stream, distance to the nearest castle or tower house, and soil) and division of the estates into three regions (Drumlanrig, Annandale and Other)

3.2.7.3 Process

i) Sampling

The models were based on stratified random samplings of cells ‘0’ (i.e. no woodland) and ‘1’ (i.e. woodland) in the study area. Table 3.2 provides further information on the sampling procedure for each time series. The stratification was necessary as non-stratified samplings would have generated insufficient ‘1’ observations due the low coverage of the woodland during the historical periods that were studied.

A minimum distance of 200 m was set between random sample cells within the same woodland patch. The cells belonging to different woodland patches could be closer than 200 m. The same distance of 200 m was used to perform the random sampling of the cells ‘0’ (i.e. background data). The minimum distance was set as a balance between a sufficient number of points to perform the analyses and the largest distance possible to reduce *spatial effects*. Spatial effects, such as *spatial autocorrelation*, indicate that the values of neighbouring sampled cells are more similar than those further apart or, in other words, that similar cells tend to be closer to each other than as the result of random processes (Wagner and Fortin, 2005; Dormann, 2007). This effect could bias the estimated coefficient of explanatory variables and increase the likelihood of Type 1 error – false rejection of the null hypothesis which is the absence of effect (Dormann, 2007). The stratified random sampling with minimum distance has been widely used to mitigate spatial effects (e.g. Gellrich et al., 2007; Lopez, 2014; Bavaghar, 2015; Tagil 2015).

As the woodland cover is restricted to altitudes below 330 m in T1, and 360 m in T2 and T3, the sampling only retained points below respectively 350 m and 380 m. While reducing the non-stationarity of the study area (i.e. less variations in elevation data), this method also helped to assess more accurately the predictive ability of each model to discriminate cells ‘1’ from cells ‘0’ in considering only the area under elevations where woodland used to grow at these time periods (see model assessment below).

At the location of each cell, the corresponding values for the different response and exploratory variables were recorded to generate the final datasets that served to perform the LR. In total, ten datasets were produced to fit ten models. As the LR was applied to study the woodland cover in three regions during three historical time series, a total of nine analyses were initially produced. A last model was added to study past woodland cover in T1 in Annandale without sampling the plantations of the late eighteenth century, which represented about half of the woodland cover for this time series (see Chapter 2). This last analysis aimed to study the woodland cover in Annandale before the extensive planting that led to the major transformation in the woodland spatial configuration. The slightly unbalanced ‘0’ and ‘1’ sampling rate for the response variable of most datasets (Table 3.2) is not thought to affect the estimated coefficients of the explanatory variables but only the intercept (Serneels and Lambin, 2001). The sampling was done with QGIS 2.6.1 (QGIS, 2015) and the dataset was imported into the statistical software package R (R Development Core Team 3.2.3) to perform the binomial LR (rms R package v.5.1.0; Harrell, 2017).

Table 3.2 Sampling strategies and number of points sampled for the logistic regressions.

Time series	Estates	Number of sampled cells	Number of cells as 'woodland'	Sampling strategies for cells as 'woodland'
T1	Drumlanrig	1346	609	Any woodland in T1 could be sampled except the woodland known as plantation for Annandale(2)
	Annandale(1)	752	324	
	Annandale(2)	638	224	
	Other	886	430	
T2	Drumlanrig	887	296	Only the woodland appearing between T1 and T2 was sampled
	Annandale	250	99	
	Other	267	120	
T3	Drumlanrig	1720	688	Only the woodland appearing between T2 and T3 was sampled
	Annandale	416	106	
	Other	865	268	

ii) Model calibration and assessment

Multicollinearity among explanatory variables was first tested in R (R Development Core Team 3.2.3). The correlation values range between -1 (perfect inverse correlation) and 1 (perfect positive correlation) and it is widely recommended to use |0.8| as a critical threshold above which removing some of the correlated variables should be considered (Menard, 1995; Serneels and Lambin, 2001; Gellrich et al., 2007). In the present study, the correlation between pairs of explanatory variables was below |0.6|. Consequently, it was decided that all the explanatory variables could be used.

Due to the limited number of explanatory variables, an exhaustive combination of the variables was possible to fit all possible models. The variables without statistical significance (Wald test) were excluded and the best models (i.e. final models) were selected by comparison of the Akaike information criterion (AIC), with smaller AIC indicating a better goodness-of-fit (Bozdogan, 1987). For continuous explanatory variables, the Wald test indicated whether each explanatory variable was significantly linked to the response variable. For the soil variable, which is the only categorical variable, the Wald test indicated how much each category was statistically different from the category of reference. The category ‘Brown earths’ was chosen as the reference as it is both the dominant category in the study area (Figure 3.4) and most suitable for woodland (Wilson, 2015, p.24).

Models quality was assessed using McFadden's pseudo-R^2 and prediction accuracy. McFadden's coefficient assesses the level of improvement over a model without explanatory variable. A pseudo-R^2 between 0.2 and 0.4 indicates a relatively good performance of the model (Serneels and Lambin, 2001; Wilson et al., 2005). The predictive accuracy was assessed using receiver operating characteristics (ROC) curves and, in particular, through calculation of the area under the ROC curves (AUC). The ROC measures the predictive ability of a model to discriminate cells '0' and '1' according to different probability thresholds while the AUC indicates the overall model accuracy. The AUC values range between 0.5 and 1; for a perfect fit, AUC = 1, while for a random fit, AUC = 0.5 (Ayalew and Yamagishi, 2005; Triantakonstantis et al., 2013). To prevent an overestimate of the models' predictive ability, the AUC was tested on external validation datasets, different from the calibration datasets that served to create the models (Wilson et al., 2005). The validation datasets were generated following a sampling procedure similar to that used to generate the calibration datasets.

However, ROC and AUC were found to be strongly biased and would sometimes remain high independently of the quality of the model. Indeed, the predictive ability of a model considers equally the ability to identify accurately the sample cells as '0' and '1', while in some situations it can be very simple for a model to identity the cells '0'. For instance, although the analysis was done on sample cells with elevations below 350 m or 380 m, this threshold remains high for the woodland in T1, T2 or T3. Hence, it was easy to predict accurately that most cells with higher elevations were likely to be '0' (i.e. non-woodland) and the AUC values would increase as the amount of sample cells with higher elevation increases – this amount is also different between the datasets being based on random sampling in regions of contrasted elevations, sizes, and for different time series.

To address this issue, another indicator, namely the *F-score,* was also used to assess only the ability of a model to predict accurately cells '1', independently of the number of '0' cells in the dataset. The *F-score* is calculated for a fixed probability threshold and based on the harmonic mean of two complementary indicators, namely *sensitivity* (or *recall*) and *precision* (Guns et al., 2012). Sensitivity and precision were calculated from *contingency tables* that compared the prediction of each model against real data from the historical woodland cover reconstructions and using an arbitrary probability, $p = 0.5$ as decision threshold (i.e. for a given cell, when $p > 0.5$, the model predicts the cell as '1'):

$$F - score = 2 \times \frac{(\text{precision} \times \text{sensitivity})}{(\text{precision} + \text{sensitivity})} \quad (4)$$

$$\text{sensitivity} = \frac{(\text{number of true positives})}{(\text{number of true positives} + \text{number of false negatives})} \quad (5)$$

$$\text{precision} = \frac{(\text{number of true positives})}{(\text{number of true positives} + \text{number of false positives})} \quad (6)$$

where the ‘true positives’ are the cells that the model correctly predicted as ‘1’; the ‘false positives’ are cells incorrectly predicted as ‘1’; and the ‘false negatives’ are cells incorrectly predicted as ‘0’.

3.3 Results

3.3.1 Woodland metrics

3.3.1.1 Overall trends for woodland cover and vegetation classes

Table 3.3 Woodland cover (in ha) estimated for each time series. Percentages are indicated in brackets and calculated from the total coverage of each study area (see Figure 3.1). T4a includes all polygons categorised as "Woodland" in the NFI (included "Assumed Woodland", "Ground prepared", etc.; i.e. land-use). T4b considers only broadleaved, mixed woodland and conifers sites in the NFI (i.e. land-cover).

Time series	Area 1 (T1 and T2)	Area 2 (T1)	Area 3 (T2)	Area 4 (T1 and/or T2)
T1 (1740-1799)	1,265 (3.0)	2,727 (3.1)	-	-
T2 (1801-1833)	1,931 (4.6)	-	2,994 (4.7)	-
T3 (c.1860)	3,468 (8.3)	5,420 (6.3)	4,775 (7.6)	6,762 (6.3)
T4a (2014)	9,600 (22.9)	22,922 (26.5)	13,618 (21.6)	26,969 (25.0)
T4b (2014)	6,531 (15.6)	14,385 (16.6)	9,224 (14.6)	17,104 (15.9)
Total coverage	41,980 (100)	86,526 (100)	63,098 (100)	107,698 (100)

“-“ for no data

Table 3.3 shows the considerable expansion of the woodland cover over time and for each division of the study area. In Area 2, while the woodland covered approximately 3% (2,727 ha) of the landscape in T1, it had doubled by c.1860 to reach 6.3% (5,420 ha). Likewise in Area 3, we can observe a sharp increase by 3% (1,781 ha) of the woodland cover between T2 and T3, to reach 7.6% by c.1860.

Logically these trends are reflected in the estimates provided for Area 1, which correspond to the area covered by all the time series. In this area, the expansion of the woodland cover was much higher between T2 and T3 (1,537 ha) than between T1 and T2 (666 ha), suggesting an acceleration of the expansion dynamics during the first half of the nineteenth century. In Area 4, the trend shows an increase of the woodland cover from 6.3% in c.1860 to 15.9% - 25% in 2014, depending on whether we consider woodland as land-use (T4a) or land-cover (T4b).

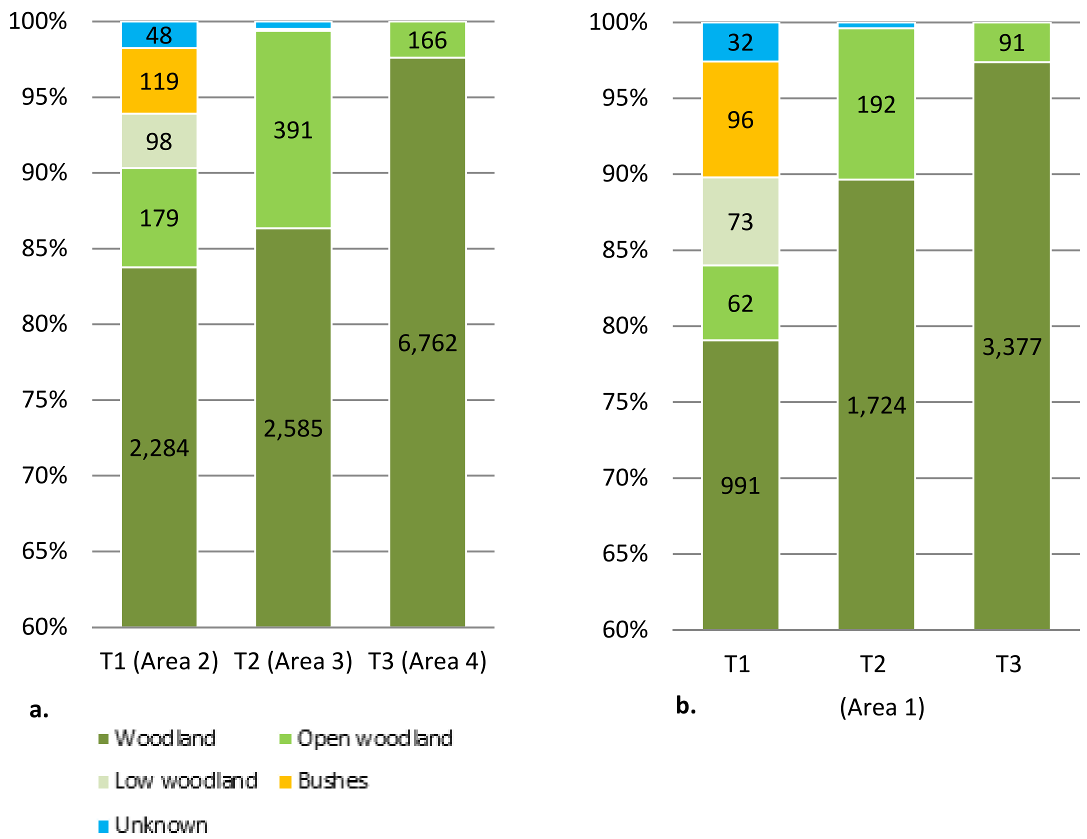


Figure 3.5 Changes in the proportion of the different woodland classes based on the evidence provided by estate plans (T1 and T2) and First Edition Ordnance Survey (T3). The values are expressed in ha and percentages calculated from the total wooded area – to improve readability, the stacked bars start at 60%. (**a.**) Results are based on calculations for Area2, Area3 and Area4 (i.e total coverage for respectively T1, T2 and T3); (**b.**) Results are based on calculations for Area1 (i.e. covered by all time series).

Figure 3.5 illustrates the proportions of the different woodland vegetation classes identified from estate plans for T1 and T2, and First Edition OS maps (T3, evidence about 'Open woodland' only) – see Chapter 2 for further details about the classes. Firstly it is noteworthy that the classes other than 'Woodland' represent 16%, 14% and 2% of the woodland cover in T1 (Area 2), T2 (Area 3) and T3 (Area 4), respectively. Given the small area covered by the woodland cover in T1 and T2, these classes do not appear important in size with regard to the total area covered by estate plans as they represent each less than 0.5% of the historical land-cover.

Secondly, these results indicate that estate plans provide more quantitative evidence of 'Low woodland' and 'Bushes' in T1 than T2. These two classes represent altogether 217 ha in the area covered by T1 (Area 2) but less than 4 ha in the area covered by T2 (Area 3). It is uncertain whether this observation can be explained by a less accurate depiction by the early nineteenth century surveyors, the lack of written evidence due to missing explanation tables – which may once have described the content of the maps – or a real decline of these two vegetation classes. Indeed, with the agricultural improvement that took place between T1 and T2, it is likely that the least profitable lands, as brushwood and bushes could be, were the object of important changes. Conversion of these lands might be expected towards more productive forms of agricultural such as pasture, woodland or arable land. This trend seems, however, less credible for ‘Low woodland’ represented by coppice as this form of management was common throughout the nineteenth century in Scotland (Lindsay, 1980; Smout et al., 2005). The total absence of references to coppice woodland in the estate plans of T2 may be explained by the fact that these woodlands were not differentiated on the plans from other types of woodland, such as conifer or mixed plantations.

Regarding the class ‘Open woodland’, the comparison between time series in Area 1 (Figure 3.5b) suggests an increase of the acreage of open woodland from 62 ha to 192 ha between T1 and T2, before a decline in T3 to 92 ha. The same uncertainty as for ‘Low woodland’ and ‘Bushes’ could also partly affects the changes observed for ‘Open woodland’ class. However, we can assume that the identification of open woodland is more consistent on historical maps due to the more explicit symbology used by mapmakers to depict these sites (i.e. scattered tree symbol). The lack of tables of contents associated with the historical plans was therefore not as important in identifying these sites. In sum, it is likely that the open woodland increased between T1 and T2 before declining between T2 and T3.

3.3.1.2 Patches and woodland cover configuration

Table 3.4 Patch metrics for each historical time series in the different sub-study areas. 'ENND' is for 'Euclidean nearest neighbor distance'.

Landscape metrics	Area 1			Area 2		Area 3		Area 4
	T1	T2	T3	T1	T3	T2	T3	T3
Number of patches	408	522	1,002	676	1,842	895	1,731	2,514
Max. patch size (ha)	85	135	509	235	578	365	746	813
Mean patch size (ha)	3.07	3.69	3.47	4.01	2.95	3.34	2.77	2.69
Median patch size (ha)	0.58	0.57	0.32	0.65	0.32	0.45	0.29	0.29
Mean ENND (m)	121	108	80	133	84	100	75	80
Median ENND (m)	40	36	25	40	32	36	29	32
Mean shape index	1.96	2.01	2.10	2.03	2.05	1.92	2.04	2.02
Median shape index	1.60	1.65	1.78	1.62	1.76	1.58	1.73	1.71

The patch metrics (Table 3.4) can portray over time the changes that affected the woodland cover at the scale of a woodland site (i.e. woodland patch). As the surface of woodland expanded (see Table 3.3), the number of patches in each sub-study area increased (e.g. from 408 patches at T1 to 1,002 patches at T3 in Area 1). Likewise the maximum patch size grew considerably over time (e.g. from 235 ha at T1 to 578 ha at T3 in Area 2). In contrast, the mean patch size seems to decrease over time, from 4.01 ha to 2.95 ha in Area 2, and 3.34 ha to 2.77 ha in Area 3. In Area 1, we can observe more variations with a slight increase between T1 and T2 (3.07 ha to 3.69 ha) and more stability between T2 and T3 (3.47 ha). These variations however may be influenced by a few considerably larger patches as the median patch size indicates a decrease over time for each sub-study area (e.g. from 0.65 ha to 0.32 ha in Area 2 between T1 and T3, and an estimate at T3 of 0.3 ha in Area 4). Estimates for ENND show a decrease of the minimum edge to edge distance between patches for all sub-study areas. For example, in Area 1, the median is 40 m for T1 and 25 m for T3. These results indicate that the woodland sites became less and less isolated over time. As a result, it seems that the increase of the woodland cover between T1 and T3 occurred both via the multiplication of small size clustered woodland sites and plantation of woodlands of very large size (Figure 3.6).

Regarding the shape index of woodland patches, the mean and median increased over time (e.g. median from 1.60 in T1 to 1.78 in T3). The trend remains consistent between each time series and for each sub-study area. As the shape index increases, the more irregular become the woodland patches (the lower limit is 1 for square compact patches, McGarigal et al., 2012). Therefore the results suggest that the woodland sites are decreasingly compact with time (Figure 3.6).

Several uncertainties raised by McGarigal et al. (2012) that can affect the metrics must be noted. As some woodland may extend outside the boundaries of the study or sub-study area, the analysis may underestimate the real size of several patches. This issue would also influence the shape index of these patches. Likewise, the ENND may be overestimated due to the presence of unmapped woodland sites located close but outside the boundaries of the study area. As a result, the nearest woodland neighbor of a focal patch is not always within the boundaries of the study area but can be in an unmapped area. However, it is thought that the effect of these uncertainties is mitigated when the size of the patches is low compared to the extent of the studied landscape (McGarigal et al., 2012), which is the case in the present work. In addition, the analysis was done on hundreds of patches of which only a small proportion was located at the edge of the sub-study areas.

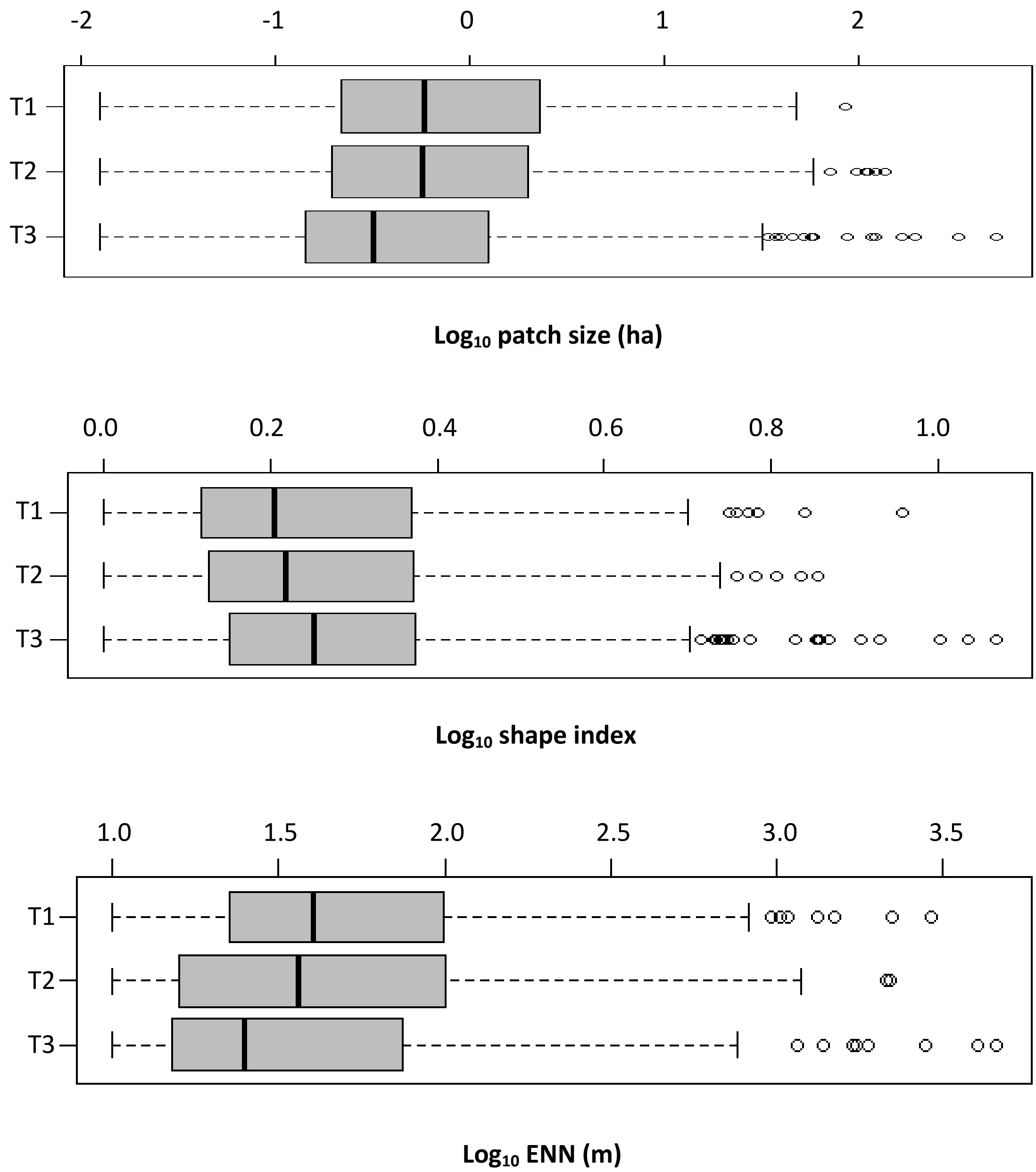


Figure 3.6 Boxplots of the $\log_{10}$ of size, shape index and Euclidean nearest neighbor (ENN) of woodland patches in Area 1 for the three historical time series. The outliers on the boxplot of the $\log_{10}$ of patch size reflect the higher amount of very large woodland sites in T3.

3.3.2 Change detection analysis

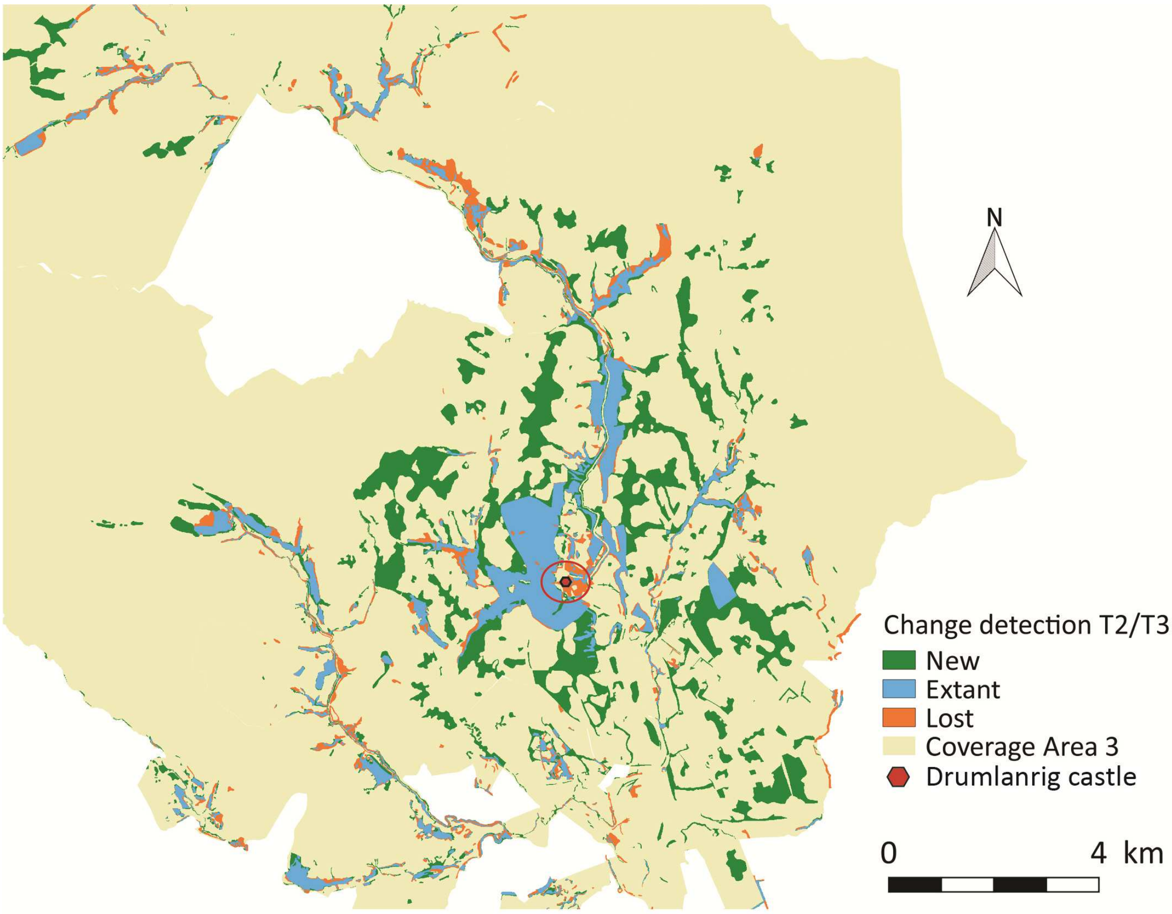


Figure 3.7 Example of change detection analysis map between T2 and T3 around Drumlanrig castle (in red circle).

3.3.2.1 Relative changes in woodland cover

Table 3.3 and Figure 3.5 above reflect the net increase in woodland over time but do not provide any information about the relative loss that occurred in the meantime. Pairwise comparisons of the woodland cover reconstructed for each time series enabled to map the relative changes (i.e. the woodland which is new, extant or lost between two time series, Figure 3.7) and to extract quantitative estimates (Figure 3.8). We define the 'absolute change' as the sum of the 'relative changes', independently of their direction, i.e. the total area that underwent changes, which comprised both the area that lost woodland and the area – formerly pasture, meadow, etc. – converted into woodland.

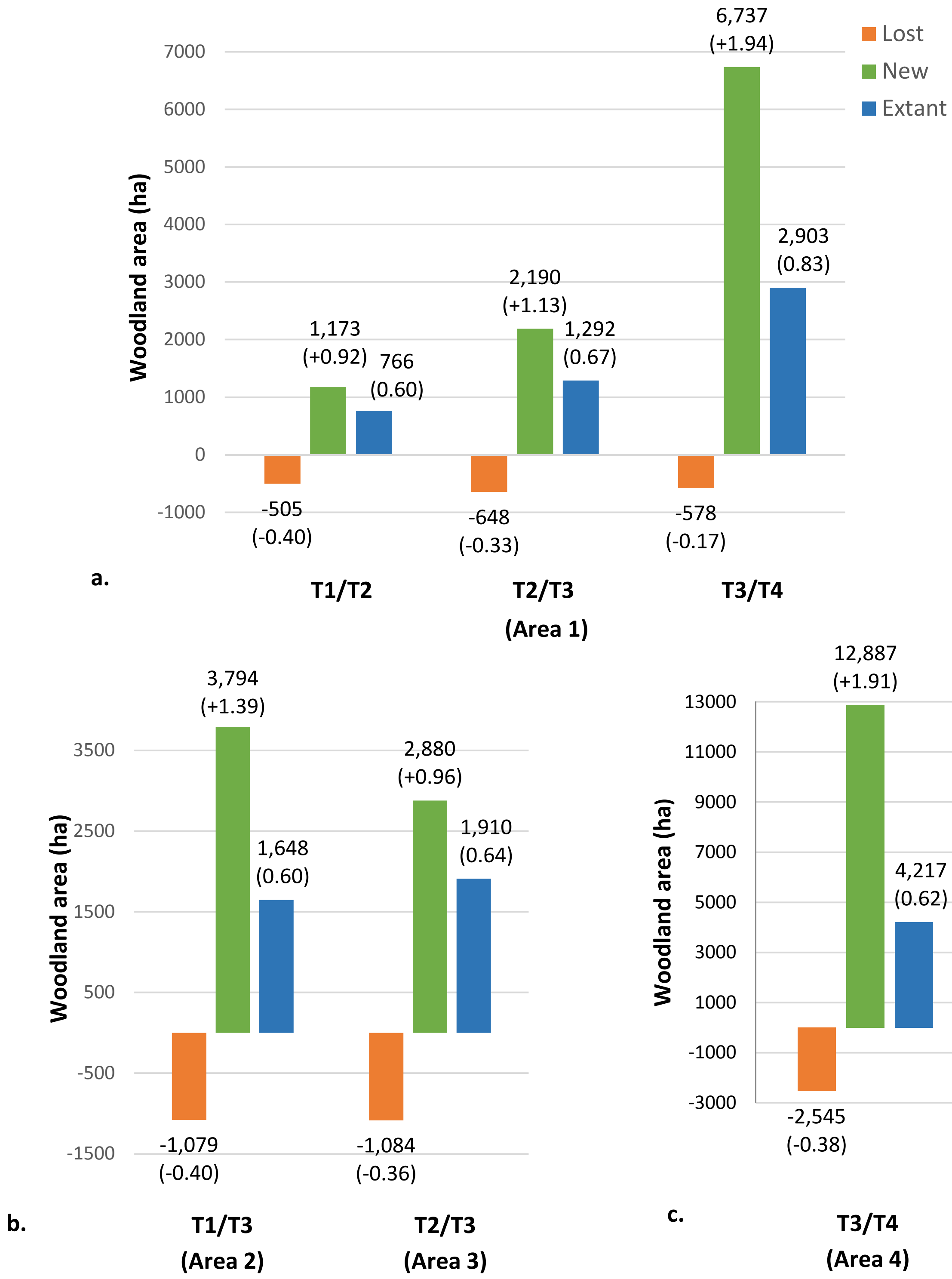


Figure 3.8 Relative changes of the woodland cover from pairwise comparisons of time series (ha). The relative percentages of woodland as new, lost or extant are indicated in brackets and calculated from the initial amount of woodland cover. (**a.**) in Area 1 between T1 and T2 (T1/T2); T2 and T3 (T2/T3); and T3 and T4 (T3/T4); (**b.**) in Area 2 between T1 and T3 (T1/T3); in Area 3 between T2 and T3 (T2/T3); (**c.**) in Area 4 between T3 and T4 (T3/T4). As the sub-study areas cover different areal extents, it is to be noted that the estimates of woodland acreages are not directly comparable between Areas 1,2,3 and 4.

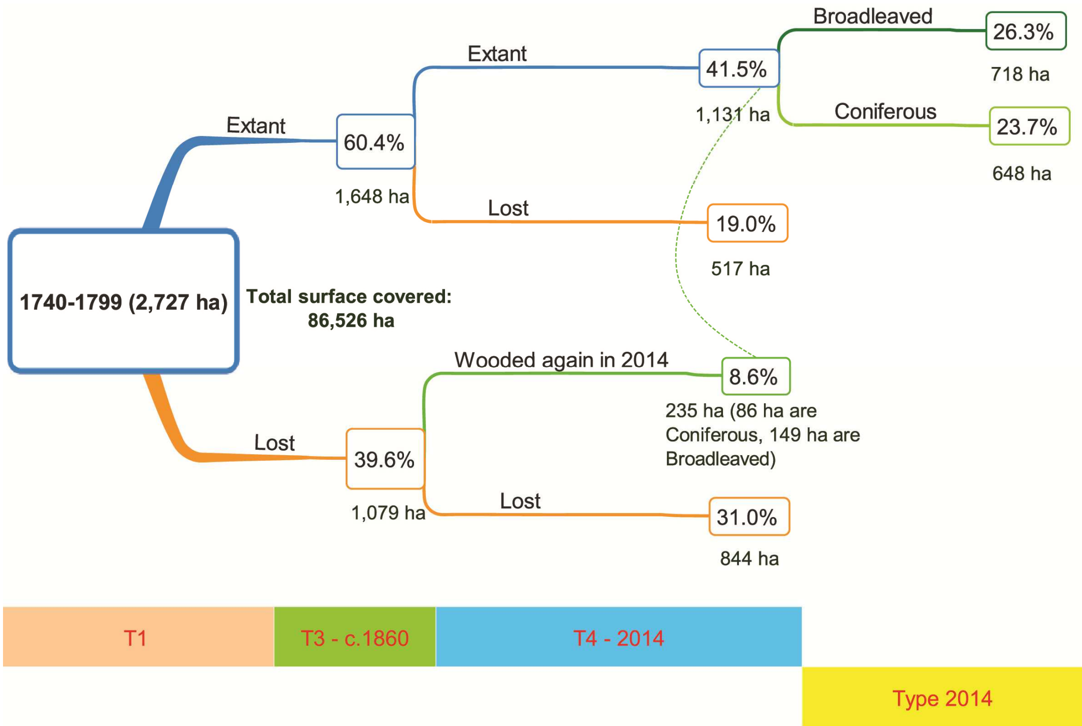
Figure 3.8 illustrates that the net increase of the woodland cover hides more complicated dynamics of loss and gain. On Area 1, despite a net gain of more than 660 ha between T1 and T2 (Table 3.3), 505 ha of the initial woodland cover in T1 (40%) were in fact lost by T2 (Figure 3.8a). The absolute change of 1,678 ha – including the 1,173 ha of land converted into woodland – is considerably higher than the net increase (660 ha), which highlights an important turn-over of the woodland cover between T1 and T2. Likewise, between T2 and T3, the net increase of 1,542 ha, compared to the 2,190 ha of relative gain, and 648 ha of relative loss, suggests that the high turn-over of the woodland cover observed between T1 and T2 lasted for the first half of the nineteenth century at least.

In contrast with the pairs T1/T2 and T2/T3, the changes between T3 and T4 in Area 1 show a smaller percentage of relative loss of woodland, with 17% of the woodland in T3 lost in T4. As a result, the amount of woodland lost seems stable between each successive time series (from 505 ha to 648 ha) while the afforestation increased considerably with a relative gain from 1,173 ha (between T1 and T2) to 6,737 ha (between T3 and T4). The fact that the time span between each time series is different must be also considered. The longer time span between T3 and T4 (about 150 years) undoubtedly explains the considerably higher area of lands converted into woodland while it confirms the high stability of woodland loss during this time period.

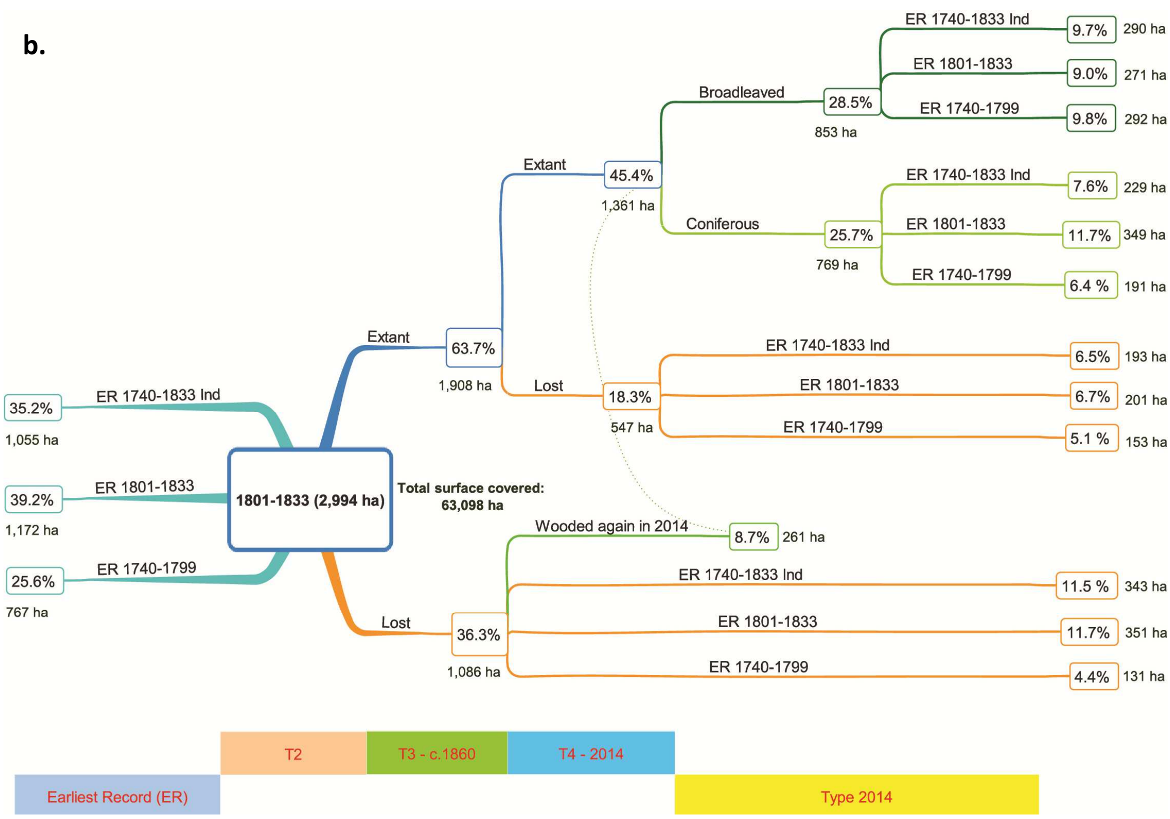
Similar trends in Figures 3.8b and 3.8c support previous observations, with slightly more than 1,070 ha of relative loss for T1/T3 (Area 2) and also for T2/T3 (Area 3), while the relative gain is respectively 3,794 ha and 2,880 ha. It is noteworthy that the areal extent of woodland loss is close in Area 2 and Area 3 although the comparison in Area 3 (T2/T3) covers a shorter period of time than in Area 2 (T1/T3). Consequently, this observation tends to illustrate a higher rate of relative loss during the nineteenth century in Area 3 than Area 2. In all cases, the absolute change is considerably higher than the net gain as the important loss of woodland occurring over time is compensated by a larger conversion of lands into woodland. Unsurprisingly, the estimates in Area 4 between T3 and T4 are similar to those for Area 1 (Figure 3.8a) with a loss of 2,545 ha that is proportionally minor compared to the 12,887 ha converted into woodland.

3.3.2.2 Diagrams of changes

a.



b.



c.

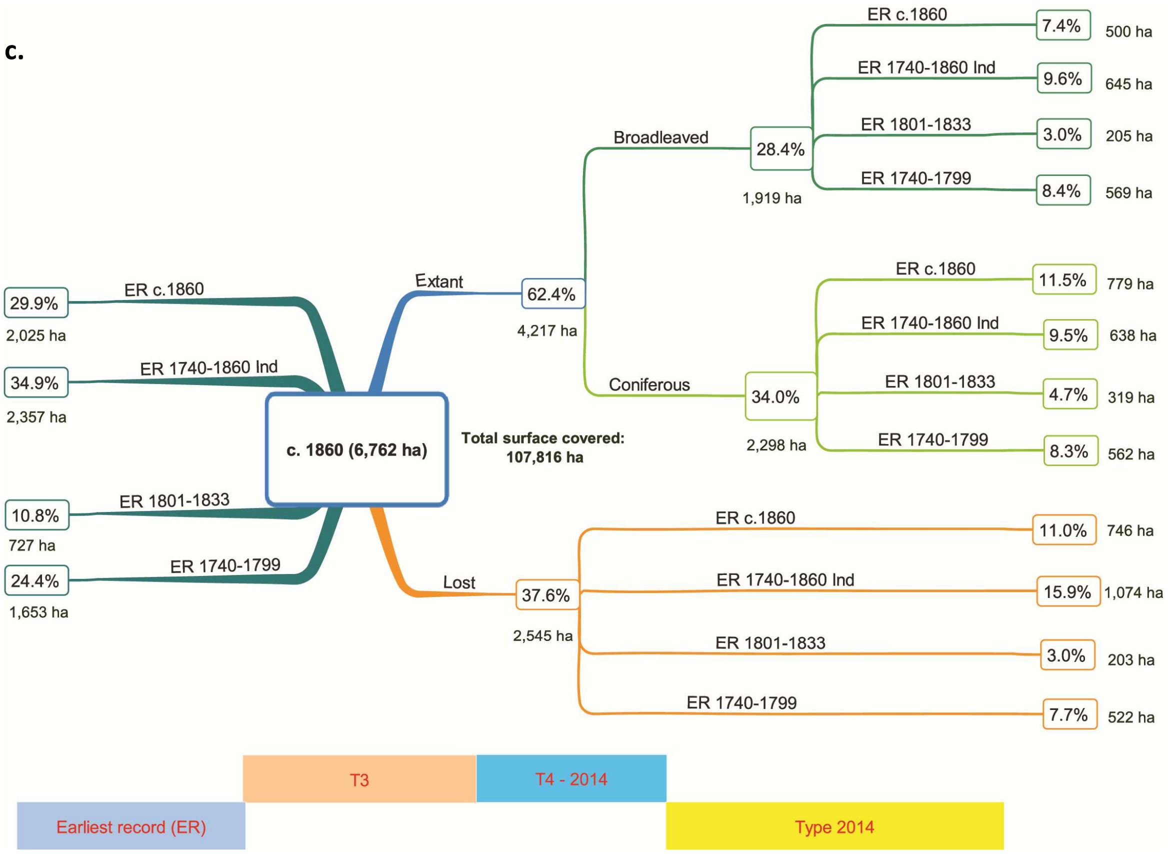


Figure 3.9 Diagrams of changes over time for the woodland cover reconstructed at T1, T2 and T3, and dominant tree type (broadleaved or coniferous) in 2014 (T4). (**a.**) 1740-1799 (in Area 2); (**b.**) 1801-1833 (Area 3); and (**c.**) c.1860 (Area 4). Percentages are calculated from the initial amount of woodland for each time-series. "Ind" stands for "indeterminate". 'ER 1740-1833 Ind' is due to missing estate plans in T1, while 'ER 1740-1860 Ind' is due to missing estate plans in T1 or T2; 'ER 1801-1833' concerns woodlands not wooded in T1 in Area1; 'ER 1740-1799' concerns woodland recorded in T1. In Figure 3.9b, the categories 'ER 1740-1799' and 'ER 1801-1833' are comparable (both identified on Area 1), while 'ER 1740-1833 Ind' concerns woodlands in the area covered by T2 but not T1.

Figure 3.9 offers a different perspective in tracing over time changes in woodland cover reconstructed for each of the three historical time series. The time-line (bottom) shows how much of the woodland reconstructed at time *t* (T1, T2 or T3) is extant or lost at *t+1*, *t+2* and *t+3* (e.g. *t+2* (T3) and *t+3* (T4) for the woodland at *t* in T1, Figure 3.9a). Figures 3.9b and 3.9c indicate further how much woodland recorded for the first time in 1740-1799, 1801-1833 and c.1860 (i.e. 'ER categories') were extant in 2014 and what the dominant tree type of each category was in 2014.

First, it has to be noted that the 'ER categories' refer to the earliest evidence provided by the historical maps used for this project and not exactly the 'ancientness' of the woodlands, which remain unknown. As a result, the woodlands recorded as 'ER 1740-1799' may be centuries older, while the woodland 'ER 1801-1833' appeared sometime between T1 and T2, and 'ER c.1860' concerns woodland that grew between T2 and T3. The accuracy of some estimates was also occasionally limited by the lack of woodland data for the missing time series. Categories 'ER 1740-

1833 Ind' in Figure 3.9b, and 'ER 1740-1860 Ind' in Figure 3.9c, both encompass woodland of unknown age.

Figure 3.9a and Figure 3.9b show that a significant portion of the woodland recorded in T1 and T2 was lost by T3 (c.1860). This loss represents 40% of the woodland cover recorded in T1 — as already seen in Figure 3.8 – while the extant woodland remained more stable until T4, with only 19% lost between T3 and T4 (Figure 3.9a). Likewise, the loss of woodland between T2 and T3 (36%) is double than lost between T3 and T4 (18%) (Figure 3.9b). However, we notice both on Figure 3.9a and 3.9b, that about 9% of the woodland lost by T3 had been wooded again sometime between T3 and T4. As we will see in section 3.3.3 on trajectory analysis, it is likely that this estimate can be partly explained by the varying planimetric accuracy of the woodland reconstruction from historical maps.

Regarding category 'ER 1801-1833' in Figure 3.9b, it is noteworthy that 351 ha (of 1,172 ha) was already lost by T3, meaning that almost a third of the area newly afforested in the early nineteenth century had remained woodland for a few decades only. This observation supports previous evidence of higher woodland dynamics that apparently operated between T2 and T3. Perhaps a large amount of plantation of the late eighteenth or early nineteenth century was converted back to non-wooded areas because of their unsuitability to produce good crops. In contrast, a lower 17% of the category 'ER 1740-1799' was lost by T3 in the same area (i.e. 131 ha in T3 over 767 ha initially in T2). These results suggest a higher stability until the mid-nineteenth century of the most ancient woodland compared to the newly afforested area in T2.

Regarding the woodland type in 2014, in Area 2, a slightly higher amount of the remaining woodland of category 'ER 1740-1799' was broadleaved (718 ha) than coniferous (648 ha) (Figure 3.9a). In Area 1 (Figure 3.9b), the estimates of broadleaved and coniferous woodland are different according to the ER categories. As for 'ER 1740-1799', a larger amount was broadleaved than was coniferous woodlands (respectively 292 ha and 191 ha) while, conversely, the remaining woodland of 'ER 1801-1833' was more coniferous (349 ha) than broadleaved woodlands (271 ha). These results may reflect differences in original trees composition between category 'ER 1740-1799' and category 'ER 1801-1833'. However, as we will see in section 3.4 (Discussion), the type of woodland cover has not remained stable with important changes in tree composition having already occurred by T3.

Contrary to Figure 3.9b, the categories 'ER 1740-1799' and 'ER 1801-1833' in Figure 3.9c are not comparable to each other as the estimates were done on different sub-study areas. This diagram should therefore be used carefully. Despite these limitations, some observations remain of interest. In 2014, a higher number of categories 'ER 1860' and 'ER 1801-1833' were coniferous (779 ha and 319 ha, respectively) rather than broadleaved woodland (500 ha and 205 ha). In contrast, for

'ER 1740-1799', the woodland was about equally divided with 569 ha as broadleaved woodland and 562 ha as coniferous, which is very similar to the observations in Figure 3.9a and Figure 3.9b. Furthermore, there is also higher amount of woodland broadleaved in T4 for 'ER 1740-1799' (569 ha) than for 'ER c.1860' (500 ha) despite more woodland in T3 for the latter category (1,653 ha for 'ER 1740-1799' while 2,025 ha for 'ER c.1860'). These observations tend to confirm that the category 'ER 1740-1799' constitute a larger part of the broadleaved woodland in 2014 than any other category. Finally, we note that 746 ha of 'ER c.1860' were lost by 2014 (i.e. 37%), which suggests the low persistence as woodland of an important portion of the newly afforested area in T3.

3.3.2.3 Woodland cover in 2014

Figure 3.10 summarises some estimates from the change detection analysis to show for Area 1 the contribution of each ER category that form the woodland cover in 2014. We can observe that categories 'ER 1740-1799' and 'ER 1801-1833' together consisted of less than only 18% of the woodland cover in 2014, with an almost equivalent contribution of about 620 ha each. Regarding tree composition, the proportion of broadleaved woodland was higher for 'ER 1740-1799' (383 ha) than for 'ER 1801-1833' (271 ha). In the most recent woodland – 'ER c.1860' and 'ER 2014' – the proportion of coniferous woodland continued to increase considerably more than broadleaved. We should, however, remember that these estimates do not necessary reflect the original nature of the woodland cover. A certain amount of broadleaved 'ER 1740-1799', 'ER 1801-1833' and 'ER 1860' might result from conversions of broadleaved woodland into coniferous woodland, and conversely.

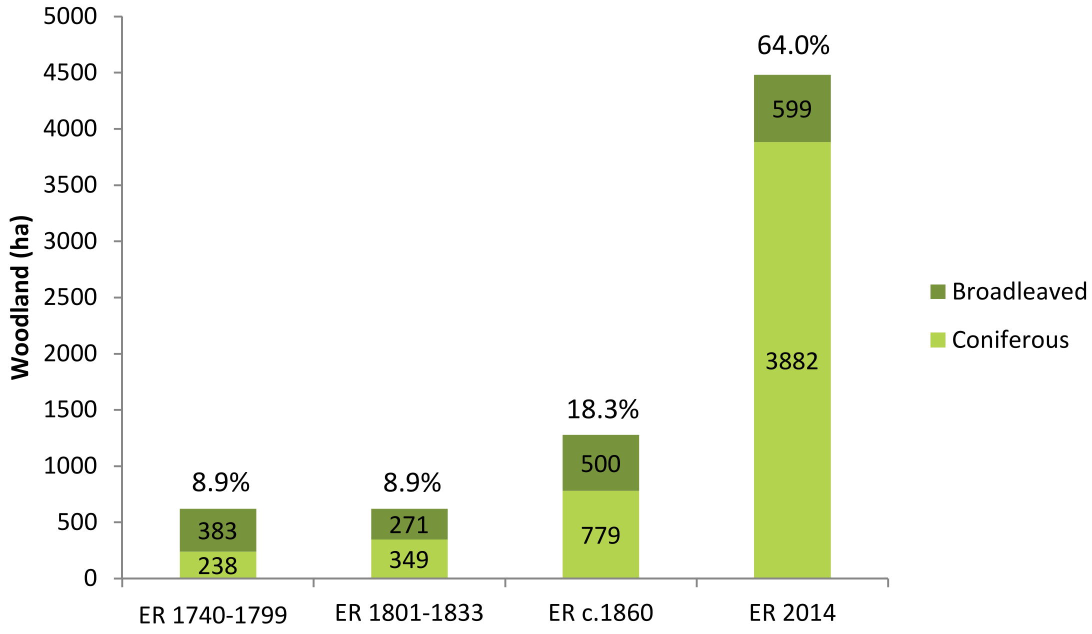


Figure 3.10 Contribution of the different ER categories to the woodland cover in 2014 (in Area 1)

3.3.2.4 Changes in woodland class and management type

Table 3.5 Woodland area with different vegetation classes and management types remaining wooded in T3 and T4 (in ha). In brackets, the remaining percentages are calculated from the initial estimate for each class and type at T1, T2 and T3. 'Low woodland', 'Bushes' and 'Unknown' were ignored for T2 due to very low evidence from estate plans (less than 15 ha for each). Only 'Open woodland' could be recorded for T3 (c.1860) – details in Chapter 2.

			T3	T4		
T1 (Area 2)		**Initially**	**Woodland**	**Broadleaved**	**Coniferous**	**Total T4**
	Open woodland	179	61 (34)	38 (21)	22 (12)	60 (33)
	Low woodland	98	62(63)	27 (28)	29 (30)	57 (58)
	Bushes	119	41 (35)	19 (16)	14 (12)	33 (28)
	Unknown	48	12 (24)	10 (21)	5 (10)	15 (31)
	Grazed	181	60 (33)	38 (21)	14 (8)	52 (29)
	Plantation	575	480 (83)	100 (17)	247 (43)	347 (60)
T2 (Area 3)						
	Open woodland	391	161 (41)	96 (24)	37 (9)	133 (31)
	Grazed	162	69 (42)	38 (23)	24 (15)	62 (38)
	Plantation	779	670 (86)	142 (18)	401 (51)	543 (70)
T3 (Area 4)						
	Open woodland	166	-	30 (18)	20 (12)	50 (30)

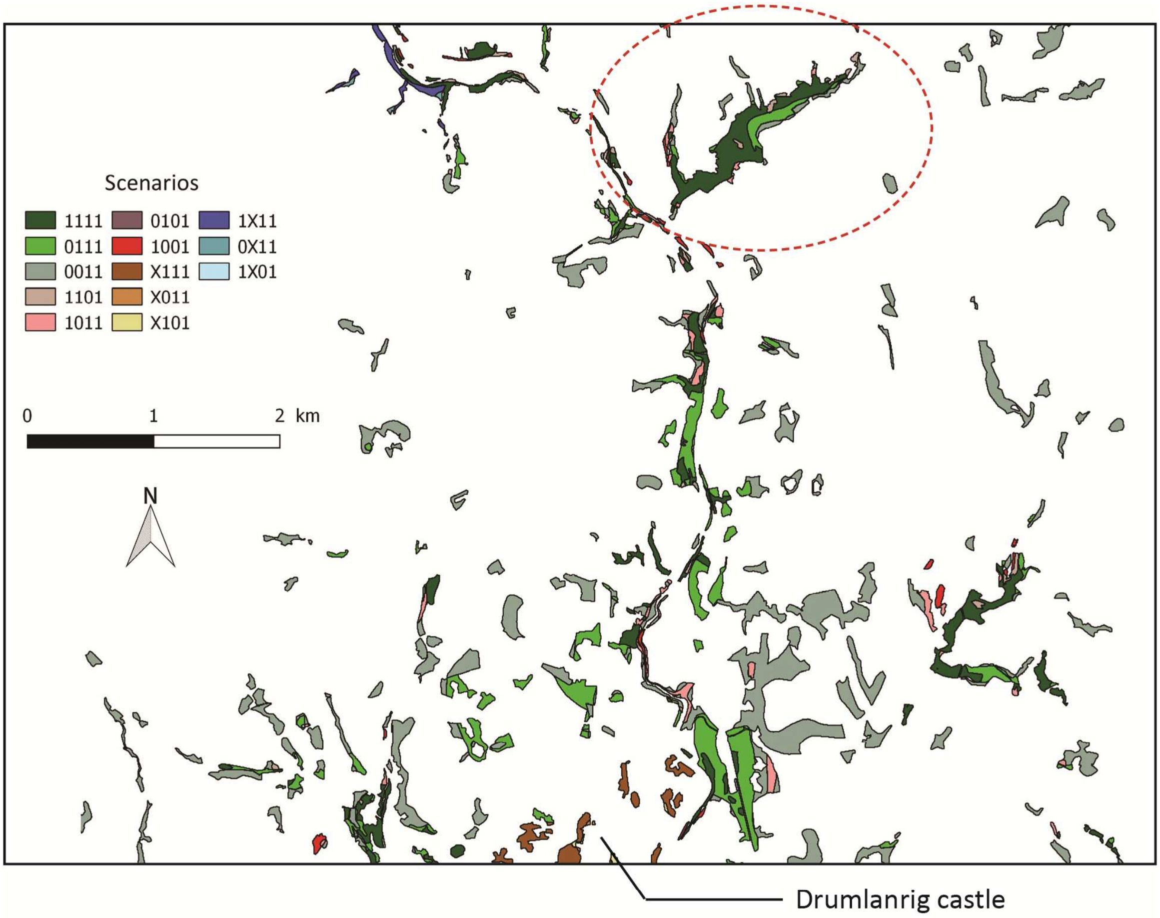
Table 3.5 summarises how much of the woodland with different vegetation classes and management types – based on evidence from historical estate plans – remained wooded by T3 (c.1860) and as broadleaved or coniferous woodland by T4 (2014). While limited due to the uncertainties affecting these estimates from estate plans and OS maps – in particular, the management types were not comprehensive and the vegetation classes may be based on fuzzy and ambiguous evidence (see Chapter 2) – the results provide insight into some historical trends. As already discussed in Chapter 2, it is noteworthy that plantations mentioned as such by mapmakers on estate plans arguably represent a portion only of the real extent of historical plantations. Therefore, the estimates of woodland plantations in T1 and T2 provided in Table 3.5 must be considered as underestimates.

Firstly, a considerable area of the open woodland identified from estate plans was definitely lost by T3. Only 34% left of the open woodland identified in T1 (61 ha over 179 ha initially), and 41% the open woodland in T2 (161 ha over 391 ha initially) was woodland by T3. In addition, only 2 ha and 26 ha of the open woodland, in T1 and T2 respectively, remained as open woodland by T3 (not shown in Table 3.5). Most of the open woodland that remained wooded was therefore converted into dense woodland. Between T3 and T4, more continuity in cover is evident. The open woodland from T1 that was extant as woodland by T3 was still wooded in 2014. This woodland was more broadleaved (38 ha) than coniferous woodland (22 ha) in 2014. Likewise, most of the open woodland areas from T2 that were extant in T3 were wooded in T4 with considerably more broadleaved (96 ha) than coniferous woodland (37 ha). Despite the fact that open woodlands in T1 and T2 have remained wooded until at least 2014, these results suggest that a considerable portion did not remain broadleaved woodland but was converted into coniferous woodland.

Secondly, it seems that among the different vegetation classes, the low woodland class has been more persistent over time with 63% (62 ha) remaining as woodland by T3 and 58% (57 ha) by T4. The low woodland was originally composed of broadleaved trees (see Chapter 2). Nonetheless, 30% of the low woodland in T1 being coniferous in T4 – against 28% as broadleaved – suggests that a substantial area was actually converted into coniferous plantations, as for open woodlands. In contrast, only 28% of the area identified as bushes in T1 was woodland in 2014. Most of the bushes were lost between T1 and T3 as only 35% of the area dominated by bushes in T1 was wooded by T3. It is possible that, unlike low woodland, the area dominated by bushes was less suitable to be converted into woodland. These results should, however, be interpreted cautiously due to the very low area of lands concerned.

Regarding the management types, 83% (480 ha) and 86% (670 ha) of the woodland identified as plantation from estate plans in T1 and T2 respectively (575 ha and 779 ha initially) were extant in T3. This result confirms the loss of young woodland plantation by T3 but by a lower amount than suggested previously from estimates in Figure 3.9. The fact that only a small portion of the plantations was identified as such from estate plans might partly explain these discrepancies. Afterwards, plantations from T1 and T2 diminished to 60% and 70% in 2014 and were largely dominated by coniferous woodlands. Conversely, a high portion of the woodland for which grazing activities was known in T1 and T2 had been definitely lost by T3, with 33% (60 ha) and 42% (69 ha) respectively remaining as woodland by T3. By T4, 21% (T1) and 23% (T2) of these grazed woodlands were still broadleaved, while a minor part was converted into coniferous woodland (i.e. 8% from T1 and 15% from T2).

3.3.3 Trajectory analysis



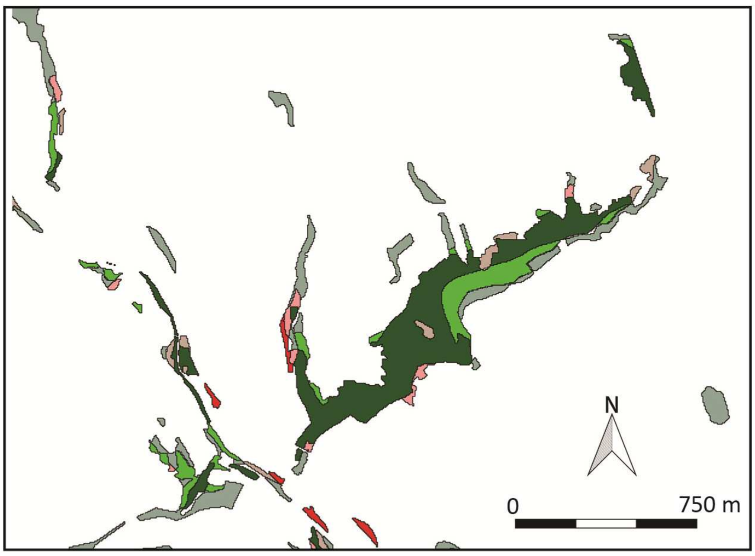


Figure 3.11 Example of trajectory map around Drumlanrig castle. In red circle and below, a map of Coshogle wood – a Site of Special Scientific Interest (SSSI). Only part of the woodland presently has been wooded since at least T1 (scenario 1111).

Table 3.6 Categorisation of the broadleaved woodland cover with historical record into different woodland trajectories (1 = woodland; 0 = non-woodland; X = no data).

	Trajectory (T1-T2-T3-T4)	Coverage (ha)	Sum
Area 1			
	1-1-1-1	280	
	0-1-1-1	206	987 (82.6%)
	0-0-1-1	501	
	1-0-0-1	40	1027 (86.0%)
	1-0-1-1	63	1090 (91.3%)
	1-1-0-1	41	1131 (94.7%)
	0-1-0-1	64	1195 (100%)
Area 2			
	1-X-1-1	256	459 (87.3%)
	0-X-1-1	203	
	1-X-0-1	67	526 (100%)
Area 3			
	X-1-1-1	225	440 (87.5%)
	X-0-1-1	215	
	X-1-0-1	63	503 (100%)

The trajectory analysis focused on the broadleaved woodland cover in 2014 with historical mapping record. All cells were categorised in each of the trajectories listed in Table 3.6. In the end, this analysis allowed mapping all broadleaved woodland in 2014 according to their historical trajectory in a *stability map* (e.g. Figure 3.11). In addition, the PAR of each woodland patch was calculated from the stability map.

For each sub-study area, the woodland that has remained apparently continuously wooded since its first record, such as ‘1-1-1-1’, ‘0-1-1-1’ and ‘0-0-1-1’, covered a much larger area (82.6% of the woodland) than the less stable trajectories, such as ‘0-1-0-1’. In Area 1, Area 2 and Area 3, the proportions of all stable trajectories represented respectively 82.6%; 87.3% and 87.5% of the woodland cover with historical mapping record.

Kaim et al. (2014) assumed that stable trajectories can be considered as ‘very realistic’, while the trajectory ‘1-0-0-1’, reflecting an early woodland clearance before re-growth in the most recent period, was considered as ‘realistic’. The categories with short periods of clearance such as ‘0-1-0-1’ or ‘1-1-0-1’, are therefore considered as ‘less realistic’. These latter can be due to variations in spatial accuracy of the datasets that were overlaid during the trajectory categorisation process, or they may correspond to woodland overlooked during the historical surveys. In applying the interpretation by Kaim et al. (2014) of trajectory analysis, the considerably higher scores of the most realistic trajectories compared to the less realistic trajectories (Table 3.6) tend to confirm the overall reliability of the changes mapped and quantified in this chapter. As the most uncertain trajectories represent only between 10 and 15% of the historical broadleaved woodland coverage in 2014, these results tend to support, by extension, the reliability of the woodland records from historical maps and confirm that the planimetric accuracy of the woodland reconstructions is still sufficient to investigate woodland cover changes over time.

Moreover, it is still possible that some of the least realistic trajectories account in part for true changes. For instance, 150 years separated T3 for T4, which may be considered as long enough for realistic woodland clearance and regrowth decades later. Likewise, 80-90 years could separate two surveys of the same area between T1 and T3, a time period during which woodland clearance by T2 and re-growth by T3 was still possible. It is also noteworthy that the least realistic trajectories being mapped in the stability maps can help to pinpoint the most controversial areas. A visual assessment from historical maps may enable subsequent verification of whether the trajectories correspond to true changes.

Further to assessing the reliability of the woodland trajectories, it was assumed for this project that the perimeter-area ratio (PAR) of the trajectory patches could constitute another useful indicator of the reliability of the different trajectories. The higher the PAR of a patch, the less likely it is that the patch represents real changes (De Keersmaeker et al., 2015). Figure 3.12 illustrates the relationship between the cumulated woodland area according to the PAR of patches for two realistic trajectories (plain line) and four less realistic trajectories (dashed line). The relationship shows major differences in the trends according to the reliability of the trajectory. Regarding the two most realistic trajectories, all patches with a PAR > 0.2 – the least reliable patches – covered a cumulative woodland area that represented 10 ha, while for the least realistic trajectory, i.e. ‘0-1-0-1’, the cumulative woodland area more than doubled to reach 24 ha. In addition, while, 10 ha do not represent much compared to the total area covered by the realistic trajectories (> 220 ha each), 24 ha represent about 38% of the area covered by ‘0-1-0-1’ (i.e. 64 ha in total). Likewise, the area covered by all the patches with PAR > 0.13 – where the grey line representing ‘1-1-1-1’ starts to cross the red dashed line ‘1-0-1-1’ – was systematically higher for each of the less realistic trajectories than for the two realistic ones.

A visual comparison of the shape of the trajectory patches with historical maps shows further that for patches with a PAR > 0.2, the reliability of a trajectory becomes very uncertain. Below this threshold, a larger number of patches seem to reflect real changes with more confidence – such as the occasional disappearance or appearance of woodland vegetation along the watercourses. The total area covered by patches with 0.15 < PAR < 0.2 and PAR > 0.2 was reported for each trajectory in Figure 3.13. These results are used as an indicative basis to determine how the contribution of the most uncertain patches – with PAR over these two indicative thresholds – may affect differently the acreage of each trajectory.

Figure 3.13 confirms that the acreage of the most stable, and therefore realistic trajectories, are less affected by patches with high PAR than the least realistic trajectories. It also illustrates that trajectories such as '1-1-0-1' and '0-1-0-1' are more represented in extent by the most uncertain patches and, therefore, tend to be less reliable than other less realistic trajectories such as '1-0-1-1'. In total, about 81% of the area is covered by trajectory patches with a PAR < 0.15; 8% with 0.15 < PAR < 0.2 and; 11% with PAR > 0.2.

The depiction of watercourses represents an important concern regarding the reliability of trajectories due to the varying planimetric accuracy of historical maps. Surveying and redrawing accurately these features on a map was likely to be one of the most challenging tasks for an estate surveyor but not necessarily a priority (Cousins, 2001). Comparison of historical maps covering the same area may highlight important variations in watercourse's shape and sinuosity. These differences are reflected in the trajectories of woodland areas lying along the watercourses. While it is difficult to know how much the uncertain long linear woodland trajectories along watercourses can be explained by a poor survey or actual changes, we should keep in mind that this issue may greatly affect the accuracy of spatial studies such as the change detection analysis on the riparian woodlands. For instance, Figure 3.14 shows that an important part of the woodland with the most uncertain trajectories (PAR > 0.2) lies along the River Nith.

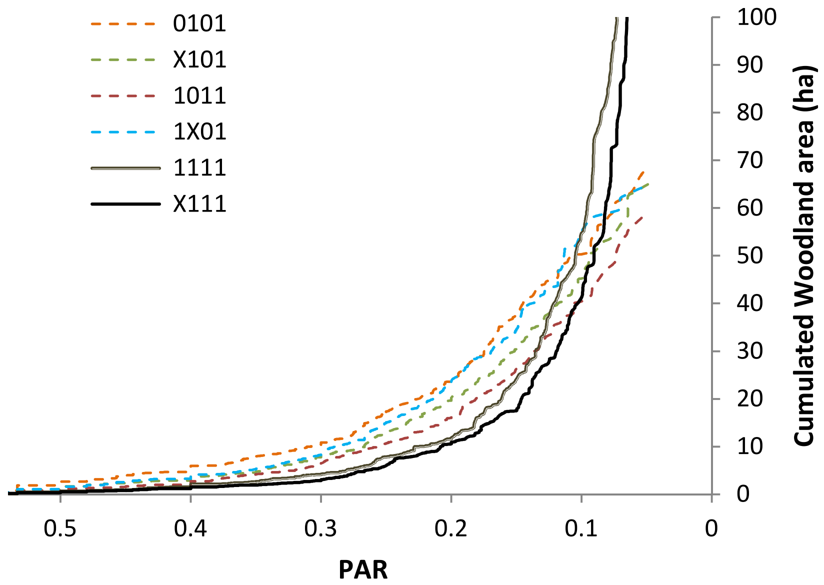


Figure 3.12 Comparison of the relationship between cumulated woodland area (ha) and perimeter-area ratio of the patches (PAR) for different trajectories. The two most realistic trajectories are in plain lines. The less realistic trajectories are in dashed lines.

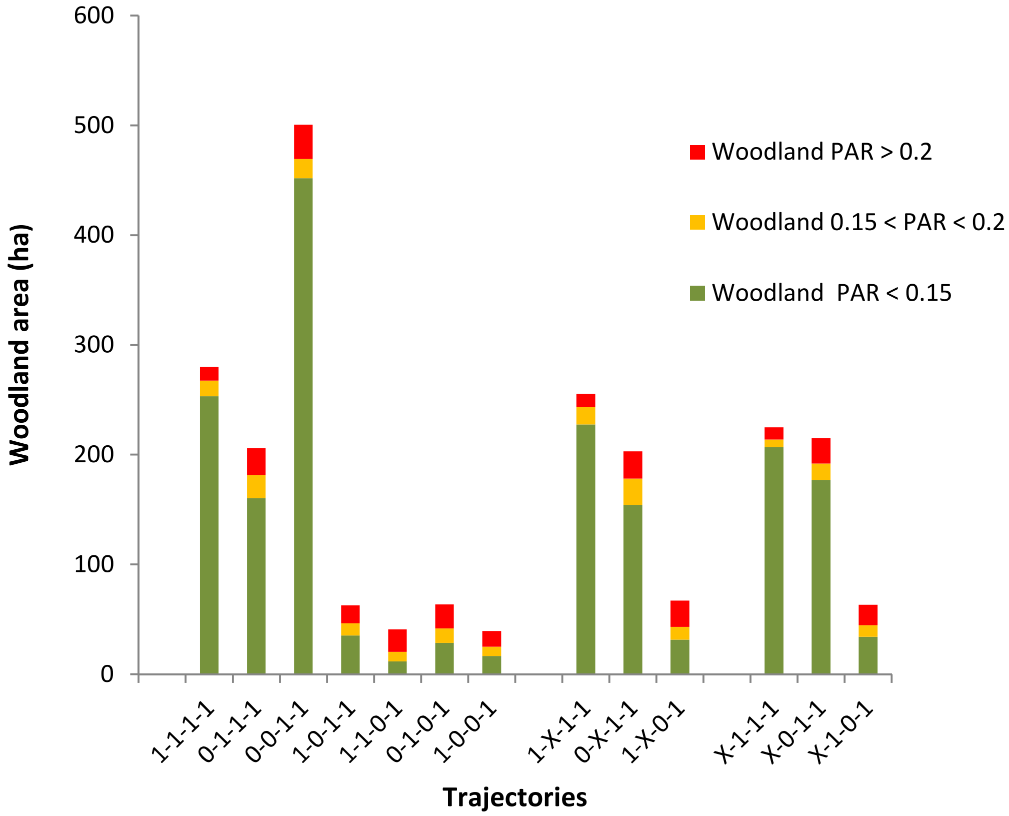


Figure 3.13 Proportion of woodland patches with 0.15 < PAR < 0.2 and PAR > 0.2 for the different woodland trajectories composing the broadleaved woodland cover in 2014.

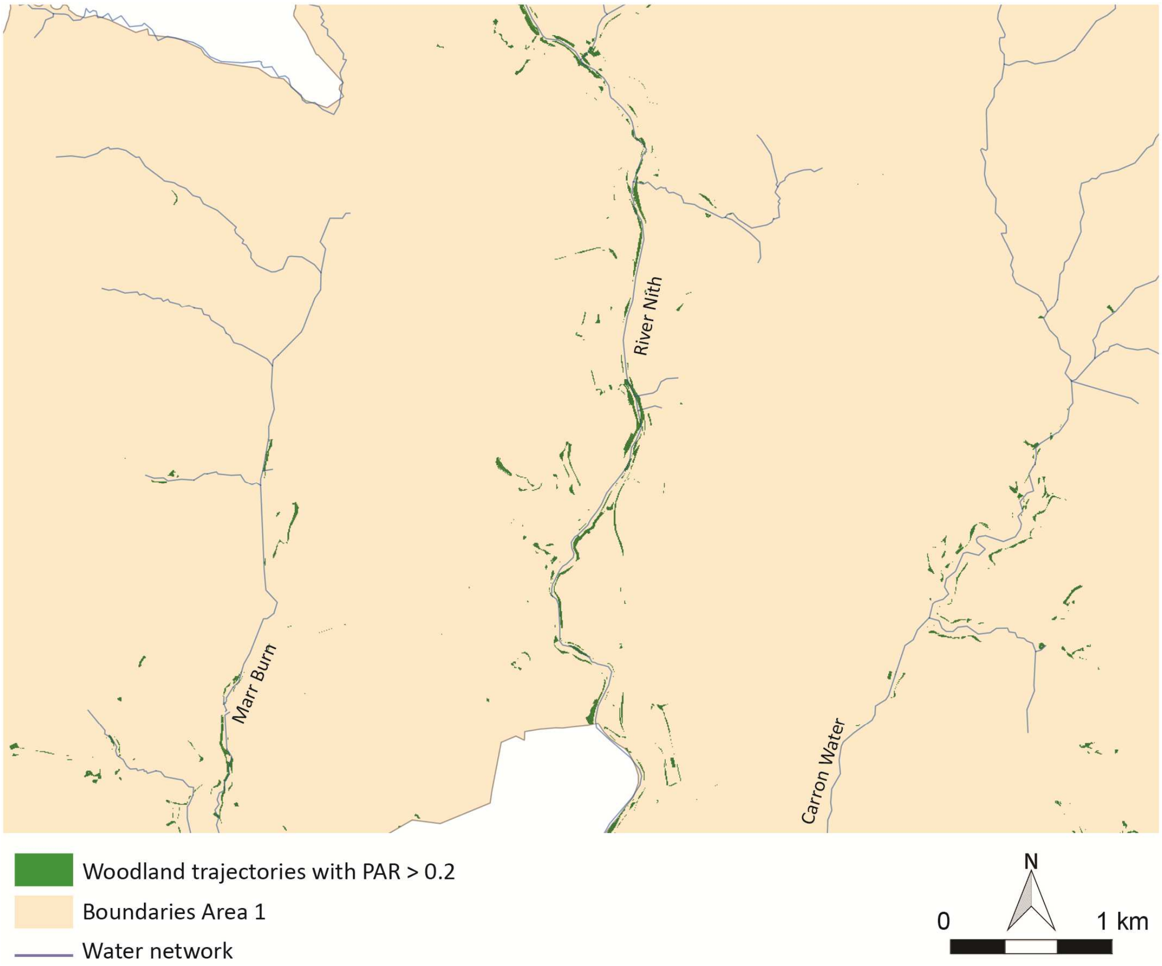


Figure 3.14 Broadleaved woodland trajectories patches with calculated PAR > 0.2 in the estates around Drumlanrig (subset). The uncertain trajectories are mostly located along the river Nith.

3.3.4 Logistic regression models

Table 3.7 Assessment of the models quality. McFadden's Pseudo-R^2 > 0.2 indicates a relative good fit and AUC > 0.7 indicates a relatively good discriminatory power between woodland and non-woodland (Serneels and Lambin, 2001; Wilson et al., 2005).

Time series	Region	Models	pseudo-R^2	AUC	*F-score* (p>0.5)
T1	Drum	1	0.37	0.87	0.74
	Annan	2	0.26	0.80	0.65
	Annan	3	0.32	0.87	0.68
	Other	4	0.22	0.82	0.71
T2	Drum	5	0.35	0.86	0.69
	Annan	6	0.28	0.82	0.59
	Other	7	0.17	0.75	0.66
T3	Drum	8	0.21	0.77	0.63
	Annan	9	0.20	0.75	0.29
	Other	10	0.04	0.60	0.22

Table 3.8 Logistic regression results for the distribution of the woodland cover in T1. Odds Ratio (OR) and 95% confidence intervals (CI) were calculated as exp(β_n) for each explanatory variable showing statistical significance and which served to fit the best model. OR > 1 indicates higher odds of a cell to be woodland and OR < 1 indicates lower odds. Significance is indicated with ***, **, and * for respectively $p < 0.001$, $p < 0.01$ and $p < 0.05$. ΔAIC represents the difference in Akaike 's criterion (AIC) between the best model and the model after omitting or adding the variable. Therefore, ΔAIC indicates the relative importance of each explanatory variable.

	T1							
	1. Drum		2. Annan(1)		3. Annan(2)		4. Other	
Variables	**OR [CI]**	**ΔAIC**	**OR [CI]**	**ΔAIC**	**OR [CI]**	**ΔAIC**	**OR [CI]**	**ΔAIC**
Elevation	0.982 [0.978-0.987]***	258	0.994 [0.989-0.999]*	57	0.994 [0.988-0.999]*	54	0.987 [0.983-0.991]***	40
Slope	1.231 [1.143-1.332]***	69	1.285 [1.163-1.436]***	42	1.320 [1.182-1.495] ***	39	1.124 [1.084-1.168]***	45
D_watercourse	0.997 [0.997-0,998]***	42	0.999 [0.998-1,000]*	3	0.997 [0.996-0.998]***	20	0.998 [0.997-0.999]***	36
Eastness	1.264 [1.029-1.555]*	3	1.244 [1.002-1.548]*	2	1.602 [1.238-2.086] ***	11	-	0
Northness	-	0	-	0	1.487 [1.035-2.146] *	3	-	2
D_castle	0.999 [0.999-1.000]*	3	0.999 [0.999-1.000]***	8	-	-1	0.999 [0.999-1.000]*	3
Soil	-	33	-	13	-	8	-	30
Alluvial soils	0.229[0.114-0.457]***	-	-	-	-	-	0.390 [0.210-0.718]**	-
Surface-water gleys	3.022[1.828-5.059]***	-	0.180 [0.041-0.545]**	-	0.133 [0.020-0.487]**	-	-	-
Ground-water gleys	-	-	-	-	-	-	0.156 [0.048-0.424]***	-
Podzols	-	-	0.336 [0.117-0.834]*	-	0.219 [0.048-0.707] *	-	-	-
Peats	-	-	-	-	-	-	0.195 [0.086-0.411]***	-
Elevation x Slope	(***)	11	(***)	16	(**)	12	-	-

- : not significant at 95%

Table 3.9 Logistic regression results for the woodland expansion between T1 and T2. See Table 3.8 above for explanations.

	T2					
	5. Drum		6. Annan		7. Other	
Variables	**OR [CI]**	**ΔAIC**	**OR [CI]**	**ΔAIC**	**OR [CI]**	**ΔAIC**
Elevation	0.995 [0.989-1.000]*	62	-	17	1.019 [1.010-1.029]***	13
Slope	1.220 [1.116-1.345]***	18	1.602 [1.250-2.145]***	13	1.250 [1.116-1.426]***	15
D_watercourse	0.998 [0.997-0.999]***	13	-	1	0.997 [0.998-0.999]*	4
Eastness	-	0	0.614 [0.411-0.904]*	4	-	1
Northness	-	0	-	-2	0.552 [0.349-0.860]**	5
D_woodlandT1	0.998 [0.997-0.999]***	74	0.999 [0.998-0.999]***	23	0.998 [0.997-0.999]***	22
Soil	-	0	-	-5	-	3
Alluvial soils	-	-	-	-	-	-
Surface-water gleys	-	-	-	-	-	-
Ground-water gleys	-	-	-	-	-	-
Podzols	-	-	-	-	-	-
Peats	-	-	-	-	-	-
Elevation x Slope	(***)	14	(**)	13	(**)	5

- : not significant at 95%

Table 3.10 Logistic regression results for the woodland expansion between T2 and T3. See Table 3.8 above for explanations.

	T3					
	8. Drum		9. Annan		10. Other	
Variables	**OR [CI]**	**ΔAIC**	**OR [CI]**	**ΔAIC**	**OR [CI]**	**ΔAIC**
Elevation	0.996 [0.993-0.999]**	90	0.989 [0.984-0.994]***	19	-	0
Slope	1.146 [1.090-1.208]***	25	1.095 [1.052-1.143]***	19	1.093 [1.062-1.125]***	40
D_watercourse	1.001 [1.001-1.002]***	30	-	1	-	0
Eastness	1.218 [1.045-1.421]*	4	-	-1	-	-2
Northness	-	0	-	0	-	0
D_woodlandT2	0.999 [0.999-1.000]***	16	-	-1	-	0
Soil	-	61	-	8	-	0
Alluvial soils	0.360 [0.201-0.635]***	-	-	-	-	-
Surface-water gleys	0.220 [0.129-0.360]***	-	-	-	-	-
Ground-water gleys	0.326 [0.178-0.569]***	-	-	-	-	-
Podzols	0.479 [0.304-0.746]**	-	0.226 [0.132-0.370]**		-	-
Peats	-	-	-	-	-	-
Elevation x Slope	(***)	22	-	-	-	-

- : not significant at 95%

3.3.4.1 Woodland cover in T1 (Tables 3.7 and 3.8)

The distribution of the woodland cover in T1 was well explained by each of the four models, with a pseudo-R^2 between 0.22 and 0.37, AUC between 0.80 and 0.87, and *F-score* between 0.65 and 0.74 (Table 3.7). The odds ratio (OR) are associated with higher (OR > 1) or lower odds (OR < 1) of a cell being woodland ('1') when the explanatory variable increases of one unit (e.g. one degree for 'slope', or one meter for a distance-based variable). As the explanatory variables are expressed in different units, the OR cannot be compared between each other and the OR associated with variables with a large range of values such as elevation or distance to the nearest stream was necessary lower than the OR associated with variables with a restricted range such as aspect (northness and eastness) and slope.

The results suggest that the woodland cover in T1 was associated with areas of lower elevations and steeper slopes (Table 3.8). Indeed, in all models, the odds of a cell being 'woodland' decreases as the elevation increases (OR < 1) but the odds increase as slope steepness increases (1.124 < OR < 1.320). In addition, with the exception of the region 'Other', an interaction term between these two explanatory variables was found to better fit the models as the effect of slope varies according to elevation – the slope steepness has a lower effect in higher elevation because no woodland can possibly grow above a certain elevation (i.e. the tree line). As the region 'Other' corresponds to an area of lower elevations, the interaction term did not improve model 4.

The distribution of the woodland cover in T1 seems also to be closely related to distance to the nearest stream as the odds decreased as the distance to the nearest stream increased. The evidence was, however, less clear for the model of Annandale which integrated the late eighteenth century plantations (model 2, ΔAIC = 3 and *p*-value close to 0.05) compared to the model that left out these plantations (model 3; ΔAIC =20; $p < 0.001$). These results might suggest that the location of the late eighteenth century plantations in Annandale was independent of the stream network. In general, the model that did not consider the late plantations (pseudo-R^2 = 0.32; AUC = 0.87; *F-score* = 0.68) offered a better explanation of the woodland distribution in T1 than did the model that considered all woodland in Annandale (pseudo-R^2 = 0.26; AUC = 0.80; *F-score* = 0.65). In other words, the location of late eighteenth century plantations seems to be less predictable than the most ancient woodland cover.

When considering 'D_castle' alone, the odds of an area being woodland decreased significantly ($p < 0.001$) as the distance to the nearest castle or tower house increased. Even though the effect of 'D_castle' on the response variable is observed for each model, the evidence was less clear when elevation and slope were integrated into the models. This observation tends to suggest that while the woodland was more likely to be near a castle or tower house, environmental variables associated with these sites were sufficient to explain the woodland cover distribution. In sum, it is likely, for each of the three regions, that the location of these historical sites fails to partly explain the woodland cover in T1. Moreover, the statistical significance of 'D_castle' in model 2 ($p < 0.001$) highlights the need for caution when interpreting the effect of this variable. Indeed, there seems to be no historical reason for late eighteenth century plantations being purposely planted near centuries older castles or tower houses.

For Drumlanrig and Annandale, it seems that the odds of an area being woodland increased significantly with increasing eastness (i.e., with increasingly easterly aspect). The evidence was however only clear for Annandale before the campaign of plantations (model 3, $p < 0.001$). It is possible that the strong south-west winds had an influence on the woodland cover distribution in T1, the woodland being perhaps more likely to be preserved on the more sheltered east slopes. Regarding soil data, unsurprisingly, the odds of a cell being woodland decreased on soils with poor drainage such as gley soils and peats compared to the more suitable brown soils, with the notable exception of Drumlanrig where the surface-water gley soil located in the north of the region was quite wooded. More acidic – sometimes infertile – podzols seem also to have decreased the odds of supporting woodland in Annandale. As a result, the soil variable was often highly significant and had a relatively high importance ($8 < \Delta AIC < 33$) in all models.

3.3.4.2 Woodland expansion between T1 and T2 (Tables 3.7 and 3.9)

The distribution of the woodland expansion between T1 and T2 was well explained for Drumlanrig (model 5, pseudo-$R^2 = 0.35$; AUC = 0.86; *F-score* = 0.69) (Table 3.7). Firstly, as for T1, the results show that the odds of a cell being woodland increased with the steepness of the slope (OR= 1.220 ad CI =1.116-1.345) and decreased as the distance to the nearest stream increased (for every 100 m away of a stream, OR = 0.818 and CI = 0.741-0.905) (Table 3.9). This last observation is in agreement with the historical estate plans as many plantations from the early nineteenth century were located on the banks of the river Nith. Elevation remained also an important variable as the odds of an area being woodland decreased with elevation and, as for T1, the effect of slope steepness interacted with elevation values.

Secondly, in Drumlanrig as in the two other regions, the most recent woodland recorded by T2 was located near pre-existing woodland in T1 (D_woodlandT1, $p < 0.001$). These results suggest that the woodland appearing between T1 and T2, which include mostly plantations, was more likely to be located in the vicinity of the woodland cover that already existed.

Thirdly, the models for Annandale and region 'Other' (models 6 and 7) did not explain as well the woodland expansion as for the region of Drumlanrig. As it was easier to predict a cell to be '0' (i.e. not woodland) in Annandale than in region 'Other' – the higher elevations in Annandale cover an area that is less likely to be wooded – the AUC was higher for Annandale (0.82) than 'Other'

(0.75). Nonetheless, the predictive ability to identify accurately cells ‘1’ was lower for Annandale (*F-score* = 0.59) than for ‘Other’ (*F-score* = 0.66). For both regions, slope steepness and elevation remained important factors in the best models (13 < ΔAIC < 17 and $p < 0.001$). However, in contrast with previous observations, the odds of a cell being ‘1’ in region ‘Other’ increased with elevation, which may reflect the fact that afforestation took place on higher elevations than previously. In this region the maximum elevation is constrained to 280 m, which is low enough for the trees to grow anywhere.

It is noteworthy that the distance to the nearest watercourse had a low importance in ‘Other’ (ΔAIC = 4; $p < 0.05$) and there was no evidence that it had any influence in Annandale. Regarding the other variables, the results tend to suggest that the woodlands in Annandale were more likely located on the slopes facing west ($p < 0.05$) and in the region ‘Other’ on the slopes facing south ($p < 0.01$). Finally, there was no evidence that the soil type affected the probability of an area being afforested between T1 and T2.

3.3.4.3 Woodland expansion between T2 and T3 (Tables 3.7 and 3.10)

The distribution of the woodland expansion between T2 and T3 was also better explained for Drumlanrig than for Annandale and region ‘Other’. However, the model quality was lower in Drumlanrig (model 8, pseudo-R^2 = 0.21; AUC = 0.77; *F-score* = 0.63) than it was for the same region in T1, and to explain the expansion of the woodland cover between T1 and T2 (Table 3.7). In addition, the quality and predictive accuracy were poor for Annandale with a low *F-score* (model 9, pseudo-R^2 = 0.20; AUC = 0.75; *F-score* = 0.29) and very poor for region ‘Other’ (model 10, pseudo-R^2 = 0.04; AUC = 0.60; *F-score* = 0.22). For the latter, the model did not perform well in identifying cells ‘0’ as suggested by the low AUC, which implies that the predictive ability of model 10 was close to random (when AUC = 0.50).

The slope steepness and elevation remained significant factors and had the same effect for Annandale and Drumlanrig as previously (Table 3.10). This implies that the afforestation that took place between T2 and T3 occurred preferably on steeper slopes and at lower elevations. Although still not statistically significant in Annandale, the distance to the nearest watercourse had an opposite effect in Drumlanrig than previously as the odds of afforestation increased with the distance from the nearest stream (OR > 1; $p < 0.001$). Therefore, the newly afforested areas in Drumlanrig in T3 were located further away from the streams than they had been, perhaps because the most suitable areas on the banks were already wooded. As for the soil, this variable had a strong explanatory power in Drumlanrig only (ΔAIC = 62) and the results showed that any other type of soil than brown soil decreased significantly ($p < 0.001$) the probability of an area being afforested between T2 and T3.

Regarding the distance to the pre-existing woodland in T2, the area in the vicinity of the woodland cover in T2 was more likely to be wooded in Drumlanrig. However, this variable had no longer any effect in Annandale and region 'Other'. Overall, the set of explanatory variables fail to explain the patterns of woodland expansion between T2 and T3 for these two regions.

In general, it is clear that the explanatory power of the variables used in the different models decreases with time. Because the area transformed into woodland over time is arguably explained by plantations rather than natural woodland regeneration, the progressive loss of link between plantations and the different explanatory variables as well as differences between the regions certainly reflect changing practices in woodland planting over time and space.

3.4 Discussion

3.4.1 Expansion of the woodland cover from the second half of the eighteenth century to c.1860

The results of the present chapter demonstrate that the woodland cover underwent a major expansion between the second half of the eighteenth century (T1) and c.1860 (T3), with a coverage from about 3% of the study area in T1, to 4.5% in T2, and to 6.5-8.5% in T3 (Table 3.3). To the author's knowledge, this study is the first spatially explicit reconstruction of past woodland cover in Scotland. The results based on evidence from estate plans – for the earliest time series – and the First Edition OS maps are consistent across the whole study area.

These estimates are, however, significantly lower than tentative estimates by Smout et al. (2005, pp.64-65) who concluded that about 9% of Scotland was wooded by c.1750 as well as the beginning of the nineteenth century (T2). For the latter, Smout et al. (2005, pp.64-65) assumed that the cover consisted of 7% semi-natural woodland and 2% plantation. Currently accepted by several authors (e.g. Albritton Jonsson, 2013, p.46; Peterken, 2015; Wilson, 2015, pp.60-61), Smout et al.'s (2005) estimates are revisions of those of Sinclair (1814) and Lindsay (1980), and based mostly on the Ancient Woodland Inventory of Scotland and Smout et al.'s understanding of the Roy map.

Using samples of the Roy map, Lindsay (1980, p.272) found that the woodland cover in c.1750 was near 2 to 3% in parts of the Lowlands, while Sinclair (1814, p.321) assumed that by 1814 the woodland covered 5% of lands with less than 3% as "natural" (i.e. not plantations). In both cases, Smout et al. (2005, pp.61-64) considered these figures as underestimates needing revision. The authors argue that the Roy map overlooked perhaps half of the woodland cover as these maps depicted mostly the woodlands of military interest and the woodland areas were underestimated in many cases (Smout et al., 2005, pp.59-64). Moreover, according to Smout et al. (2005, pp.65-66), previous figures such as the first *Statistical Accounts of Scotland* and the *County Agricultural Reports*, on which Sinclair (1814) based his work, overlooked uncommercial wooded areas. Even though the estimates calculated in this chapter are based on the study of a relatively small portion of Scotland (i.e. 107,700 ha or about 1.5% of Scotland), they remain much closer to Lindsay (1980, p.272) for T1 and Sinclair (1814, p.321) for T2 than Smout et al.'s estimates (2005) for the whole Scotland.

In addition, it appears that some assumptions by Smout et al. (2005) about past woodland changes in Scotland do not apply to Nithsdale and Annandale, in particular that 1) the woodland cover did not vary much during the nineteenth century (2005, p.258); and 2) the early 1900s correspond to the lowest woodland coverage with 6% of woodland cover (2005, p.68). According to Smout et al. (2005, pp.68-69) a minor net loss of the woodland cover, mostly due to more intensive sheep farming, would have occurred over the nineteenth century. In contrast, the present study indicates a sharp increase from the early to the mid-nineteenth century. Nor do the results of this chapter corroborate the assumption that the First Edition OS maps overlooked many ancient woodland sites (Smout et al., 2005, p.68). Indeed, the trajectory analysis in Area 1 showed that only 3% (41 ha) of the total woodland in T1 and T2 is not depicted in the First OS (Table 3.6, trajectory 1-1-0-1), half of it being probably due to the planimetric accuracy of historical maps (about 21 ha for PAR > 0.2, see Figure 3.13).

Finally, the present results differ from the expectation that half of the woodland cover in c.1860 and 1914 would have been ancient semi-natural woodland as it has been suggested by various authors (Anderson, 1967, pp.394-395; Pryor and Smith, 2002; Smout et al., 2005, p.259). In Area 2, only 30% of the woodland in T3 was already depicted in T1 (1,648 ha over 5,442 ha, Figure 3.8b). Considering that by T3 at least 480 ha of the woodland in Area 2 was plantation from T1 (i.e. not ancient woodland) (Table 3.5), only 21% of the woodland cover by c.1860 is likely to be ancient semi-natural woodland. This estimate should also be understood as an upper estimate as woodland plantations were already common practices in T1 (see section 3.4.3 and 3.4.4 below) but not always acknowledged by estate surveyors (see Chapter 2).

3.4.2 Minimum coverage

In the field of woodland history, authors have often tried to identify the period of minimum coverage and the related proportion of woodland (e.g. Cinotti, 1996; Smout et al., 2005; Loran et al., 2016). As a very careful 575 ha was identified as woodland plantation in T1 (1740-1799), of a total of 2,727 ha of woodland, the lowest coverage was arguably earlier in time and lower in extent for the study area. While all plantations are not indicated as such on historical maps and considering the very early written evidence of planting woodland in the region (see sections 3.4.3 and 3.4.4 below), a larger amount of plantation amongst the woodland cover reconstruction in T1 should indeed be expected. As a result, while Smout et al. (2005, p.67) assumed that a fifth of the woodland cover in the early nineteenth century was plantation of native and non-native tree species, this chapter shows that this proportion might have been already reached decades earlier in the study area. After ruling out all the plantation woodlands identified in T1 (i.e. at least 21% of the woodland was plantation), the woodland coverage drops to 2.5% of the lands. This estimate would be a generous upper estimate of the minimum woodland coverage in the study area, given the general lack of mapping indication to identify the plantations. Furthermore, these estimates consider "woodland" on a broad sense as they integrate open woodland, brushwood and bushes identified from estate plans.

The centuries of war experienced by this part of Scotland (Maxwell, 1896; Marchbank, 1901, p.127) perhaps accounted for a considerable shrinkage of the woodland cover when it reached its minimum sometime before T1. However, only similar studies elsewhere in Scotland will clarify the extent to which the results presented in this PhD reflect the woodland history in the Lowlands. Although it is difficult to know whether the woodland coverage and the clear woodland increase observed in Nithsdale and Annandale between T1 and T3 are representative of a larger context, the next chapter (Chapter 4) shows different conclusions from those of Smout et al. (2005) with regards to the reliability of the Roy map for the study area. This chapter also questions the reliability of the Ancient Woodland Inventory used by Smout et al. (2005) for their own estimates.

3.4.3 Evidence of woodland tree composition and changes

3.4.3.1 From historical maps

Although historical estate plans can help to determine with great accuracy the changes in past woodland cover since the eighteenth century, they unfortunately provide little evidence about the tree species composition. Annotations such as "alder bog" (McCartney, 1782; and Wells, 1778), "wood mostly birch and oak" (Leslie, 1763), "close oak wood" (Leslie, 1763), "oak wood" (Morrison, 1804), "fir plantation" (Tait, 1773 and Morrison, 1804), "clump of firs" (Lewars, 1814), "young wood consisting of oak and ash" (Lewars, 1795), "thorns and hollies" (McCartney, 1782) provide some of the rare evidence about woodland composition on the estate plans that were studied.

It is also to be noted that the earliest mapping evidence of planting woodland in the study area is Shambellie wood in the parish of New Abbey, which is described as "fir planting on the Hill" by Tait in 1759. During the eighteenth and early nineteenth century, "fir", "Scots fir" or "Scotch fir" was regularly used to refer to Scots pines (Smout et al., 2005, p.74). Private forestry archives indicate further that Shambellie wood was planted with oak, ash and Scots pine by 1752 while the woodland expanded in the following years. By 1772-1779, larch, beech, birch and alder were mentioned, as well as elm by 1805 (unpublished).

In general, tree symbols on estate plans did not provide enough information to distinguish broadleaved, mixed or coniferous woodland. A few exceptions from estate plans drawn in the nineteenth century are, however, noteworthy and could reflect past practices that were more widespread. On the Drumlanrig estates plans from 1820-1825, Crawford undoubtedly used different symbols to differentiate broadleaved from coniferous trees (Figure 3.15A and B). It is unclear whether these symbols were drawn solely for aesthetic purposes, but it is interesting to note that most woodland depicted by Crawford which was already on Leslie’s plans about 50 years earlier are drawn with broadleaved tree symbols only. In contrast, most plantations identified as such by Crawford, or after comparison with Leslie’s plans, are mixed woodland (e.g. Morton wood (Figure 3.15A) or coniferous woodland. These observations suggest that Crawford’s depiction of tree types was at least partly accurate and that many plantations from the late eighteenth or early nineteenth centuries were mixed or coniferous woodlands.

Although it is well known that an effort was made to differentiate the woodland types on the First Edition OS maps (Harley, 1979), important discrepancies were highlighted when comparing the First Edition 25-inch to the mile maps (first printing) with the First Edition 6-inch to the mile maps of the study area (Figure 3.15C and D). More specifically, the 25-inch maps tend to distinguish broadleaved stands next to mixed stands whereas the 6-inch maps depict the whole woodland as mixed (Figure 3.15C and D). As the 25-inch maps’ depictions agree with Crawford’s estate plans (1820-1825) and corroborate our knowledge of some ancient woodlands in the region (e.g. Coshogle wood, Figure 3.11), these larger scale OS maps seem to be more reliable. To the best of our knowledge, such discrepancies have not hitherto been identified (Richard Oliver and Ifan Shepherd, pers. comm). These differences may account for a change in policy and are worth further investigation as the reduction from the 25-inch maps to the 6-inch maps may have resulted in a loss of information about woodland type, at least concerning the First Edition OS coverage of Dumfriesshire.

Based on the assumption that the 25-inch to the mile OS version was more reliable, an attempt was made to map broadleaved, coniferous, mixed and open woodlands during T3 in Drumlanrig, Annandale estates and part of the parish of Keir (Figure 3.16). If the depiction is true, it would confirm that the broadleaved woodland represented only a little portion of the woodland cover in T3 (i.e. about 17%, Table 3.11) while most of the sites would have been mixed woodland (almost 70%)

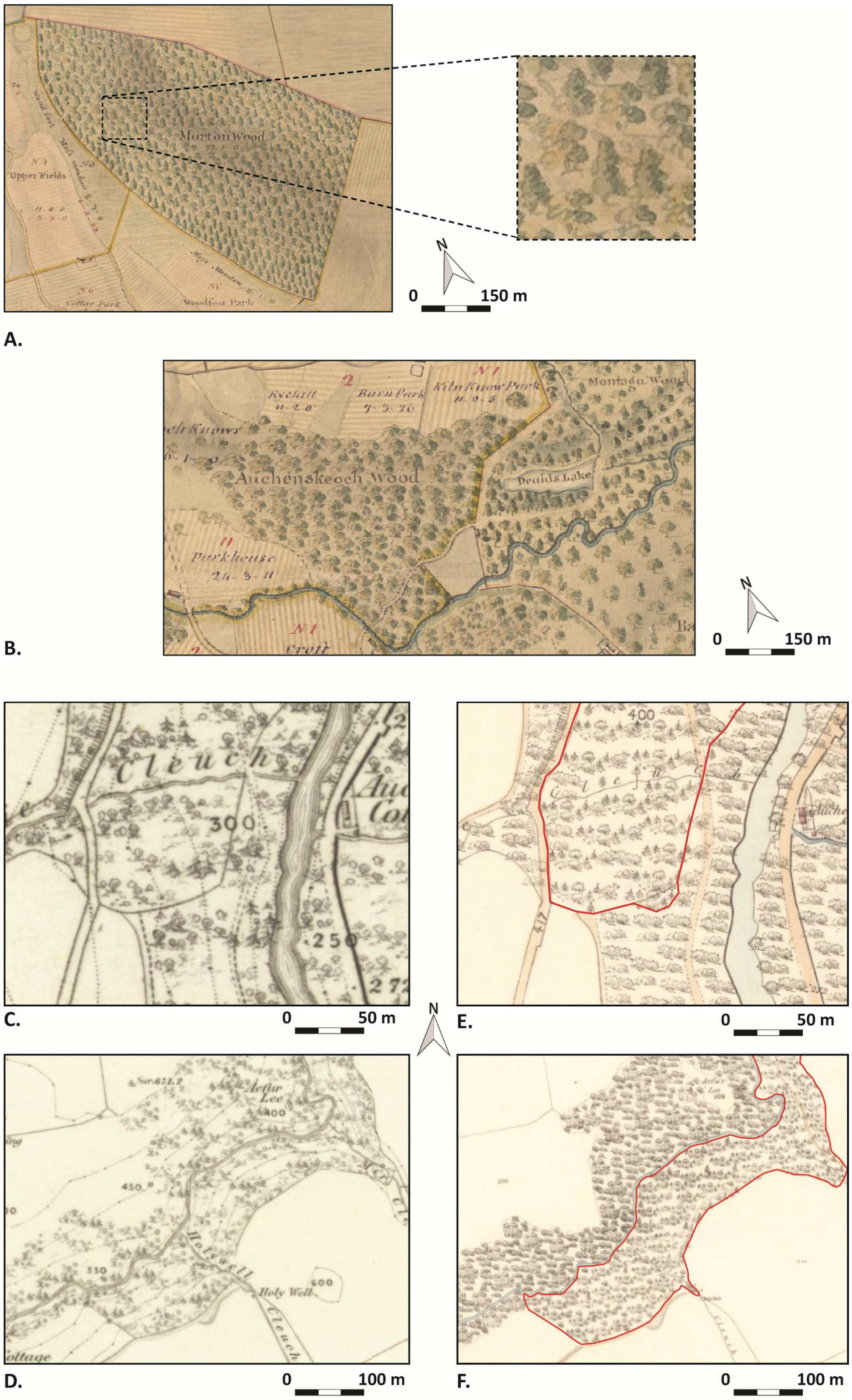


Figure 3.15 Deciduous and coniferous tree symbols on estate plans and First Edition OS maps. Morton wood (**A.**) (Crawford, 1820) is depicted as mixed woodland inside and a belt of coniferous trees on the outside. Auchenskeoch wood (**B.**) is depicted with broadleaved trees (left) while Montagu plantation is mixed woodland (right) (Crawford, 1820). Malcomflat (**C.**) and Coshogle (**D.**) woods are both depicted as mixed woodland on the First Edition OS map 6-inch to the mile whereas the 25-inch to the mile maps (**E.** and **F.**) make distinction between broadleaved and mixed woodlands (mixed woodlands are within red boundaries). The mixed woodland part of Coshogle wood (**F.**) is south of the watercourse and corresponds to the plantations identified in T2 and T3 (see Figure 3.11).

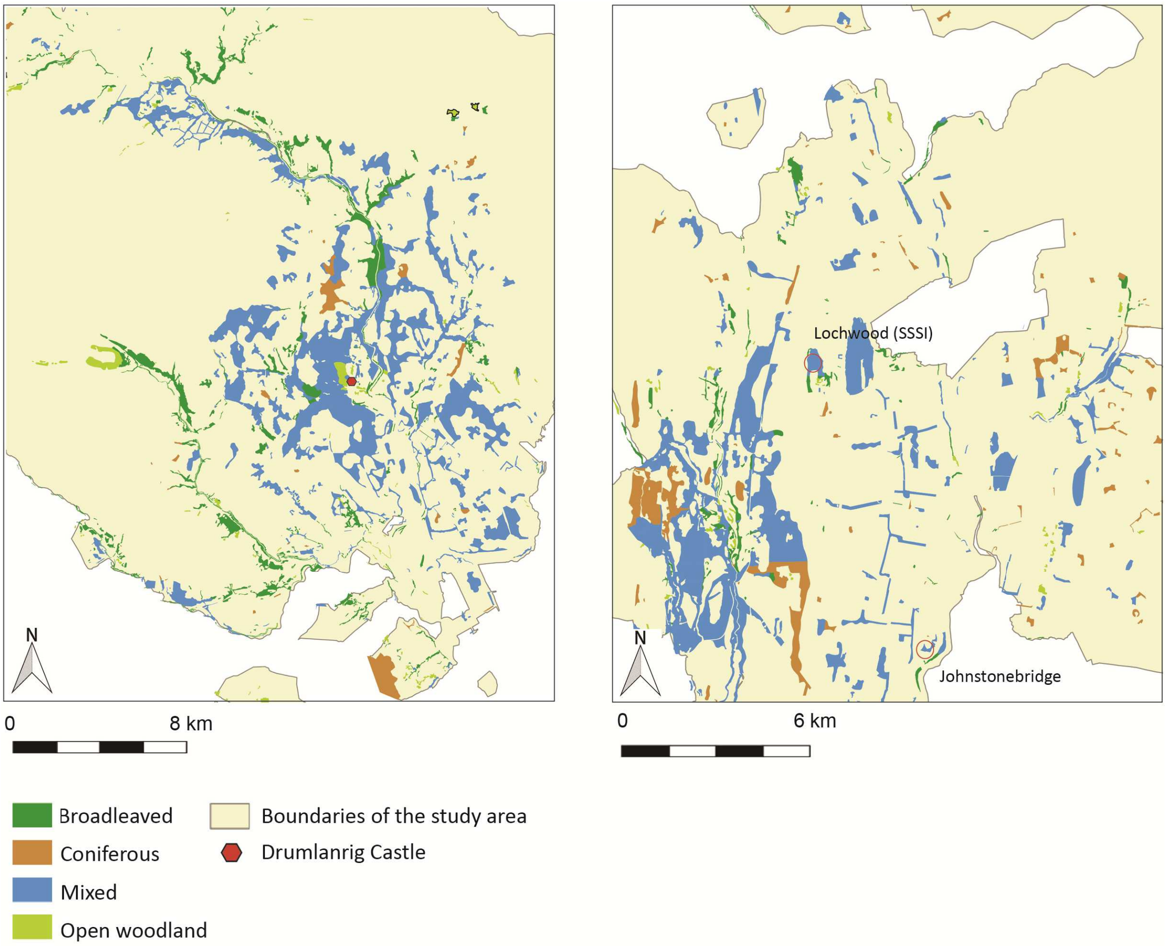


Figure 3.16 Woodland cover types from the First Edition OS maps – 25-inch to the mile (subsets showing estates in Nithsdale on the right and estates in Annandale on the left).

Table 3.11 Woodland type in part of Nithsdale and Annandale covered with the First Edition OS 25-inch to the mile maps (ha).

Woodland type	ha	%
Broadleaved	798.13	17.1
Conifers	530.69	11.4
Mixed	3211.49	68.9
Open	123.12	2.6

3.4.3.2 From the Statistical Accounts of Scotland (1791-1845)

Further knowledge in woodland tree composition is crucial to better portray the changes in past woodland cover and to assess the ecological implications at present-day. Although unequally detailed between parishes, the Old and New Statistical Account of Scotland (1791-1799 and 1834-1845, respectively) were written by local ministers and include relevant information about the woodland to complement the information provided by estate plans.

From the Old Statistical Account (OSA), there is no doubt that plantations formed a large part of the woodland cover of the late eighteenth century in many parishes of the study area. For instance, in the "estate of lithoch", parish of Sanquhar (OSA, 1793), it is mentioned a plantation consisting of larch, pines, silver and balsam firs with various hardwood such as oak, elm, birch, beech, rowan and ash. Evidence of plantations of similar composition is also available for Moffat (OSA, 1792). Along with the oak, ash, birch, hazel and alder trees covering the parishes of Keir (OSA, 1794) and Kirkpatrick-Juxta (OSA, 1792), Scots pine plantations are mentioned, while mixed plantations of oaks and pines are reported for the parish of Troqueer (OSA, 1791). In the parish of Closeburn, plantations would have composed more than half of the woodland cover as the minister estimated 300 Scottish acres of plantations and 200 acres of "natural wood" (OSA, 1794).

In agreement with the nineteenth century estate plans, the New Statistical Account of Scotland (NSA) corroborates the fact that extensive mixed woodland plantations were common. For the parish of Tynron (NSA, 1845), the minister stated:

> The natural woods are oak, ash, birch, plane, mountain-ash, alder, and willow. Those planted are generally Scotch fir, spruce, silver, larch, balm of Gilead; and of late years, principally oak, and other hard woods mixed with the above varieties of fir [note that 'balm of Gilead' certainly refer to the North American fir *Abies balsamea* also named balsam fir (Grigor, 1841)].

Similar types of plantations are mentioned for most parishes covered in the study area (e.g. Keir, Sanquhar, Troqueer, New Abbey, Holywood, Moffat, and Dumfries). Larch, Scots pine, oak, beech, elm and ash seemed to be regularly favoured but variations could occur according to local preferences. For instance, in the parish of Johnstone, it is said that silver fir and larch were preferred as best adapted to the local environmental conditions (NSA, 1845). In this parish, plantations were estimated from 1,200 to 1,500 acres over the last 50 years. Nearby, in the parish of Kirkpatrick-Juxta (NSA, 1845), where extensive plantations were mapped in T1, the minister refers to "plantations of Scotch fir, larch, and spruce, oak and ash, also a few beeches and elms (…)". Finally, in the parish of Wamphray, most plantations consisted in Scots fir or larch, and the estimates refer to 250 acres of plantations while 50 to 60 acres of ash and oak of "natural growth" (NSA, 1845).

This evidence reinforces the information provided by the woodland reconstructions regarding the growing area occupied by plantations in the woodland cover between T1 and T3. In suggesting that a very large portion of the woodland cover by c.1860 consisted in mixed plantations, the written archives tends to support the reliability of the woodland composition as depicted on the First OS maps 25-inch to the mile. It is also noteworthy that the woodland composition could change after thinning. For instance, in the parish of Durisdeer (NSA, 1845), the minister noted:

> All kinds of trees are planted, but principally hardwood and they are so arranged that in the thinning they shall finally consist of oak only.

Reasons to plant mixed woodland can be found in several eighteenth and nineteenth centuries' treatises. Anderson (1777, p.62) advised to plant Scots pine "(…) for thickening plantations, with a view to shelter other trees from the hurtful effects of wind". Likewise, according to Grigor (1841), while Scots pines produce better – less knotted – timber when grown alone, they offer valuable shelter from the wind to other tree species including oak. As such, the author recommended planting the pines four years before the oaks, which endorses the fact that the tree composition of woodland plantations could vary greatly over time. Monteath (1824) and Grigor (1841) recommended also to plant larch trees with oaks as the former would afford "warmth and shelter" to the latter (Monteath, 1824, p.30).

Regarding the reasons to plant many species altogether, Anderson (1777, p.56) and Michie (1872) stated that it was a also common practice amongst planters when they still ignored which tree species would adapt best to local conditions – the species that did not grow well were thinned afterwards. In addition, ornamental reasons certainly accounted for the diversity of the trees that were planted (e.g. Monteath, 1824, pp.69-71, Grigor, 1841). The belt of coniferous tree symbols around Morton plantation Crawford's map (1820) (see Figure 3.15A) may well illustrate the recommendations by Monteath (1824, pp.69-70) to grow coniferous on the outside – for shelter and ornament – and the hardwood inside.

For woodland ecology, a better understanding of past practices for planting woodland is particularly relevant. Although an increase of the woodland cover can improve the connection between woodland patches and thus facilitate the movement of species, plantations of non-native tree species do not support the same biodiversity as native woodland (Brockerhoff, 2008; Pedley et al., 2014; Wilson, 2015). Likewise, the fact that the woodland sites have been less compact over time – as indicated by the progressive increase of the shape index – suggests that the woodland cover may have been increasingly affected by the edge effect. In sum, the marked increase in woodland cover observed in the study area does not necessary mean better conditions for woodland species.

3.4.4 Drivers of past woodland changes

3.4.4.1 Explanatory variables in the logistic regression models

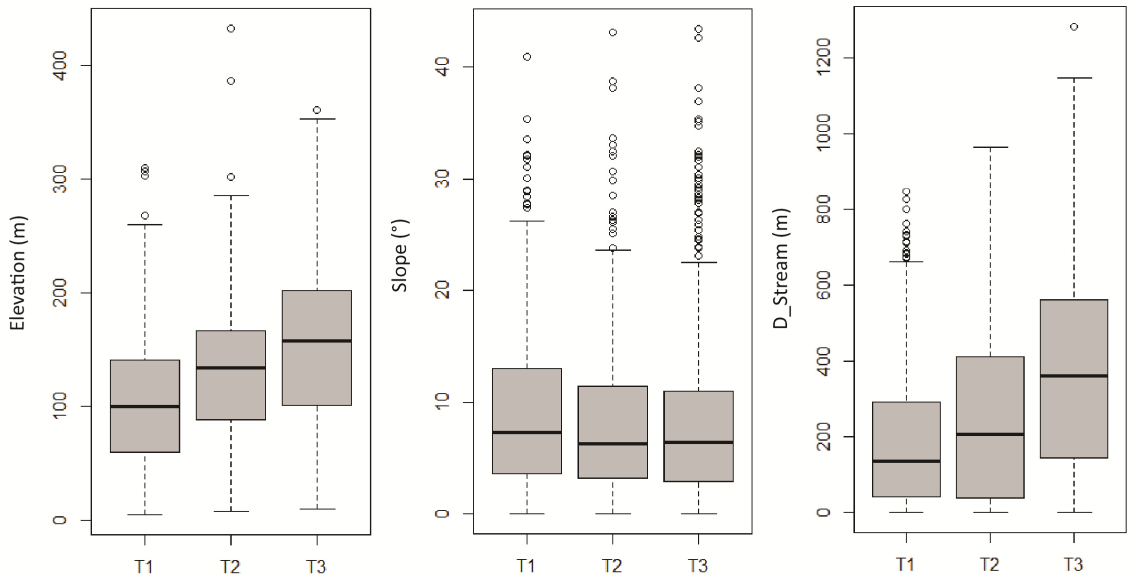


Figure 3.17 Boxplots of the elevation (m), slope (°) and distance to the nearest stream (m) in Area 1 for woodland in T1 and woodland appearing in T2 and T3.

Using the sampling points that served to fit the logistic regression models (Figure 3.17) illustrates the differences observed for Area 1 – the area covered by all the time series – regarding three of the most important continuous variables that were identified in the models to explain past distribution of woodland (i.e. elevation, slope, and distance to the nearest stream). As the increase of the woodland cover between T1 and T3 account for plantations more than natural spread, these results highlight different practices with regards to woodland planting location.

The results indicate a significant increase of the upper tree line over time ($p < 0.001$). It is very likely that this increase reflects plantations of coniferous or mixed woodlands which are more suited to higher elevations where the temperature is lower and wind speed generally higher. It is also possible that the choice of planting trees on higher elevations was dictated by the progressive lack of suitable areas lower down. The most suitable lands would have been already occupied by woodland or used for other agricultural purposes.

The most ancient woodland (T1) is to be found, in general, on steeper slopes. Statistical tests show a significant decrease between T1 and T2 ($p < 0.05$), T1 and T3 ($p < 0.01$) but not between T2 and T3, although slope remains an important explanatory variable of the woodland distribution in each model (i.e. the probability of an area being wooded increases with slope steepness). The more difficult access and less suitable properties of the steepest slopes for other purposes such as arable lands could explain why these areas were more likely to be wooded. In addition, the possibility of planting trees on slopes at higher elevation would provide new areas suitable for woodland while, on areas of lower elevation, it would decrease the competition with other land-use types such as arable lands.

The distance to the nearest stream (D_stream) increases significantly between all the time series ($p < 0.001$) (Figure 3.17), which indicates that the woodland cover expanded over time further away from the streams. In Annandale, while this variable was important in the two models fitted for T1, it had no longer any predictive power for T2 and T3 (Tables 3.9 and 3.10). In this region, it is also noteworthy that this variable already loses an important part of its predictive power in the model that includes the late eighteenth century plantations (model 2, Table 3.8), which corroborates the assumption that woodlands were planted without considering the stream network. The largest watercourses – where the width made it possible – could be also used to transport timbers down the streams (Lynch, 2011, p.598). At some point in the woodland history, wood transport is therefore likely to have had an influence on the choice to maintain or to plant woodlands along the water network. However, with the progressive improvement of roads, this variable may have been seen as less essential, which would account for the loss of predictive power of this variable over time for each region of study. Additionally, it is possible that, as for the variables 'slope' and 'elevation', all suitable areas along the stream were progressively occupied, which led to planting woodlands elsewhere. In Drumlanrig, this would at least partly explain why many plantations occurred first along the river Nith in T2 before occupying lands further away on the hills in T3.

Regarding the influence of soils, the models indicate in general that the woodland was more likely to be on brown earth soil in T1. While no effect of this variable is identified in T2, it seems clear that plantations in T3 avoided all other types of soil than brown earth for the region of Drumlanrig, and to a lesser extent, for Annandale, where podzols seem to have lower odds to be planted (independently of the other variables). The importance of soil on wood quality was increasingly discussed during the nineteenth century and might have influenced the consideration of suitable areas for woodland plantations (see Monteath, 1824, pp.364-369; Brown, 1847, p.44; and the NSAs for Johnstone or Closeburn in 1845, in which the most suitable soils for each tree species are discussed).

Finally, there is no clear indication that the geographical aspect ('eastness' and 'northness') influenced past woodland distribution. The most conclusive evidence is for the region of Annandale in T1 only, and before the period of extensive plantations, as the probability of a cell to be woodland seems to increase on the slopes facing east. As there was no large woodland on east facing slopes to incorrectly influence the statistical significance of 'eastness' through spatial autocorrelation, an inadequate sampling cannot explain this result. Although the significance of ‘eastness’ for the region of Annandale in T1 remains unclear, as is discussed below (section 3.4.4.3), prevailing wind conditions may have been of importance.

3.4.4.2 Quality of the models

The explanatory power of the different models differs substantially. The models’ performance was better when determining the woodland cover in T1 than determining where the woodland expanded between T1 and T2. Further radical changes regarding the location of plantations seem to occur between T2 and T3 as, outside the region of Drumlanrig, the models for T3 perform poorly (see Table 3.7). The First Edition OS maps show that many plantations were located along arable fields. As a result, the field pattern may better determine the configuration of the plantations occurring between T2 and T3 than the set of explanatory variables that were tested. The fact that woodland plantations in T3 do not seem to be influenced by the proximity to pre-existing woodland (Table 3.10) seems to corroborate this observation.

For each time series, it seems that the predictive power of the models was higher for the region of Drumlanrig. More suitable environmental conditions for woodland such as the presence of steep slopes at a relatively low elevation may explain why past woodland cover is easier to model for Drumlanrig. In contrast, flat and low elevation lands as in the parishes along the Solway Firth – also dominated by a large floodplain – may be more suitable for other land-uses, such as arable lands, and the woodland development could be dominated by other explanatory variables than the ones included in the models. Moreover, the temporality of the plantations may also explain some of the differences observed. The regions that were subject to early extensive plantations such as Annandale in T1 are likely to be more difficult to model as the woodland distribution pattern was both influenced by the most ancient coverage and more recent plantations driven by contemporary practices. Plantations, but also open woodland, bushes or brushwood, certainly affect the quality of the models as they add more variability to the woodland distribution patterns. In that regard, Appendix C shows the variability in spatial distribution of the different woodland vegetation classes in T1 according to elevation, slope and distance to the nearest stream.

As the logistic regression models are mostly based on environmental explanatory variables they should be considered as exploratory methods which can be improved after integrating other variables of importance that might account for past woodland cover (i.e. distance to the roads, population, local needs, etc.). Thus, the possibility of producing spatially explicit probability maps from the models (R, package ‘raster’, version 2.6.7; Hijmans, 2017) (Figure 3.18) is relevant to locating areas where the models do not explain accurately past woodland distribution. In addition, these maps can help to locate very early plantations not identified as such on the estate plans (i.e. *false negatives* such as woodlands in T1 on areas with lower probability of being wooded). For instance, Chapter 4 illustrates how probability maps can help to identify the woodlands listed in the provisional Ancient Woodland Inventory that are the most likely to be eighteenth or early nineteenth century plantations rather than ancient woodland.

Likewise, probability maps such as Figure 3.18 can be used to locate non-wooded areas where the probability of being wooded is nonetheless high (i.e. *false positives*). *In fine*, local history and additional relevant variables could fill gaps in our understanding of past woodland distribution in explaining at least part of the discrepancies observed between the models and past woodland cover (e.g. lower needs for wood in some areas, supply from a location outside the area covered with historical maps, etc.). Finally, to improve the quality of the models, an increase of the study area would allow sampling more woodland and mitigating further the effect of spatial autocorrelation in increasing the distance between sample cells.

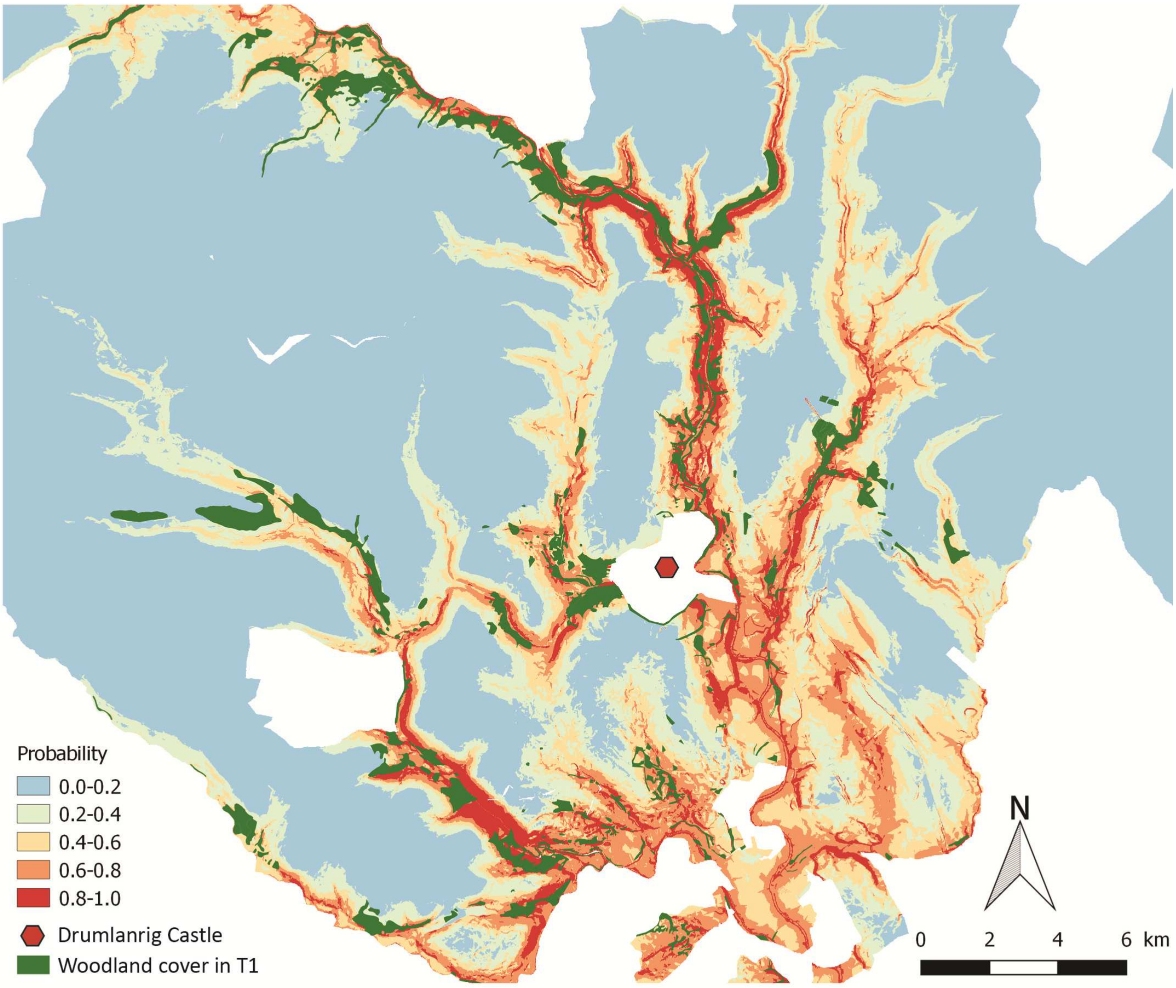


Figure 3.18 Woodland cover in T1 overlaid with the predicted probabilities of woodland in T1 for the region of Drumlanrig.

3.4.4.3 Drivers of woodland changes based on written archives

There are certainly multiple reasons behind the increase of the woodland cover observed from the eighteenth to the mid-nineteenth centuries. Firstly, historical population censuses estimate that Dumfriesshire saw its population increase from 39,788 in 1755 to reach a peak of 78,123 in 1851 (Donnachie, 1971, p.13), which would have augmented local requirements in wood. Imports in wood – and particularly softwood – from the Baltic or North America to Scotland were significant (Monteath, 1824, pp.26-29; Smout et al., 2005, p.260) and could supply areas around ports, but local production could be advantageous in distant areas to limit costs of haulage, in particular before the introduction of the railway. In addition, local growing industries requiring woods such as coal and lead mining in the area of Sanquhar (OSA, 1793; NSA, 1845; Smout, 1962) are likely to have encouraged further home grown woodland products. Secondly, variations in importations from abroad due to fluctuating import tax rates (McConnel, 2010; Smout et al., 2005, p.274) and the strong limitations at the time of Napoleon's 'Continental System' (Crimmin, 1996; Smout et al., 2005, p.274) are additional reasons which could have boosted the needs in local wood supply. While these hypotheses to explain the expansion of the woodland cover in the study area do not aim to be exhaustive, they represent some avenues to explore for future research directions.

Local written archives can help to contextualise the historical changes highlighted during the eighteenth and nineteenth centuries and to identify further some of the driving forces and actors responsible for the changes in the study area. In the Old and New Statistical Account, several ministers refer to aesthetic considerations when writing about woodland plantations (e.g. OSAs for Morton, 1794; Closeburn, 1792; Moffat, 1792). This aesthetic purpose is often discussed over the late eighteenth and nineteenth centuries under the influence of writers such as William Gilpin and Walter Scott who emphasized the importance of woodland to beautify the landscape and encouraged plantations to impress viewers (Gilpin, 1792; Oliver, 2009).

In addition, plantations could provide shelter to sheep and cattle (e.g. OSA, Keir, 1794; NSAs, Kirkpatrick-Juxta and Torthorwald, 1845), particularly on higher grounds. This woodland use would be supported by the rise in the tree line over time as observed in Figure 3.17. In general, plantations seemed valuable to make local climate conditions more suitable. Hence, for the parish of Buittle, it is said that woodland plantations could ameliorate the climate to produce “both grain and pasture of better quality” (NSA, 1845). For the parish of Kirkconnell (NSA, 1845), the minister wrote about the need of “broad belt of planted woods, at convenient distances, and in a proper direction; as it is usually observed that, under this kind of shelter, even the frost makes no impression (…)”. The use of plantation as shelter from wind and frost may have also influenced the decision to plant woodland differently according to geographical aspect and account for part of the plantations observed on the First OS maps along arable fields.

In terms of industrial development, the Statistical Accounts covering the study area do not mention directly the use of the wood to support emerging industries. Nonetheless, in addition to growing mining activities as in the parish of Sanquhar, the ministers regularly note the flourishing weaving industry in the region of study, an activity that required important amounts of wood (e.g. bobbin mills, see Smout et al., 2005, pp.264-266) and which therefore may have encouraged woodland plantations. While discussing of Dumfriesshire, Forsyth (1805, p.232) mentions also fishery as another wood-demanding activity:

> there are likewise large and thriving plantations of various kinds of fir, also of ash, elm, etc. which (being carefully enclosed, and great numbers of them were sold yearly for stakes used in the salmon fisheries upon the Solway Firth) are no less beneficial to the proprietor than ornamental to the country.

As the estate plans coverage presents multiple gaps, the parishes surrounding the study area that were not mapped could constitute other locations of wood consumption. Likewise, exports of wood products further away, such as England, could have benefited from extensive woodland plantations in a growing wood market. Exportations by boat to England are mostly mentioned from ports in parishes outside the study area, such as Buittle (NSA, 1845), Kirkcudbright (NSA, 1845), and Annan (NSA, 1845) but it is also reported that timbers made of larch from the inland parish of Johnstone in Annandale (NSA, 1845) were exported to Lancashire and Cheshire for railways construction.

Besides the probable failure of some plantations to provide suitable wood products and the competition with other types of land-use, several strong gales that were reported as responsible for serious damages in Dumfries and Galloway's woodland could account for part of the relative woodland decline over time in the study area. For instance, the OSA for Durisdeer (1792) mentions damage in Drumlanrig woods in 1786, while the NSA for Kirkbean (1845) refers to another very damaging gale in 1839. As reported by Smout et al. (2005, p.69), the development of sheep farming may also have caused some of the woodland loss observed from T1 to T3 through increasing grazing (though most woodland in the study area was already enclosed by T3).

Although the results of this chapter clearly indicate an increase of the woodland cover over time in the study area, the temporal resolution of the mapping reconstruction may still underestimate the magnitude of past woodland changes. This uncertainty constitutes another significant application-oriented uncertainty (see Chapter 2). As shown by Muller and Carruthers (2017), written evidence from the Statistical Accounts of Scotland, eighteenth and nineteenth centuries travellers, and local historians indicate extensive woodland clearance under the reign of the Fourth Duke of Queensberry, from 1778 until his death in 1810. These events inspired a poetic production which until recently has been wrongly attributed to the Scottish poet Robert Burns (Muller and Carruthers, 2017). The extent of the woodland clearance initiated by the Duke could not be confirmed with historical estate plans as the felling would have happened after the production of estate plans in the years 1764-1772 (T1) and before the next survey campaign that produced plans in the years 1820-1825 (T2). By that time, major plantations already occurred on the estates under the influence of the Scotts of Buccleuch and these plantations certainly reforested areas affected by the tree felling. Therefore, the woodland clearance in Drumlanrig during the time of the Fourth Duke of Queensberry might have been at least partly overlooked in the spatial analyses undertaken in the region between T1 and T2. In general, the trends highlighted by the spatial analyses at the scale of the study area might overlook lower temporal and regional changes. A careful study of written archives appears to be crucial to supplement the evidence from historical maps to improve our understanding of past woodland cover changes at a better spatio-temporal resolution.

3.5 Conclusion

This chapter highlights a marked increase in woodland cover between the second half of the eighteenth century and, at least, c.1860. The woodland expansion observed in the study area was associated with a progressive extension of clustered small woodland sites and the appearance of plantations of much larger sizes. While plantations constituted already a great part of the woodland cover by the end of the eighteenth century, it seems that the woodland change – loss and gain – accelerated from the early nineteenth century to, at least, the mid-nineteenth century. These estimates differ significantly from the most recent estimates available for Scotland for this time period. Moreover, in contrast with the narrative hitherto accepted for Scotland, the present study indicates that the minimum woodland coverage in the study area occurred during or before the eighteenth century and that only a small fraction of the ancient semi-natural woodland (i.e. 21%) was likely to be extant by c.1860.

The results from the logistic regression models illustrate the varying roles of different natural driving forces such as elevation, slope, soil and distance to the nearest stream to account for the distribution of the woodland cover in the eighteenth century and the plantations that occurred until c.1860. Contrasted observations over time and space within the study area might reflect different environmental constraints and varying practices in establishing woodland. Moreover, these models produce probability maps of woodland which can offer new avenues to explore further the driving forces and the role of the local history in investigating past changes at a better spatio-temporal resolution. In addition to the consistent results of the trajectory analysis, the explanatory power of some environmental variables to account for past woodland cover constitutes strong evidence of the reliability and the spatial accuracy of the woodland cover reconstructions from historical maps.

In combination with the spatial analyses, historical written archives offer a complementary insight into past woodland cover composition and changes. They confirm that an important portion of the woodland cover was plantation by the eighteenth century and that planting mixed woodland was a common practice. This evidence corroborates additional findings that indicated that depiction of the woodland cover type is more reliable on the First Edition OS 25-inches to the mile map than on their counterpart First Edition 6-inches to the mile maps. In addition, written archives provide further evidence regarding the reasons that encouraged woodland plantations and they indicate how the temporal resolution of the mapping reconstruction may still underestimate the magnitude of past woodland changes.

While it remains difficult to know how the present results reflect a wider Scottish context, this chapter demonstrates that, taken together, the change detection analysis, trajectory analysis and logistic regression methods can serve to elucidate past woodland cover changes and assess the reliability of the woodland cover reconstruction from historical maps. Finally, this work offers a unique opportunity to examine at multiple levels some of the potential long-lasting ecological implications of these changes on present-day woodland ecosystems as is now examined in Chapter 4.

Chapter 4

Testing woodland continuity: A cartographic assessment of the Ancient Woodland Inventory and ecological implications

4.1 Introduction

4.1.1 The Scottish Ancient Woodland Inventory

In the UK, the 'ancient woodland sites' are defined as areas that have been continuously wooded since at least 1750 A.D in Scotland, and 1600 A.D in England and Wales (Spencer and Kirby, 1992; Goldberg et al., 2007). These sites are recognised as areas of greater ecological value that deserve higher protection than recent woodlands (Goldberg, et al., 2007; Houses of Parliament, 2014; Goldberg, 2015). The UK ancient woodland sites have been the subject of provisional inventories since the 1980s when there were concerns about the relatively recent loss of many sites. Some have been converted into other land-use types while others have been replanted with commercial tree species (Kirby, 1988; Hopkins and Kirby, 2007; Goldberg et al., 2007). Today, the so-called 'provisional Ancient Woodland Inventory' (AWI) is considered as a key source of information for conservation planning (Houses of Parliament, 2014; Goldberg, 2015) and the data are available for analysis by GIS.

The concept of 'ancient' or 'recent' woodland has been found more convenient to use than 'primary' or 'secondary' woodland (Goldberg, 2015). As it is not possible to confirm that an interruption of the woodland continuity has never occurred since the forest's origins, the status of 'primary' woodland cannot be proved and remains hypothetical, contrary to the definition of ancient woodland. However, it is noteworthy that the use of a threshold date implies that ancient woodland can be also secondary woodland, for instance, when woodland plantations occurred before the threshold date (Goldberg, 2015).

In Scotland, the threshold date to define ancient woodland was decided on the availability of the earliest cartographic evidence covering both the Scottish Highlands and Lowlands, namely Roy's Military Survey sheets (also known as 'the Roy map', 1747-1755). The underlying assumption was that woodland plantations were relatively scarce by c.1750 (Smout et al., 2005) and, consequently, the woodland depicted on the Roy map was likely to originate from much older times. Implemented in the 1980s by the Nature Conservancy Council (NCC), the Scottish AWI encompasses all areas that have been continuously wooded since the 1750s, or which had evidence of clearance over only short periods of time (Kupiec, 1997).

Distinct groups have been created for the classification of ancient woodlands in the UK, namely the ‘Ancient Semi-Natural Woodland Sites’ (ASNW) composed of a majority of native trees and shrub species that originated from natural regeneration (i.e. self-sown or stump regrowth), and the ‘Plantations on Ancient Woodland Sites’ (PAWS), which were ancient woodlands converted to non-native – mostly conifers – plantations. Initially, the Scottish AWI categorised further the ‘ancient woodland sites of semi-natural origin’ according to the history of their cover starting from the Roy map (1747-1755), and using the First Edition Ordnance Survey maps (c.1860) and contemporary OS maps. ‘Category 1a’ comprised the woodland depicted as ‘semi-natural’ both on the Roy map and the First Edition OS maps. ‘Category 2a’ concerned ‘semi-natural’ woodland depicted on the First Edition OS maps only. It is noteworthy that present-day woodland in ‘category 2a’ is now considered as ‘ancient’ even though there is less concreate evidence of its antiquity (SNH, n.d.). This choice occurred in the 1990s, after revision of the initial inventory, and based on the assumption that these woodland sites might have been overlooked during the Roy mapping (Kupiec, 1997).

As the woodland was not an object of particular attention other than when it formed a natural barrier that could impede troops’ movements, provide a fuel resource or give cover to armies along roads, it is expected that many woodlands were omitted on the Roy map (Kupiec, 1997; Smout et al., 2005, pp.61-62; Crawford, 2009). Other authors argue that the ink to depict the tree cover has progressively faded over the years (Walker and Kirby, 1989). In addition, it is said that woodland colours were not visible on the black and white copies of the survey to compile the ancient woodland sites for the Scottish inventory (Roberts et al., 1992; Kupiec, 1997; Goldberg et al., 2007). More generally, in the UK, only a fraction of all ancient woodland sites are believed to have been recorded and the AWI contains little information about the ecological conditions and historical value of these sites (Goldberg et al., 2007; Rotherham, 2011). In Scotland, the recent Native Woodland Survey (NWSS) was able partly to fill this gap in providing important information on the ecological characteristics of the ASNW sites, including dominant habitat, maturity of the woodland, level of grazing pressure and presence of invasive species (NWSS, 2014). The initial lack of integration in the AWI of sites smaller than 2 ha represents another concern in the UK (Goldberg et al., 2007). However, this issue does not apply to the Scottish AWI covering Dumfries and Galloway, as it does not appear that a minimum threshold was used – about 600 ancient woodland sites of semi-natural origin (categories 1a and 2a) that are smaller than 2 ha have been recorded.

ASNW sites have also often been regarded as potential remnants of the pre-Neolithic woodland cover (Rackham, 1993; Peterken, 2000). These sites being certainly managed at some point in the past, their putative link with the last post-glacial 'wildwood' remains largely questionable (Smout et al., 2005; Rotherham, 2011; Barnes and Williamson, 2015, p.5; Goldberg, 2015). Nevertheless, considerable research has highlighted the rather unique biodiversity of ASNW (Peterken, 1974; Peterken and Game, 1984; Hermy et al., 1999; Hermy and Verheyen, 2007; Schmidt et al., 2014). Studies have shown that these sites can provide habitats to rare and threatened species which are less likely to be found elsewhere (Peterken and Game, 1984; Hermy and Verheyen, 2007). For conservation goals, they can act as reservoirs of native woodland species and represent potential nuclei for future expansion to new areas (Gkaraveli et al, 2004; Watts, 2006). In addition, the inherent connection of these woodlands to past landscape organisation and the record they may provide of long-term historical management have increased their recognition as sites of high cultural heritage value (e.g. old trees including coppice stools and old pollards, wood-banks, and archaeological artefacts related to the historical exploitation of the wood) (Rackham, 1993; Smout et al., 2005; Rotherham, 2011).

It has been estimated that almost 40% of ASNW were converted into PAWS between the 1930s and 1980s (Forestry Commission, 2003). Despite their altered biophysical conditions – including plant composition and structure, light condition, soil properties – the PAWS are also the object of particular attention for conservation planning (Wilson, 2015, p.128). As such, the identification of PAWS remains crucial. These sites can retain remnant ecological or historic features and it is thought that many of them have the potential for restoration to native woodlands (Smout et al., 2005, p.1; Crawford, 2009; Wilson, 2015).

4.1.2 Indicator species of ancient woodland sites

Indicator species of long woodland continuity include bryophytes, lichens (Fritz et al., 2008; Whittet and Ellis, 2013) or invertebrates (Buse, 2012; Cateau et al., 2018) but vascular plants – easier to locate and identify – have been hitherto the most commonly used indicators (Rose, 1999; Barnes and Williamson, 2015, p.7). In Europe and North America, plant communities in ancient forests have been found distinct from that of recent forests (Rose, 1999; Sciama et al., 2009; Schmidt et al., 2014).

Kimberley et al. (2013) studied plant traits in order to determine the biological characteristics shared by the species associated with British ancient woodland. They argued that British ancient woodland indicator plants are mostly short perennial species, short height and with heavy seeds. These characteristics reflect poor dispersal ability, which has been regarded as the main factor limiting the colonising of new woodlands (Verheyen et al., 2003; Hermy and Verheyen, 2007). Due to dispersal limitations and related slow response to land-use changes, indicator plant species seem particularly vulnerable to habitat disturbances such as loss, fragmentation or high grazing regime (Verheyen et al., 2003; Kimberley et al., 2013). Indicator species of ancient woodland may also have more restricted requirements in terms of biophysical conditions to thrive – including soil properties, humidity and light (Hermy et al., 1999; Wulf, 2003). For that matter, it has been suggested that the long-lasting effect of past land-use – particularly former arable lands – can hamper the establishment of ancient woodland indicator species in more recent woodland (Honnay et al., 1998; De Keersmaeker et al., 2004; Flinn and Vellend, 2005; Fraterrigo et al., 2006). This *recruitment limitation* (Hermy et al., 2007) can occur via competitive exclusion by other species and/or unsuitable soil characteristics such as higher phosphorus or nitrogen content (Honnay et al., 1998; De Keersmaeker et al., 2004; Flinn and Vellend, 2005).

Initiated by Peterken (1974), the species strongly associated with long continuity have been compiled in lists of indicator species. The lists can serve as a tool to identify ancient woodlands where there is a lack of historical sources (Rose, 1999; Hermy et al., 1999; Schmidt et al, 2014, Hermy, 2015). However, the challenge to accurately identifying ancient woodland sites from historical evidence is not the only limitation to drawing up a robust list of ancient woodland indicator species. With variations in geology, soil or climate/micro-climate conditions, the lists can differ from region to region and be difficult to use locally (Hermy et al., 1999; Hermy and Verheyen, 2007; Crawford, 2009; Rotherham, 2011). Moreover, as indicator species are not confined to ancient woodland, it may be unclear as to how much a species need to be associated with ancient woodland to be considered an indicator (Rotherham, 2011). Likewise, as a vegetation community approach seems necessary, it is often uncertain how many indicator species can more reliably indicate ancient woodland (Glaves et al., 2009b; Crawford, 2009; Webb and Goodenough, 2018). The richness in indicator species may vary according to woodland characteristics such as size, soil properties, geomorphological features within the woodland, and overall variations in micro-habitats availability (old trees, dead wood, wet areas, etc.) for niche specialists (Rotherham, 2011).

More importantly, what the occurrence of ancient woodland indicator species indicates on its own has been increasingly questioned (Rolstad et al., 2002; Rotherham, 2011; Nordén et al., 2014). According to Rotherham (2011), indicators of ancient woodland might actually be plants that grow preferentially on soils with historically low disturbance. The current ecological characteristics of ancient woodland might also well be inherited from historical management practices such as former European widespread coppice or coppice-with-standards (Buckley and Mills, 2015; Hermy, 2015). As argued by Barnes and Williamson (2015, p.15-16 and p.107), different forms of wood exploitation and restricted grazing pressure may have created environmental conditions that are favourable for many of these indicator species to thrive more than ever before. As such, the present botanical character of ancient woodlands may result more from relatively recent changes of woodland habitats than from long continuity.

Studies have also questioned the importance of the local landscape context in explaining the occasional high occurrence of indicator species in relatively recent woodlands (Dupouey et al., 2002b; Stone and Williamson, 2013; Barnes and Williamson, 2015). For instance, some remnant populations of ancient woodland indicator species could successfully colonise new woodlands from nearby 'woodland-like' refuge areas such as hedges and ditches (Dupouey et al., 2002b; Stone and Williamson, 2013; Barnes and Williamson, 2015). These *reservoirs* could provide conditions known to be suitable for most plant indicator species (e.g. a relatively humid and shaded environment) while offering protection from grazing (Barnes and Williamson, 2015, p.155). Ancient woodland indicator species identified in recent woodland can also result from a slow transfer directly from an ancient woodland site located nearby (Brunet and Von Oheimb, 1998; Hermy et al., 1999). In sum, as pointed out by Rotherham (2011), the occurrence of ancient woodland indicator species could reflect any form of ecological continuity and not only woodland antiquity.

4.1.3 Research objectives

The UK Ancient Woodland Inventory is considered as a valuable tool for conservation purposes (Goldberg et al., 2007; Houses of Parliament, 2014). It can also serve to draw up lists of ancient woodland indicator species while investigating the remarkable environmental characteristics of these sites. In Scotland, although some doubts surround the reliability of the Roy map (c.1750) – the prime historical source to list ancient woodlands –, a critical assessment of the Scottish Ancient Woodland Inventory's overall accuracy and reliability does not seem to have ever been undertaken. This shortcoming is likely to result from the restricted access and limited existence of pre-Ordnance Survey cartographic data (Chapter 2). Therefore, the use of 352 pre-OS estate plans covering about 107,700 ha in Nithsdale and Annandale offers a unique opportunity to fill this gap for South-West Scotland.

These estate plans were used to reconstruct past woodland cover accurately for times when historical evidence is usually scarce and incomplete (Chapter 2). The reconstructions and subsequent spatial analyses offer new insights into woodlands' history. They inform about woodland cover changes and the evolution of management practices from the late eighteenth to mid-nineteenth centuries (Chapter 3). For instance, the results demonstrate that a large amount of woodland was planted during the eighteenth and nineteenth century. These findings can have important, even profound, implications for the assumption that any semi-natural woodland on the First Edition OS maps only (c.1860, category 2a) can be considered 'ancient'.

Using the past woodland cover reconstructions from estate plans and drawing upon previous findings, the first objective of this chapter is to investigate the accuracy and overall reliability of the Scottish Ancient Woodland Inventory (AWI) in the study area. In addition, the logistic regression models developed in Chapter 3 are tested to determine whether these models can be used to identify errors in the inventory. By extension, this cartographic assessment can help to investigate the accuracy and reliability of the depiction of the woodland cover on the Roy map, and to test whether the woodland of category 2a should be considered as ancient.

The second objective of this chapter is to determine whether differences in plant communities occur between probable ancient woodlands and more recent woodland plantations in the study area. The field survey takes advantage of the superior planimetric accuracy of estate plans (Chapter 2) to test the assumption that ancient woodland sites have a unique ecological value. While quantitative analysis is undertaken, a closer look at specific case studies aims also to gain insight into the mechanisms that account for present day distribution of the species indicators of long continuity. This work attempts to address the following questions: are there significant differences in vegetation between the ancient woodlands and native woodlands that appeared later in the eighteenth and nineteenth centuries or even more recently? Is there any determinable threshold or gradient in the age of woodlands that marks particular changes in their ecological features? What is the relative importance of the landscape context versus the temporal continuity of woodland cover?

The methods and results of the AWI cartographic assessment are followed by the methods and results of the study of plant communities in the study area's woodlands. Based on the results from the two approaches, the present chapter aims to critically assess the current criteria to define ancient woodland and to discuss implications of the results for conservation planning of woodlands. While focusing on Nithsdale and Annandale, it is expected that the results offer general outcomes that can be applied beyond the study area.

4.2 Methods for the cartographic assessment of the Ancient Woodland Inventory

4.2.1 Spatial accuracy and reliability

4.2.1.1 Ancient Woodland datasets

The Scottish AWI is available online as shapefile format on the SNH website[5]. Even though the AWI considers today's woodlands of categories 1a and 2a as 'ancient', this initial categorisation has remained available in the AWI. The two categories were treated together as well as separately for comparison of their respective accuracy.

Besides the ASNW of categories 1a and 2a, the AWI compiles: 1) the woodlands that are of plantations origin identified from the Roy map and/or the First Edition OS maps ('Long-established woodland sites', category 2b); and 2) other woodlands of any origin on the Roy map but unwooded in c.1860 (category 3). The present chapter focuses only on the woodland identified as 'Ancient (of semi-natural origin)' located within the boundaries of the study area. The most recent compilation of PAWS is available in the Native Woodland Survey of Scotland (NWSS, 2014). In the end, four data shapefiles (AW datasets) were extracted as follows from the AWI and the NWSS:

1. 'Category 1a', corresponding to the ancient woodland of semi-natural origin identified from the Roy map and depicted on the First Edition OS maps;

2. 'Category 2a', corresponding to the ancient woodland of semi-natural origin identified from the First Edition OS maps only;

3. 'Category AW' (the ancient woodland of semi-natural origin) as in the most recent revised inventory, which includes both categories 1a and 2a, based on the assumption that the woodland of category 2a was ancient but omitted in the Roy map; and

4. 'Plantations on Ancient Woodland Sites' (PAWS).

As described in Chapter 3 (section 3.2.2), we considered 'Area 2' and 'Area 3' as the whole area covered by estate plans in T1 and T2, respectively (see Figure 3.1). The area estimated as 'ancient woodland' is provided for each study area in Table 4.1.

[5] https://gateway.snh.gov.uk/natural-spaces/dataset.jsp?dsid=AWI

Table 4.1 'Ancient Woodland' (in ha) in Area 2 and Area 3 according to the AWI (categories AW, 1a, 2a and PAWS). Percentages are indicated in brackets and calculated from the total coverage of each study area (i.e. 86,526 ha for Area 2 covered by estate plans in T1 and 63,098 ha for Area 3 covered by estate plans in T2).

	AW (1a and 2a)	1a	2a	PAWS
Area 2	1643 (1.90)	1190 (1.38)	453 (0.52)	891 (1.03)
Area 3	1556 (2.47)	1149 (1.82)	407 (0.64)	822 (1.30)

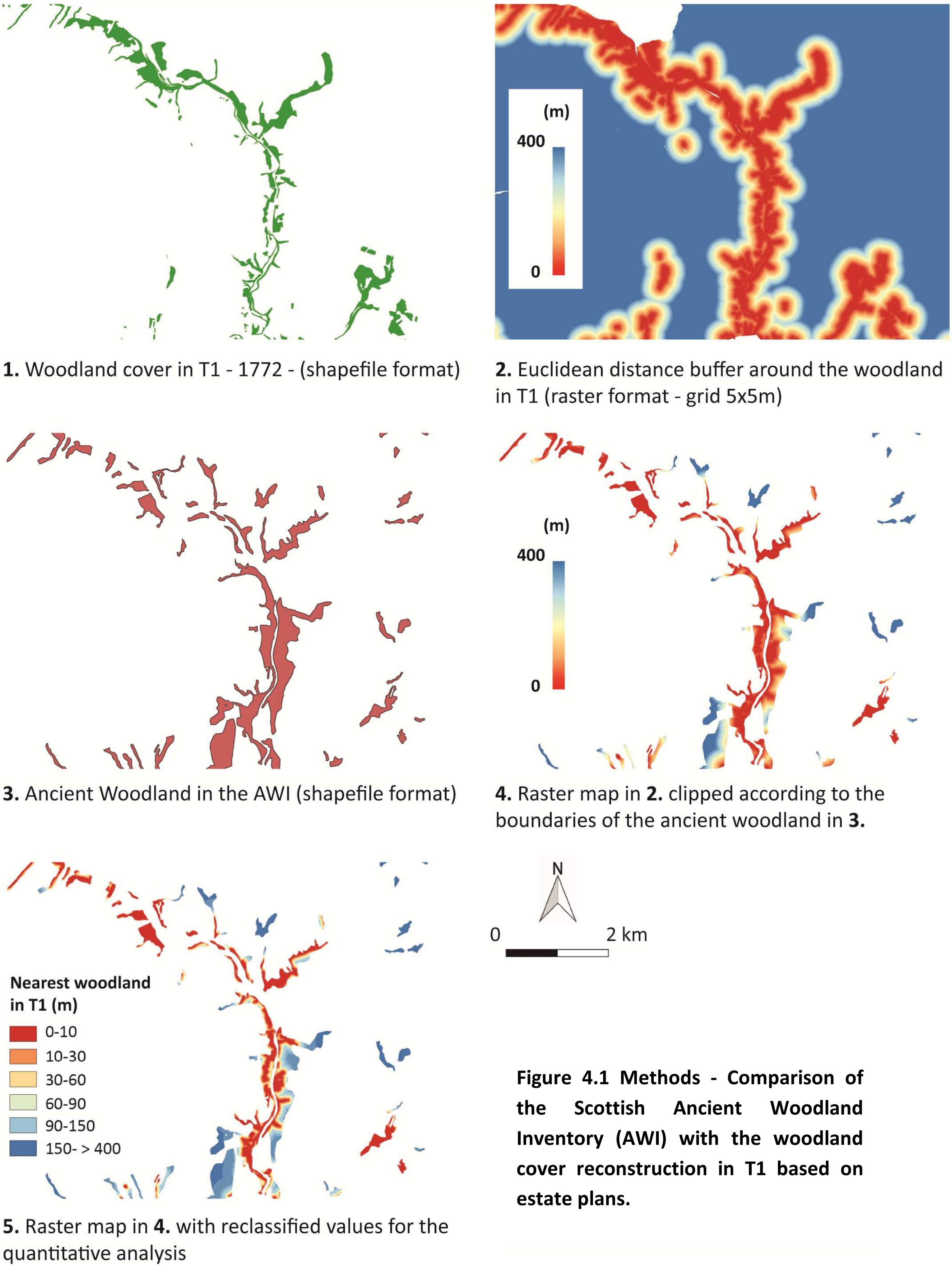
4.2.1.2 Comparison between the AWI and the woodland cover reconstructions

The study is based on the comparison between the woodland cover reconstructions for the two earliest time series – T1 (1740-1799) and T2 (1801-1833) – and each of the four AW datasets (extracted from the Scottish AWI and the NWSS as described above). The underlying assumption is that the woodland sites listed as 'ancient of semi-natural origin' or 'PAWS' would have been recorded in estate plans in T1 and/or T2. In estimating how much ancient woodland of semi-natural origin and PAWS in the four datasets was wooded or not, according to the estate plans from respectively T1 and T2, this analysis aimed to serve as a quantitative assessment of the spatial accuracy and overall reliability of the AWI in the study area. In addition, the breakdown of ancient woodland into categories 1a and 2a aimed to test the assumption that present-day native woodland sites depicted as 'semi-natural' on the First Edition OS map only (category 2a) are likely to be ancient (SNH, n.d.).

Because of the varying planimetric accuracy of estate plans (production and transformation-oriented uncertainties, see Chapters 2 and 3), the spatial uncertainty of the woodland reconstruction for T1 and T2 had to be considered when assessing the accuracy of the four AW datasets. To do so, each AW dataset in shapefile format was first converted into raster format with a grid cell of 5x5 m (similar grid size to that in Chapter 3, see section 3.2.3). For the comparison with the woodland cover reconstruction in T1 (Area 2), the value of each cell of the raster files was calculated according to its Euclidean distance to the nearest woodland in T1 using the 'Proximity (Raster Distance) analysis tool' in QGIS v2.6.1 software (QGIS, 2015) and following the procedure illustrated in Figure 4.1. Where the modern inventories overlapped with the historical woodland cover in T1 the cell value was '0' (i.e. distance to the nearest woodland in T1 is 0 m) and increased in increments of 5 m as the distance to the nearest woodland in T1 increased. Thereafter, the Euclidean distances were categorised using different distance thresholds (i.e. tolerance) as follows: 0-10 m, 10-15 m, 15-25 m, with an increment of 10 m until 95 m, and 95-150 m, 150-200 m and 200-400 m. The same process was repeated for the comparison with the woodland cover reconstruction in T2 (Area 3). To improve the readability of Figure 4.1 below, the categories depicted in 'step 5' were reduced in number and simplified.

Consequently, it was possible to assess for each AW dataset how much woodland is located within a distance of 0-10 m to over 400 m from the closest woodland in T1 on Area 2; and the closest woodland in T2 on Area 3. As the distance to the nearest woodland in T1 and T2 increased, the likelihood of a woodland site of being incorrectly considered as 'ancient' increased. It was therefore possible for each inventory to map and quantify the woodland that is the most or least likely to be ancient while considering the spatial uncertainty of the historical woodland cover reconstructions. The QGIS python plugin *LecoS* (*Landscape ecology Statistics* – Jung, 2016) served afterwards to extract quantitative data (i.e. the total area of ancient woodland within a distance of 0-10 m; 10-15 m; 15-25 m; 25-35 m, etc. up to 400m from the nearest woodland site depicted in T1 and/or T2).

However, it is noteworthy that as the woodland cover reconstructions from estate plans post-date 1750, it was not possible to confirm with absolute confidence that the ancient woodlands depicted in T1 or T2 were indeed 'ancient' sensu stricto (i.e. wooded since at least c.1750). The present analysis could only serve to ascertain that the woodland listed as 'ancient' in the AWI was recorded during the second half of the eighteenth century or early nineteenth century and, therefore, identify with high confidence the sites which are actually not 'ancient'.



1. Woodland cover in T1 - 1772 - (shapefile format)

2. Euclidean distance buffer around the woodland in T1 (raster format - grid 5x5m)

3. Ancient Woodland in the AWI (shapefile format)

4. Raster map in **2.** clipped according to the boundaries of the ancient woodland in **3.**

5. Raster map in **4.** with reclassified values for the quantitative analysis

Figure 4.1 Methods - Comparison of the Scottish Ancient Woodland Inventory (AWI) with the woodland cover reconstruction in T1 based on estate plans.

4.2.2 Identifying pseudo-ancient woodland sites using the logistic regression models

Some woodland sites considered as 'ancient' in the AWI are not depicted on the estate plans from the eighteenth (T1) or early nineteenth centuries (T2). These woods are, therefore, likely to be of more recent origin than expected. We name 'Pseudo-Ancient Woodland' (or 'pseudo-AW') the woodland listed as 'ancient of semi-natural origin' in the AWI (categories 1a and 2a) but not depicted in the woodland cover reconstructions for T1 and/or T2. This terminology follows that of Stone and Williamson (2013) and Barnes and Williamson (2015, p.122).

The analysis to identify pseudo-AW is based on the logistic regression models of the woodland cover in T1 for the estates of 'Drumlanrig', 'Annandale' and 'Other' as reconstructed in Chapter 3 (see Table 3.8). The aim is to test the extent to which these models can help to identify the pseudo-AW sites in the study area. The training dataset to test the models was composed of two categories of woodland: the cells (5x5 m) identified as pseudo-AW (value = '0') and the cells identified as 'ancient woodland' in the inventory and depicted accordingly in T1 (value = '1', named afterwards as 'AW in T1'). It is worth remembering that the '1' cells are only 'probable ancient woodland' as it is not possible to ascertain which woodland sites in T1 were wooded in c.1750. Therefore the tests were based on the ability of the models to classify accurately the sites which are 'AW in T1' from 'pseudo-AW'. For the estate of Annandale, of the two models, the one that did not consider the numerous late eighteenth century plantations ('model 3' in Chapter 3) was used (see Table 3.2). This model was expected to reflect better the distribution of ancient woodland and, therefore, was thought more appropriate to discriminate AW in T1 from pseudo-AW.

4.2.2.1 Sampling and generation of the dataset

The sampling method of cells '0' and '1' is similar to that used to generate the calibration datasets for the different models (see section 3.2.7.3). A random sampling was applied with a minimum distance of 200 m between each sampled cell within the same woodland patch. The sampling was stratified to balance the number of observations between values '0' and '1'.

In order to consider only the woodland area for which there is strong evidence of it being pseudo-AW (i.e. cells '0'), the sampling focused on the woodland identified as ancient in the AWI that is not located within a distance of 35 m from the nearest woodland in T1 (Area 2) and/or T2 (Area 3). This distance threshold corresponds approximately to the RMSE value of the estate plans in T1 with the lowest planimetric accuracy (see Figure 2.13). The sampling of the AW in T1 (cells '1') was done on the area where the ancient woodland in the inventory overlapped the woodland cover reconstruction in T1 that is not recognised as plantation on estate plans. As these plantations are proven not ancient, they were ruled out to maximise the likelihood that the woodland to be sampled from T1 is ancient.

The corresponding values for the different explanatory variables used by the models (i.e. slope, elevation, aspect, distance to the nearest stream and castle, and soil, see Figures 3.3 and 3.4) were recorded at the location of each sampled cell. This last step produced the training dataset that served to test the models. The sampling and the generation of the dataset were done with QGIS 2.6.1 (QGIS, 2015) and the dataset was imported into the statistical software package R (R Development Core Team 3.2.3). Table 4.2 summarises the number of sampled cells for each estate.

Table 4.2 Number of points sampled from woodland in the AWI.

Estates	Number of sampled cells	Number of cells as pseudo-AW	Number of cells as AW in T1
Drumlanrig	408	201	207
Annandale	114	59	55
Other	148	75	73
Total	670	335	335

4.2.2.2 Evaluating models performance

The probability score for each sampled cell to be '1' (i.e. woodland in T1) was calculated using the relevant models (i.e. 'Drumlanrig', 'Annandale' or 'Other') and the training dataset. Hence, it was possible to compare the probability score of each cell to be woodland in T1 (predictive output value as in Figure 3.18) with the actual observations of pseudo-AW ('0') and AW in T1 ('1').

Firstly, using a confusion matrix as in Table 4.3, it was possible to determine to what extent the models built in Chapter 3 can predict correctly the cells that are pseudo-AW. As the probability score calculated for each cell is continuous (within range from 0 to 1), it was necessary to choose a decision threshold (τ) below which a cell is considered as pseudo-AW (e.g. if the decision threshold $\tau = 0.5$, all cells with a probability score below or equal to this threshold are classified as pseudo-AW).

The optimal decision threshold accounted for the ability of the model to maximise the number of cells correctly classified as '0' (i.e. *true negatives*) while minimising the cost in number of cells incorrectly classified as '0' (i.e. *false negatives*). Thereby, it was possible to assess more specifically how the models performed to identify pseudo-AW while limiting the negative implications of considering AW in T1 as pseudo-AW. A high percentage of *false negatives* for a low percentage of *true negatives* would make the model unsuitable for identifying pseudo-AW.

Table 4.3 Confusion matrix of observed and predicted response (adapted from Pearce and Ferrier, 2000). A, B, C and D are the frequencies calculated for a given decision threshold. The decision threshold that predicts best the observed pseudo-AW cells is the one for which A is maximised and C is minimised.

	Predicted pseudo-AW	**Predicted AW in T1**
Observed pseudo-AW	A (True negative)	B (False positive)
Observed AW in T1	C (False negative)	D (True positive)

Secondly, the calculation of the area under the ROC curve (AUC, see section 3.2.7.3) helped to assess the general predictive accuracy of each model. The AUC reflects the models ability to classify accurately the sampled cells from the AWI into ‘0’ and ‘1’. The AUC is calculated from the ROC which plots the *true positive rate* (i.e. D/D+C) in function of the *false positive rate* (i.e. B/B+A) across the entire range of decision thresholds (Pearce and Ferrier, 2000). R (R Development Core Team 3.2.3) served to calculate the AUC values, to determine the optimal decision thresholds and to produce the confusion matrices.

4.3 Results of the cartographic assessment of the Ancient Woodland Inventory

4.3.1 Spatial accuracy and reliability

The results of this study permitted the assessment of the minimum distance between the ‘ancient woodland’ listed in the Scottish AWI (AW, 1a, 2a and PAWS) and the nearest woodland in T1 (1740-1799) and T2 (1801-1833) (Figure 4.2). Hence, it was possible to extract quantitative estimates of how much woodland in the inventory was not depicted on estate plans (i.e. pseudo-AW) while considering different threshold distances to the nearest woodland in T1 or T2 (Figure 4.2). For the woodlands that are not located within the different threshold distances, we can consider that their likelihood to be ‘ancient’ decreases as the threshold increases. As the woodland sites identified as ‘plantation’ on the woodland cover reconstructions in T1 and T2 cannot be considered as ‘ancient of semi-natural origin’, they were removed from the distance analysis (i.e. the minimum Euclidean distance to these sites was not integrated).

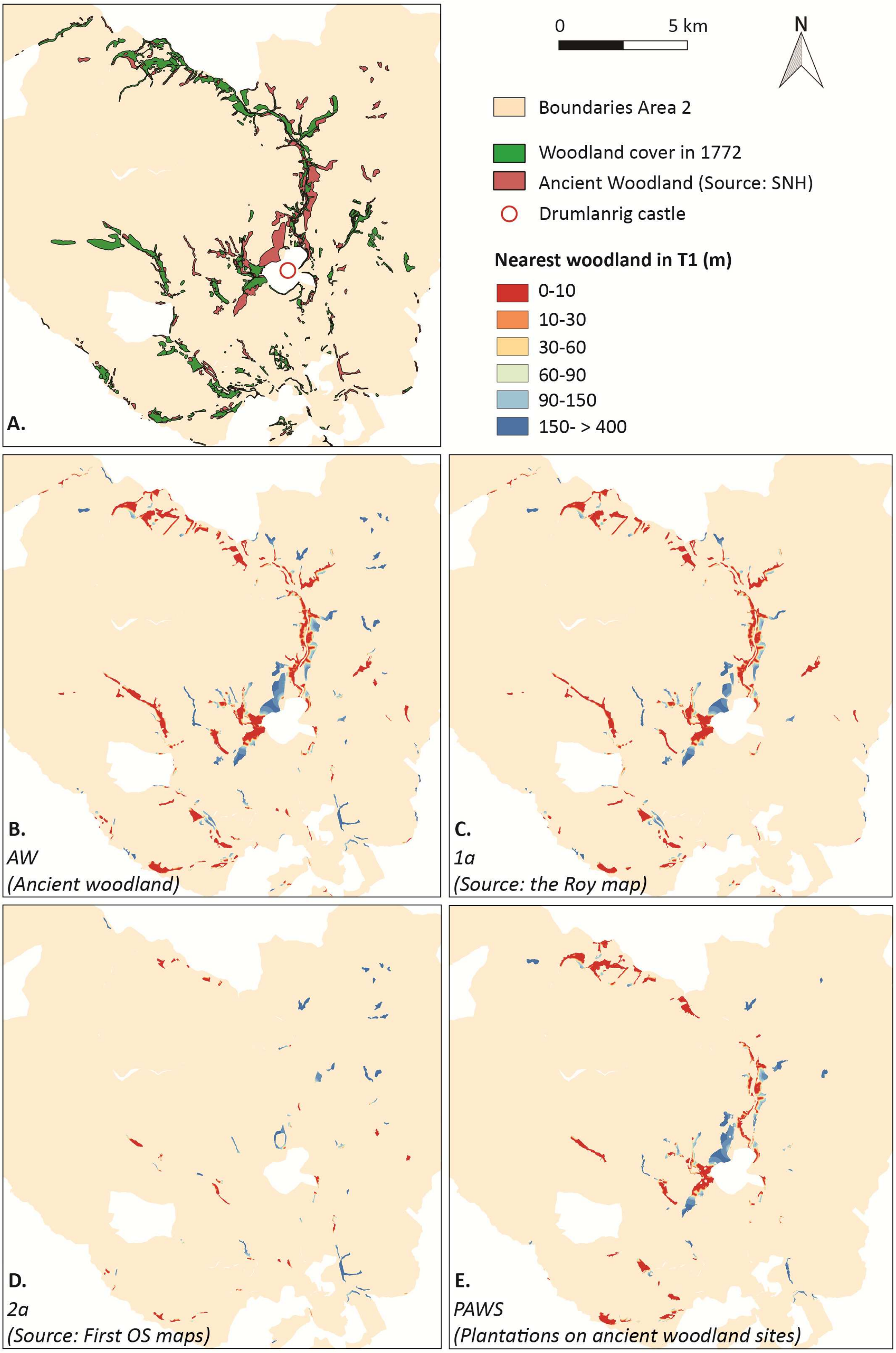
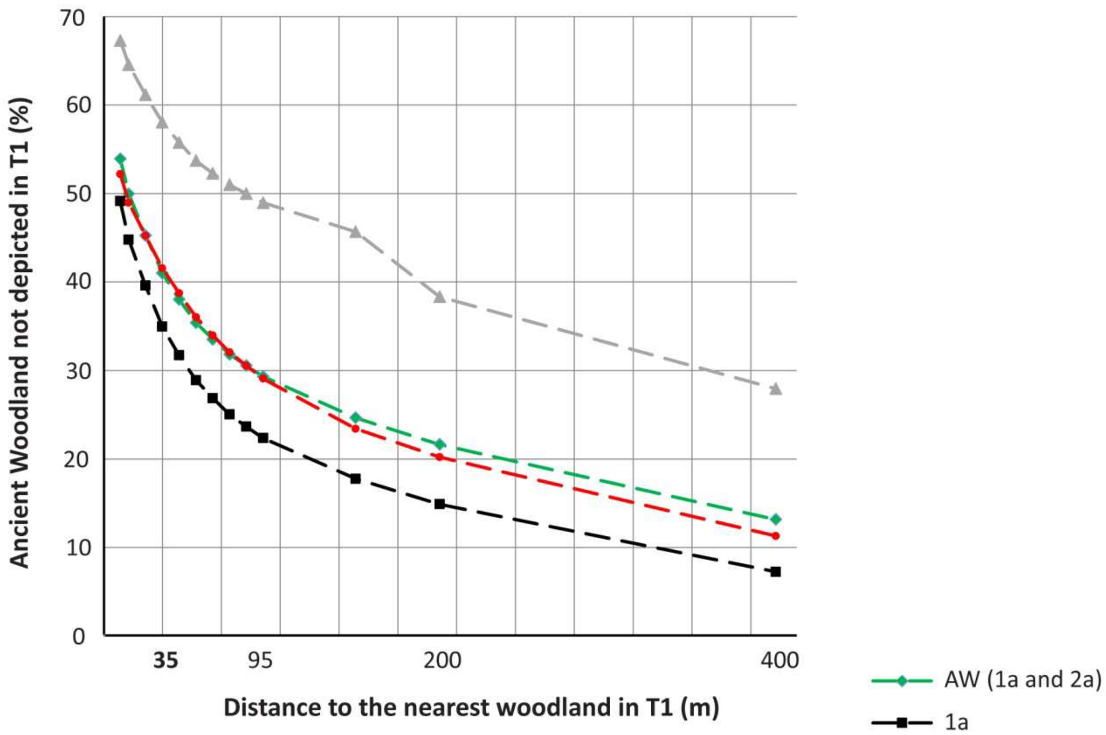
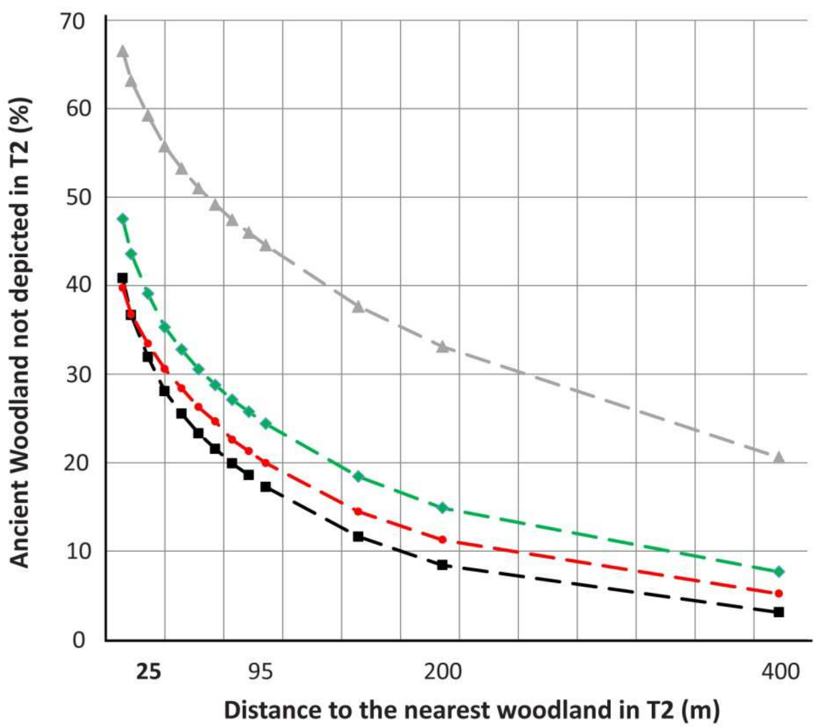


Figure 4.2 Comparison between the Ancient Woodland Inventory (AWI – categories AW, 1a, 2a and PAWS) and the woodland cover reconstruction in T1 (Area 2): example in the region of Drumlanrig Castle (parishes of Morton, Durisdeer, Penpont, Tynron and Sanquhar). In (**A.**), the extract shows the woodland cover in T1 overlaid on the 'ancient woodland' (category AW) as in the AWI.



A.



B.

Figure 4.3 Cumulative area of Ancient Woodland not depicted in T1 – Area 2 – (A.), and T2 – Area 3 – (B.). The value is expressed in % and calculated from the total area covered by each dataset. The estimates calculated from the cartographic analysis are in plain symbols and interpolations are in dashed lines. The estimates were calculated at the following distance thresholds from the nearest woodland in T1 and T2: 10, 15, 25, 35, 45, 55, 65, 75, 85, 95, 150, 200 and 400 m.

4.3.1.1 Comparison with the woodland cover in T1 (1740-1799)

The cartographic assessment of the AWI in the parishes surrounding Drumlanrig castle are given in Figure 4.2. An initial comparison by overlaying the woodland cover in T1 onto the AWI revealed that a relatively large area of woodland classified as ‘ancient’ did not seem to be woodland in T1 (Figure 4.2A). The other extracts (Figures 4.2B to 4.2E) show which woodlands are the most distant from the nearest woodland in T1 for categories AW, 1a, 2a and PAWS. As the minimum distance from T1 increases, we can consider that the likelihood of these woodlands to be pseudo-AW increases.

Quantitative estimates were derived from the cartographic assessment. Figure 4.3 represents the cumulative area listed as ancient woodland but not depicted in T1 (Figure 4.3A) and T2 (Figure 4.3B) as the distance to the nearest woodland in T1 and T2 increases. Regarding the comparison with the woodland cover in T1 (Figure 4.3A), the estimates indicate that about 53% of the area listed as ‘ancient’ (category AW) was not within a distance of 10 m from the nearest woodland in T1 and 29% did not lie within even 100 m.

For the georeferenced estate plans in T1, the assessment of the planimetric accuracy showed previously that the RMSE values range from 3 m to about 35 m (median = 17 m) (see Figure 2.13). Even though we saw in Chapter 2 that the variations in RMSE do not always reflect faithfully the accuracy of georeferenced plans, the RMSE values indicated that the inaccuracy rarely exceeds 35 m. With almost 41% of ancient woodland not located within a distance of 35 m from the nearest woodland in T1 (category AW), this lower estimate – considering the generous distance threshold – tends to indicate that a substantial amount of woodland listed in the AWI is likely to be pseudo-AW rather than AW. The PAWS curve follows a similar trend to that of category AW (Figure 4.3A). This observation might be partly explained by the fact that a large amount of AW in Area 2 was also PAWS in 2014 (as shown Figure 4.2)

After breaking down the category AW into categories 1a and 2a, the results indicate that a lower 35% of the woodland listed in category 1a does not lay within 35 m of the nearest woodland in T1; about 50% is located outside the threshold of 10 m (Figure 4.3A). In contrast, the estimates for category 2a reached 58% for a 35 m threshold and 67% for a 10 m threshold. For the long distance thresholds, such as 200 and 400 m, almost 40% and 30% of the woodland in category 2a remained outside the thresholds against less than 10% for category 1a (Figure 4.3A). In other words, it appears that the identification of ‘ancient woodland’ based on the interpretation of the First Edition OS maps only (i.e. category 2a) seems to be far less reliable than the interpretation based on the Roy map (i.e. category 1a).

It is worth remembering that the results in Figure 4.3 should be also considered as underestimates of the amount of potential pseudo-AW in the study area. This consideration is due to the fact that 1) the woodland cover reconstruction in T1 (and T2) provides an idea of the post-1750 cover, while the definition of 'ancient woodland' for Scotland uses c.1750 as a threshold; and 2) all historical woodland plantation could not be identified as such from estate plans due to missing surveyor's indications (see Chapter 2 and 3). Some of these plantations can be incorrectly considered as ancient, thereby biasing the cartographic analysis.

Finally, it was also found that 336 ha of woodland depicted in T1 and native or broadleaved in 2014 is not considered as 'ancient woodland' in the AWI. Eighty two hectares of these 336 ha are listed as 'long-established of plantation origin' (category 2b), meaning that they were not depicted on the Roy map but supposedly identified as plantation on the First Edition OS maps. Except for 13 ha depicted on the Roy map only (category 3), the woodland in T1 that is not listed in the Scottish AWI (i.e. 241 ha) could be ancient. Therefore, this area of between 241 and to 336 ha represents an upper estimate of the 'ancient woodland' potentially overlooked in the AWI covering Area 2. Without further archival research, it is not possible to confirm the antiquity of these woodlands.

4.3.1.2 Comparison with the woodland cover in T2 (1801-1833)(Figure 4.3B)

Regarding the comparison with the woodland cover in T2 (Area 3), Figure 4.3B indicates that 48% of the area considered as ancient woodland in category AW is not located within 10 m of the nearest woodland in T2. The estimate remains at 35% of category AW outside the critical distance threshold of 35 m used for the comparison with the woodland cover in T1. However, considering the fact that the estate plans in T2 have a higher planimetric accuracy than estate plans in T1 – the maximum RMSE value is about 25 m for T2 (see Figure 2.13) – a critical distance threshold that is lower than 35 m seems more appropriate for the comparison. In fact, almost 40% of the AW in the inventory falls outside the distance threshold of 25 m from the woodland in T2. Consequently, a substantial amount of woodland considered as 'ancient' in the AWI was not depicted as woodland on estate plans from the early nineteenth century. These results suggest that much of this woodland appeared at some time in the nineteenth century before c.1860, and is of considerably more recent origin than is currently believed.

As for the comparison with the woodland cover in T1, when breaking down the AW category into categories 1a and 2a, the estimates indicate that the former is relatively more accurate than the second. About 32% of the woodland in category 1a is not located within 25 m of the nearest woodland in T2, while the estimates reach almost 60% for category 2a. Moreover, about 33% of the woodland listed in category 2a remains outside the distance threshold of 200 m (and 8% for category 1a).

While the trends for categories PAWS and AW were very similar in the comparison with T1, the overall accuracy of PAWS seems somewhat better than AW as compared to T2 (Figure. 4.3B). The results suggest that about 33% of PAWS are not located within 25 m from the nearest woodland in T2. The larger difference observed between AW and PAWS in Area 3 than in Area 2 can be explained by the fact that there is less AW that was also PAWS in 2014 in Area 3.

An attempt was made to determine how much woodland in T1 may be ancient and overlooked in the AWI. Considering that T2 is much later after c.1750 and given the high amount of woodland plantations appearing between T1 and T2 (Chapter 3), it did not seem relevant to do a similar assessment here.

4.3.2 Identifying pseudo-ancient woodland sites using the logistic regression models

Table 4.4 Assessment of the models ability to classify correctly the pseudo-AW sites from the AW in T1. The numbers of cells were obtained after identifying the optimal decision threshold which maximised the identification of the true pseudo-AW and minimised the errors (i.e. AW in T1 incorrectly classified as pseudo-AW). Percentages are indicated in brackets and calculated from the total number of cells as pseudo-AW (cells '0') and AW in T1 (cells '1') in the dataset.

Models	AUC	Number of cells correctly classified as pseudo-AW (%)	Number of cells incorrectly classified as pseudo-AW (%)	Decision threshold (τ)
Drumlanrig	0.64	21 (10)	3 (1)	0.15
Annandale	0.76	22 (37)	2 (4)	0.4
Other	0.66	20 (27)	6 (8)	0.4

When detailed historical cartographic records such as estate plans are missing, models of past woodland cover can be useful to determine where the AWI is inaccurate. The logistic regression models implemented in Chapter 3 are tested for identifying the pseudo-AW sites in the AWI.

It is often accepted that a model with AUC > 0.7 indicates a relatively good discriminatory power (Serneels and Lambin, 2001; Wilson et al., 2005). With AUC = 0.76 (Table 4.4), the model 'Annandale' performs well to differentiate the cells which are pseudo-AW from AW in T1. In practice, with a decision threshold τ = 0.4, this model was able to correctly identify 37% of the pseudo-AW cells while it incorrectly identified about 4% of the AW in T1 cells as pseudo-AW.

In contrast, although the models 'Drumlanrig' (AUC = 0.64) and 'Other' (AUC = 0.66) are better than random guesswork (AUC = 0.5), they perform only moderately well. For the model 'Drumlanrig', it was possible to classify correctly only 10% of the pseudo-AW cells for about 1% of error (τ = 0.15). While the model 'Other' classifies correctly about 27% of the pseudo-AW cells, the number of AW in T1 incorrectly classified also increases to reach 8% (τ = 0.4). These results indicate that a majority of pseudo-AW cells could not be identified as such by the different models. However, the models remained able to recognise several pseudo-AW sites in minimising the error rate (i.e. false negatives).

The Wilcoxon-signed Rank test was used to test the environmental variables for which the differences are statistically significant between the sampled pseudo-AW and AW in T1 (R Development Core Team 3.2.3). When considering the whole study area, pseudo-AW tend to be located on higher elevation (W = 64931, $p < 0.001$), lower slope (W = 48579, p = 0.003), further away from the stream (W = 62008, p = 0.19) and oriented more towards west (W = 48374, p = 0.002) and south (W = 49036, p = 0.005) facing slopes than the AW in T1.

4.4 Methods for plant surveys

The results from the cartographic assessment of the AWI in the study area indicate that a large area of woodland classified as ‘ancient’ is likely to be post-1750 plantations. The AWI was implemented everywhere in the UK after ancient woodland sites were recognised as areas of greater ecological and historical value (Goldberg et al., 2007). The plant survey aims to test the role of woodland continuity to structure plant communities in the study area’s woodlands. In so doing, the study of plant communities can help to assess whether ancient woodland forms a distinct ecological category and, thereby, better identify the implications of the unreliability of the AWI for the conservation of ancient woodland.

4.4.1 Data collection

This part of the research focuses on the present-day native woodland sites listed in the NWSS (2014) and located in areas mapped by historical estate plans. The vascular plant community was recorded in 41 woodland sites (Table 4.5). These surveys aim to take advantage of the unique accuracy of the woodland cover reconstruction to determine whether woodland plantations – from the late eighteenth to the twentieth century (i.e. recent woodlands) – exhibit different botanical characteristics than woodlands with longer time-continuity (i.e. probable ancient woodlands).

Several selected case studies aim also to compare more specifically the plant community of woodland sites of different ages but spatially close to each other. *In fine*, these comparisons are expected to provide insight about the relative importance of the landscape context in the distribution patterns of several plant species currently known as ancient woodland indicators.

Three continuity classes applied to native woodland sites were identified based on the estate records and from the trajectory analysis undertaken in Chapter 3 (sections 3.2.6 and 3.3.3):

- Class ‘A’ for the woodland depicted in T1 and not identified as plantations by the surveyors. These sites are probable ancient woodland (category ‘1-1-1-1’ in the trajectory analysis, 17 sites);

- Class ‘B’ for the woodland depicted in T1, T2 and/or T3 that is identified as plantations based on 1) the surveyors’ indication or; 2) the comparison between T1 and T2 (i.e. pre-c.1860 woodland from plantation origin, categories ’1-1-1-1’, ‘0-1-1-1’ and ‘0-0-1-1’, 18 sites);

- Class ‘C’ for the woodland identified as post-c.1860 plantations (i.e. not depicted as woodland on the First Edition OS map). The dates provided in Table 4.5 were determined using the Second and later OS editions maps (category ‘0-0-0-1’, 6 sites).

Each woodland site surveyed has homogenous dominant habitat type (e.g. ‘wet woodland’, ‘upland oakwood’, based on data available in the NWSS, see Table 4.5) and homogeneous continuity class. Besides the need of strong historical mapping evidence to determine the continuity class, the area suitable for survey was based on size (at least 1 ha) and shape to mitigate the edge effect (Murcia, 1995). The woodland or parts of woodland with high perimeter-area ratio were not considered. Using QGIS (v.2.14.1, 2018), desk-based research permitted the identification of potentially suitable sample plots located at least 50 m from the woodland edge (edge effect is thought to be prominent within 50 m of the edge – Murcia, 1995).

In the field, the software Qfield (v.0.10.13, 2017) enabled the use of QGIS data on a device equipped with GPS to locate the sample plots for survey. When the location of the plot was found not convenient or not suitable for survey (e.g. limited access, local tree clearance within the canopy), it was relocated to the nearest suitable area.

The plant survey was conducted from May to July 2017. The identification of vascular plants was done on 200 m^2 rectangular plots with two or three plots for each site (i.e. at least 400 m^2 were surveyed per site as per Koerner et al., 1997; Wulf, 2003; Sciama et al., 2009). The number of plots depended on the suitable size of the area to survey and access restrictions. For the smallest sites, the two plots were set next to each other. For the largest sites, the plots were at least 200 m apart to increase the chance of surveying over different environmental conditions and thereby better reflecting the botanical diversity of each site. For similar reasons, plant species identified on the walk between two plots but not found within the plots were also recorded (as recommended by Wright and Rotherham, 2011).

The plant species were identified using *The Wild Flower Key* by Rose and O’Reilly (2006) and the *Collins Flower Guide* (Streeter et al., 2009). Due to time constraints, the survey did not estimate the abundance-dominance of each species but recorded only their occurrence for each site as in Peterken and Game (1984), Wulf (2003) or Sciama et al. (2009). Moreover, the survey taking place between May and July, it is noteworthy that some species which are mostly in leaf during early

Spring and late Summer may have been overlooked. The revised list of Scottish AWP species by Crawford (2009) was used to determine which species identified in the field are potential indicators of ancient woodland. This list was implemented after consultation of several local experts in native woodlands in Scotland (Crawford, 2009).

The fieldwork often involved difficult conditions, including steep slopes, high fences and barriers such as gullies within the woodland. These physical barriers occasionally hampered the progress and access to some parts of the sites was not possible. As a result, the plant taxa occurring in areas with limited access may have not been recorded.

In addition, soil pH was determined at each site. This environmental factor can be an important determinant of the composition of vegetation communities and was compared against the plant data. Samples of soil were collected at 8-15 cm depth using systematic scheme within the plots. Four to six samples were collected per site (i.e. approximately 300-400 g) and bulked afterwards (as in Verheyen et al., 1999; Sciama et al., 2009). The samples were oven-dried at 35°C, disaggregated in a mortar and pestle, and sieved through a 2 mm brass sieve. Afterwards, the soil was mixed with distilled water (weight/volume = 1/2.5) and left for 30 min. The analysis was done using a pH probe calibrated against pH4 and pH7 buffer solutions. To check for precision, 5% of the samples were analysed a second time. Soil preparation was sent for analysis to George MacLeod, technical specialist at the University of Stirling.

Table 4.5 List and details of the woodland sites surveyed. The site codes beginning with the same three first letters and continuing with numbers (e.g. Air1 and Air2) are woodland sites adjacent to each other but with different principal habitats or continuity classes. The site codes beginning with the same three first letters and finishing with *a*, *b*, *c* or *d* are not adjacent but located within 2 km of each other; *SSSI: Chanlockfoot (Bac1, Bac2), Coshogle wood (Cos), Lochwood (Low); 'AWI': category as currently in the Scottish AWI ('N.A' when no category is applied); 'Earliest date': the earliest date – or interval dates – since a wood is known to exist; **'**Habitat type' as in the NWSS (i.e. 'Upland oakwood'; 'Upland mixed ashwood'; 'Lowland mixed deciduous'; 'Wet woodland'); 'Plots': number of plots surveyed per site (200 m^2 each plot).

Uk Reference Grid	Site code	Continuity class	AWI	Earliest date	Habitat type	Plots
NX802990	Bac1*	A	1a	< 1772	Up ashwood	2
NX802993	Bac2*	A	1a	< 1772	Up oakwood	2
NS862048	Cos*	A	1a	< 1772	Up oakwood	3
NS881011	Eno	A	1a	< 1772	Up ashwood	2
NS881006	Mor	B	2b	1772-1820	Up oakwood	2
NX809992	Dru	C	N.A	1860-1898	Up ashwood	2
NS883028	Sch	B	2a	1820-1860	Up ashwood	2
NX946709	Mab	A	2b	< 1790	Low deciduous	2
NX929732	Hil*a*	A	N.A	< 1775	Low deciduous	2
NX921741	Hil*b*	A	1a	< 1775	Low deciduous	2
NX923742	Hil*c*	A	1a	< 1775	Low deciduous	2
NX923739	Hil*d*	A	1a	< 1775	Up ashwood	2
NS840046	Ard	B	1a	1767-1833	Up ashwood	2
NX822998	Cle1	B	1a	1772-1820	Up oakwood	2
NX822998	Cle2	A	1a	<1772	Up oakwood	2
NS827000	Cle3	B	1a	1820-1860	Low deciduous	2
NX827997	Cle4	B	1a	1772-1820	Low deciduous	2
NX845957	Ecc	B	2b	1820-1860	Low deciduous	2
NX986658	Air1	C	1a	20th c.	Wet Woodland	2
NX987658	Air2	A	3	1782	Wet Woodland	2

Table 4.5 /continued List and details of the woodland sites surveyed. *See first part of the table above for explanations.*

Uk Reference Grid	Site code	Continuity class	AWI	Earliest date	Habitat type	Plots
NT075061	Mof1	B	2b	1771-1827	Low deciduous	2
NT076061	Mof2	B	2b	1771-1827	Up ashwood	2
NT074069	Gar1	B	2b	1782	Up oakwood	2
NT073071	Gar2	B	2b	1807-1860	Up oakwood	2
NT080003	Mar	A	1a	< 1786	Up ashwood	2
NY083972	Low*	A	1a	< 1786	Up oakwood	3
NY024652	Cae1	A	1a	< 1776	Wet Woodland	2
NY023655	Cae2	C	1a	20th c.	Wet Woodland	2
NY084816	Lom	B	2b	1788-1860	Up oakwood	2
NY020803	Tin	A	1b	< 1799	Low deciduous	2
NY133969	Mil	B	1a	< 1773	Up ashwood	2
NY068923	Rah1	B	2b	1783-1790	Low deciduous	2
NY069925	Rah2	B	2b	1783-1790	Low deciduous	2
NX962690	Sha*a*	B	2b	1791-1814	Low deciduous	2
NX956688	Sha*b*	C	N.A	1860-1907	Wet Woodland	3
NX968674	Sha*c*	B	N.A	1782-1860	Wet Woodland	2
NX895733	Lor	C	N.A	1860-1895	Wet Woodland	2
NX803889	Mon	B	2b	1811	Wet Woodland	2
NX780950	Pin1	A	2a	< 1772	Wet Woodland	2
NX780952	Pin2	A	2a-3	< 1772	Up ashwood	2
NX778954	Pin3	C	1a-3	20th c.	Wet Woodland	2

4.4.2 Statistical analysis

For each site, the total number of species (i.e. species richness) is calculated, as well as the number of species thought to be indicators of ancient woodland in Scotland – following the most recent list by Crawford (2009). For each species, the Fisher's exact test is used to determine whether the frequency of occurrence in probable ancient woodland sites (class A) is significantly different from the frequency of occurrence in recent woodland sites (classes B and C). The Fisher's exact test is preferred to the χ^2–test as the former is more adapted to small-sized samples (Sciama et al., 2009; Kim, 2017).

Due to the limited number of suitable sites for the survey (i.e. native woodland with strong historical mapping record), all sites do not share comparable biophysical conditions. Environmental variables such as soil characteristics and habitat dominance may vary and partly account for variations observed in plant communities between the sites. The variations in biophysical conditions between woodland sites certainly add complexity in relating the plant community patterns to the woodland continuity class. As we see below, this issue is partly addressed by the choice of suitable statistical methods and is further considered when interpreting the results. However, it is worth noting that this study focuses on testing the possibility of identifying ancient woodland from recent woodland sites based on vegetation composition as it has been considered in previous work (Rose, 1999; Crawford, 2009). As a result, conducting a comprehensive multi-variate analysis to determine the strength of the different factors driving plant composition was judged to be beyond the scope of this study.

Plant communities are analysed using Detrended Correspondence Analysis (DCA, Hill and Gauch, 1980). Widely used in plant ecology, Correspondence Analysis and DCA have regularly served to identify patterns in species assemblage associated with woodlands' continuity or land-use history (e.g. Dupouey et al. 2002b; Bellemare et al., 2002; Ito et al., 2004; Sciama et al., 2009). DCA is an unconstrained ordination technique that can be used to summarise, in reduced dimensional space, patterns in the plant species assemblage at each sampling plot. With DCA, the plots sharing similar species assemblage are graphically closer to each other. It is also possible to relate the position of the sample plots along the ordination axes with site characteristics of interest (i.e. continuity class, dominant habitat/woodland type and pH). This procedure aims to determine more specifically whether continuity class is a latent variable that governs the variations observed in species assemblage between woodland sites. By extension, DCA aims to test if it is possible to identify ancient woodland sites in the study area based on their plant assemblage.

Following Peterken and Game (1984), tree species are ruled out of the statistical analyses because their presence or absence may result less from continuity than from plantations or deliberate selection of some species. The species that occurr only in one or two different sites are also excluded from the DCA as these taxa can distort the results (Legendre and Gallagher, 2001) and they provide little additional information for this study. It is common practice to remove rare taxa such as those with less than 5% of occurrence (e.g. Lawesson, 2000 p.39; Sørenson and Tybirk, 2000; DeSiervo et al., 2015). The DCA is performed using *decorana* function in the *Vegan* package in R (R Development Core Team 3.2.3; Oksanen, 2015). Species occurrences are coded as presence (1) or absence (0). The function *envfit* in Vegan (Oksanen, 2015) is used to test the importance of continuity class, woodland type, and soil pH to describe the variations observed in the ordination. Function *envfit* allows random permutation tests based on 1000 permutations to assess the correlation of these variables with the ordination and to infer statistical significance (Oksanen, 2015).

4.5 Results of the plant survey

4.5.1 Plant identification

The botanical survey of 41 native woodland sites resulted in the identification of 149 vascular plant species as listed in Appendix F. The frequency of occurrence of 9 species was found significantly higher ($p < 0.05$) in class A sites (i.e. probable ancient woodland) than sites of classes B and C (i.e. recent woodland pre-1860 and post-1860, respectively) (Table 4.6). Amongst these species, *Allium ursinum* (ramson), *Carex sylvatica* (wood sedge), *Mercurialis perennis* (dog's mercury), *Polypodium vulgare* (common polypody), *Potentilla sterilis* (barren strawberry) and *Veronica montana* (wood speedwell) are listed by Crawford (2009) as 'Ancient woodland indicator plants for Scotland' (AWP species). Significant differences were also found for *Corylus avellana* (common hazel, $p = 0.005$). This species was found in all class A sites, while it occurred only in 62% of class B and C sites.

Although not listed as AWP by Crawford (2009), *Digitalis purpurea* (foxglove) and *Vicia sepium* (bush vetch) were also found to occur significantly more in class A sites than class B and C sites ($p = 0.023$ and $p = 0.003$, respectively). *Vicia sepium* has been considered as AWP in several regional lists in England, Wales and Scotland but not included in the most recent Scottish list of AWP by Crawford (2009). *Crepis paludosa* (Marsh Hawk's-beard) is the only plant species that was found with a significantly higher frequency of occurrence in recent woodland sites ($p = 0.028$).

Except for *A. ursinum* and *V. sepium*, all the AWP species were identified in recent woodland. Moreover, despite the significant differences between class A and class B and C sites, the frequency of occurrence of species such as *M. perennis* – 21% in recent woodland – and *P. sterillis* – 17% in recent woodland – can be regarded as relatively high given their status as AWP. The frequency of occurrence of some other well-known AWP species such as *Anemone nemorosa* (wood anemone), *Conopodium majus* (pignut), *Lysimachia nemorum* (yellow pimpernel), *Oxalis acetosella* (wood sorrel), and *Hyacinthoides non-scripta* (bluebell) was not significantly different between probable ancient and recent woodlands. They were also found as relatively common in recent woodlands with a frequency of occurrence of 21%, 33%, 58%, 79% and 83%, respectively. Other AWP species were identified exclusively or more regularly in recent woodland, including *Geum rivale* (water avens) and *Moehringia trinervia* (three-nerved sandwort).

Table 4.6 Ancient woodland vascular plants for Scotland (Crawford, 2009) identified during the survey – number of sites where each species was recorded (percentages of occurrence for each continuity class are indicated in brackets). The association with class A or class B and C was tested with Fisher's exact test when the occurrence > 3 (*: *p*-value < 0.05; **: *p*-value < 0.01; -: non-significant; N.A: not applicable); †: can be planted or escapee (Crawford, 2009); ‡: not in Crawford (2009) but recognised as indicator species in lists by local experts (C. Miles and D. Hawker, unpublished); ϕ: not listed but associated with class A or class B and C sites (*p*-value < 0.05).

Latin	All woods (n = 41 sites)	Class A (n = 17 sites)	Class B and C (n = 24 sites)	*p*-value
Allium ursinum	4 (10)	4 (24)	0	* (*p* = 0.023)
Anemone nemorosa	12 (29)	7 (41)	5 (21)	-
Brachypodium sylvaticum	1 (<1)	1 (6)	0	N.A
Cardamine amara	2 (<1)	2 (12)	0	N.A
Cardamine flexuosa‡	18 (44)	7 (41)	11 (46)	-
Carex remota	12 (29)	6 (35)	6 (25)	-
Carex sylvatica	8 (19)	6 (35)	2 (8)	* (*p* = 0.048)
Chrysosplenium oppositifolium	24 (58)	9 (53)	15 (62)	-
Circaea x intermedia	3 (1)	1 (6)	2 (8)	N.A
Circaea lutetiana	27 (66)	12 (71)	15 (62)	-
Conopodium majus	16 (39)	8 (47)	8 (33)	-
Corylus avellana†	32 (78)	17 (100)	15 (62)	** (*p* = 0.005)
Crepis paludosa ϕ	10 (24)	1 (6)	9 (37)	* (*p* = 0.028)
Digitalis purpurea ϕ	17 (41)	11 (65)	6 (25)	* (*p* = 0.023)
Equisetum sylvaticum	3 (1)	2 (12)	1 (4)	N.A
Fragaria vesca	8 (19)	5 (29)	3 (12)	-
Galium odoratum	4 (10)	3 (18)	1 (4)	-
Geum rivale‡	3 (1)	0	3 (12)	N.A
Gymnocarpium dryopteris	3 (1)	2 (12)	1 (4)	N.A
Hyacinthoides non-scripta	37 (90)	17 (100)	20 (83)	-
Luzula pilosa	6 (15)	3 (18)	3 (12)	-
Luzula sylvatica	5 (12)	2 (12)	3 (12)	-
Lysimachia nemorum	29 (71)	15 (88)	14 (58)	-
Melampyrum pratense	3 (1)	2 (12)	1 (4)	N.A
Mercurialis perennis	15 (37)	10 (59)	5 (21)	** (*p* = 0.005)
Milium effusum	2 (<1)	2 (12)	0	N.A
Moehringia trinervia	4 (10)	1 (6)	3 (12)	-
Oxalis acetosella	34 (83)	15 (88)	19 (79)	-
Phegopteris connectilis	2 (<1)	2 (12)	0	N.A
Polypodium vulgare	4 (10)	4 (24)	0	* (*p* = 0.026)
Polystichum aculeatum	1 (<1)	1 (6)	0	N.A
Potentilla sterilis	12 (29)	8 (47)	4 (17)	* (*p* = 0.045)
Prunus padus†	4 (10)	2 (12)	2 (8)	-
Ranunculus auricomus	2 (<1)	2 (12)	0	N.A
Scrophularia nodosa	4 (10)	2 (12)	2 (8)	-
Stellaria holostea	22 (54)	10 (59)	12 (50)	-
Valeriana officinalis	6 (15)	1 (6)	5 (21)	-
Veronica montana	8 (19)	6 (35)	2 (8)	* (*p* = 0.049)
Vicia sepium ϕ	6 (15)	6 (35)	0	** (*p* = 0.003)

Low rates of occurrence (n < 3) mean that the statistical tests to compare the frequency of occurrence of plant species between class A and classes B and C could not be performed for 11 AWP species, including *Gymnocarpium dryopteris* (oak fern), *Ranunculus auricomus* (goldilocks buttercup), and *Milium effusum* (wood millet). Despite this incapacity to perform statistical tests, these species occurred more in class A sites, in agreement with their AWP status, while two species occurred more in recent woodland (i.e. *Circaea x intermedia* and *Geum rivale*). A higher site sampling would have enabled to overcome this issue but was restricted by the low number of suitable sites to undertake a survey (i.e. of native woodland sites with proper historical estate mapping records).

Table 4.7 Summary of the plant data collected for each continuity class. Species richness, number of ancient woodland indicator plant (AWP) species according to Crawford (2009) and the lists by local experts as in Table 4.6).

		Continuity class		
		Class A (17 sites)	**Class B (18 sites)**	**Class C (6 sites)**
Species richness	Mean	37.1	32.4	34.5
	Median	38	35	32
	Min	18	12	22
	Max	48	50	58
Number of AWP species	Mean	12.5	8.3	6.8
	Median	13	9	8
	Min	5	1	2
	Max	24	14	12

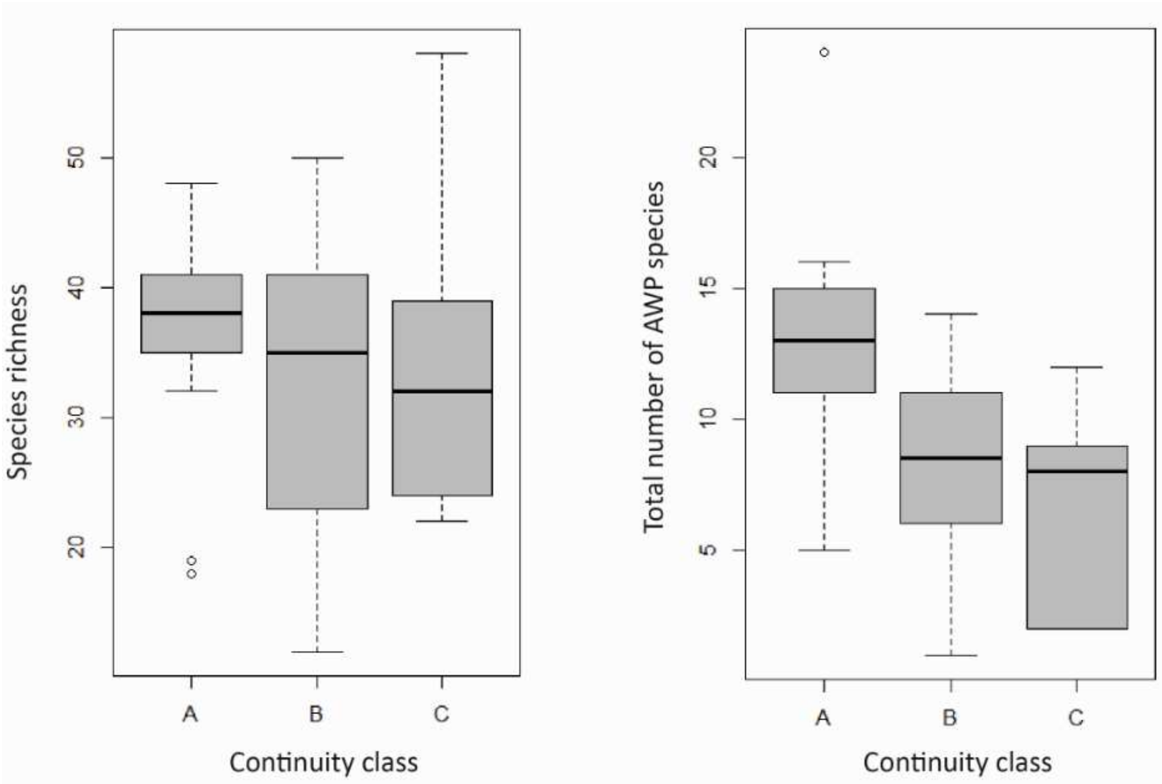


Figure 4.4 Boxplots of species richness and number of AWP species per continuity class.

Table 4.7 summarises the field data for species richness (i.e. total number of plant species per site) and total number of AWP species for each continuity class (the details for each site can be found in Appendix F). Figure 4.4 illustrates the distribution of this data for each continuity class (see section 2.2.2.4 for the key to understanding the boxplot). Statistical analyses were also performed with R (R Development Core Team 3.2.3) to test for statistically significant differences between the continuity classes.

A normality test was performed first using Shapiro-Wilk test. The results of this test indicated that the sample sites of class A did not come from a normally distributed population (W = 0.87, p = 0.020). For that reason, the non-parametric Kruskal-Wallis H test was more appropriate for data comparison.

Regarding the species richness, Figure 4.4 tends to show more variability for class B and C sites than class A. Besides two sites with a relatively low species richness (i.e. Hil*b* and Hil*c*), the species richness in class A sites ranges from 18 to 48 species (median = 38). The species richness ranges from 12 to 50 in class B sites (median = 35), and 22 to 58 in class C sites (median = 32). However, the statistical test results indicate that the species richness does not differ significantly between the three continuity classes (H = 2.29, p = 0.318).

In contrast, the Kruskal-Wallis test indicates significant differences between continuity classes for the total number of AWP species ($H = 10.258$, $p = 0.006$). The mean number of AWP in class A sites is 12.5 species (median = 13), against 8.3 for class B sites (median = 9), and 6.8 for class C sites (median = 8). Dunn's pairwise *z* test was performed as a post-hoc test and indicated significant differences between classes A and B ($z = 2.68$, $p = 0.022$) and between classes A and C ($z = 2.62$, $p = 0.013$). As a result, the number of AWP species seems to be significantly higher in probable ancient woodland than recent woodland. No significant differences were found for the comparison between recent woodland sites of classes B and C ($z = 0.72$, $p = 0.474$).

Eight sites from class B (of a total of 18 sites, i.e. 44%) exhibit more than 10 indicator species of ancient woodland and one site from class C (on a total of 6 sites, i.e., 16%) also does (Appendix F). The mean number of AWP species in recent woodland sites and the number of these sites exhibiting more than 10 AWP species can be regarded as relatively high. In sum, although probable ancient woodland sites tend to provide habitats to relatively more AWP plant than more recent woodland, many of these recent woodlands are relatively rich in AWP species. It is noteworthy that the outlier site in class A displaying 24 AWP species (Figure 4.4 and Table 4.7) is recognised as a SSSI (Chanlockfoot). The two other SSSI surveyed, namely Coshogle wood and Lochwood, are both ancient woodland and exhibit 46 plant species for 16 AWP and 42 plant species for 12 AWP, respectively.

4.5.2 Detrended correspondence analysis and environmental factors

A DCA was performed to visualise the distinctions in plant composition of sites with different continuity classes. The matrix includes 41 sites and 92 species. From the DCA, it was possible to assess the importance of continuity class to structure plant assemblage patterns in the different sites. The position of the sites onto the ordination is illustrated in Figure 4.5A and the position of the 80% species with the highest fit is illustrated in Figure 4.5B. The eigenvalues of the two first axes of the DCA ordination are 0.22 and 0.18, which indicate moderate variance. The length of each axis is 2.9 and 1.9 SD units (i.e. units of beta diversity).

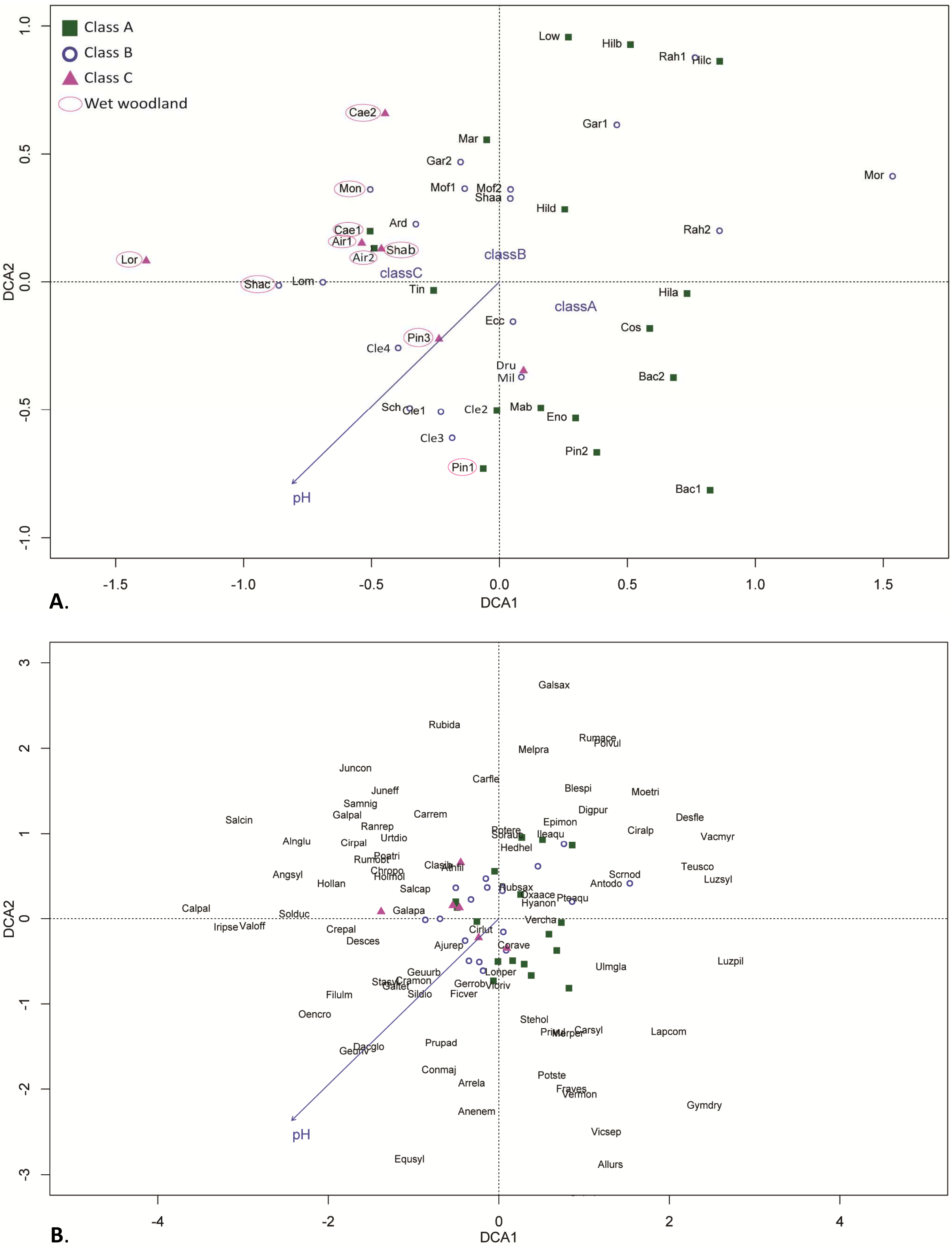


Figure 4.5 Detrended correspondence analysis (DCA) of the sites (A.) and species (B.) along axis 1 and 2. (**A.**) 'classA', 'classB' and 'classC' show the centroid of the variable 'continuity class'; (**B.**) For a matter of clarity, only the 80% of the species with the highest axis fit are labelled. The species abbreviations are the first three letters of genus followed by the first three letters of species. The full taxa list is provided in Appendix F.

Wet woodland sites (NWSS, 2014) had mostly low scores on the first axis (e.g. 'Air1', 'Air2', 'Cae1', 'Sha*b*' and 'Ard') (Figure 4.5A). The variable 'woodland type' has indeed a highly significant correlation with plant composition and, therefore, the position of the sites on the ordination (random permutation test with 1000 permutations, r^2 = 0.24, p = 0.003). This observation probably reflects a wetness gradient more than the dominant woodland habitat *per se*. Indeed, significant differences in plant composition exist to distinguish Wet woodland from the other dominant woodland habitats on the first axis (t = -3.25, p = 0.002) but there is no significant difference between the other habitats (i.e. upland oakwood; upland mixed ashwood and lowland mixed deciduous). The strongest and significant correlation was found for pH (r^2 = 0.33, p = 0.003) showing the plant response to pH gradient, which varies from 3.4 to 4.7 (see Appendix E). While not as strong as the two previous variables, continuity class was also found to correlate significantly with variations in plant composition (r^2 = 0.13, p = 0.04). However, this correlation loses its significance.after removing the 10 Wet woodland sites from the analysis.

It is noteworthy that all the significant correlations were found for the first axis. Only pH also contributed to explain the distribution along the second axis (r^2 = 0.14, p = 0.009). The variations in plant composition along this axis remain, therefore, mostly unclear. Other non-measured variables such as light gradient may control this distribution. No correlations to the third and fourth axes were identified.

Despite the significant correlation between continuity and the position of the sites on the DCA ordination, the DCA plot shows a relatively strong visual overlap between sites of different continuity classes (Figure 4.5A). The fact that the distinction is blurred is also reflected in the relatively close centroids of the three continuity classes. However, a group of 8 probable ancient woodland sites (n= 17 sites) seems relatively close with a relatively higher scores on Axis 1 and lower scores on Axis 2 (i.e. 'Cle2', 'Mab', 'Eno', 'Pin2', 'Bac1', 'Bac2', 'Cos' and 'Hil*a*').

Only two recent woodland sites (class B for 'Mil' and class C for 'Dru') share plant assemblages that are relatively similar to those of the probable ancient woodland sites mentioned above (Figure 4.5A). Unsurprisingly, these two recent woodland sites display a high number of AWP species (13 and 9 species, respectively) as does the group of probable ancient woodlands. 'Dru' is a woodland site from the late nineteenth century origin that exhibits AWP species such as *Veronica montana*, *Lysimachia. nemorum*, *Oxalis acetosella*, *Conopodium majus* and *Hyacinthoides non-scripta*. Another indicator species of ancient woodland, namely *Mercurialis perennis* was also at the edge of the wood (and therefore not integrated into the analysis). The ancient woodland sites nearest to 'Dru' are located about 300 m away and are named 'Bac1' and 'Bac2' on the ordination – ashwood and oakwood, respectively, and also part of Chanlockfoot (SSSI). All the AWP species in 'Dru' are also in 'Bac1' and 'Bac2'. It is possible that Chanlockfoot has served as 'reservoir' for AWP species that have been able to colonise this recent woodland site (i.e. 'Dru') within less than 150 years. Other more specific observations are of interest:

- 'Pin1', 'Pin2' and 'Pin3' are now part of the same woodland but exhibit different habitat types and/or continuity classes (Table 4.4). These differences may explain the variations observed in plant assemblage and, therefore, the distance between these three sites on the ordination. 'Pin3' (i.e. class C) was wooded sometimes in the twentieth century while 'Pin1' and 'Pin2' are probable ancient woodland (i.e. class A). It was found that the two latter exhibit 15 AWP species, against 8 AWP species for 'Pin3' (including *V. montana*, *P. sterilis, F. vesca, L. nemorum*, and *M. perennis*). These species were able to establish themselves in this new woodland area within a relatively short period of time, contrary to other AWP species such as *C. majus* and *A. nemorosa* both identified in 'Pin1' and 'Pin2' but not in 'Pin3'. The differences observed between 'Pin1' and 'Pin2', although both class A sites, might be explained by the fact that one site is a Wet woodland and the other one is mixed ashwood. It is unsure when 'Pin3' began to be woodland but a later Edition of the OS survey published in 1956 shows that this area was unwooded by that time. The distance between the plots surveyed in 'Pin3' and the edge of the nearest class A site is between 100 and 150 m. This example illustrates the rapidity with which these AWP species are able to establish themselves in modern woodland.

- 'Air1' (class C) and 'Air2' (class A) are currently part of the same Wet woodland. The former displays 8 AWP species against 11 for the second but they are located very close on the ordination. This observation indicates low variations in plant composition between these two sites despite different continuity class.

- 'Cle1' (class B), 'Cle2' (class A)', 'Cle3' (class B) and 'Cle4' (Class B) are part of the same woodland. While 'Cle2' (14 AWP species) is closer on the ordination to the other group of class A sites, the three class B sites remain close and display 10, 13 and 14 AWP species, respectively. It is possible that 'Cle2' served as reservoir for the three other sites, which would explain why the plant compositions of these sites are relatively similar.

- Located relatively close (< 2km) and while they all are class A, 'Hil*a*', 'Hil*b*', 'Hil*c*' and 'Hil*d*' have very distinct plant assemblage. While being probable ancient woodland, Hil*b* and Hil*c* display relatively few AWP species (6 and 5 AWP species, respectively).

- 'Sch' is a small (< 4 ha) woodland site that appeared sometime between 1820 and 1860. While historically isolated from more ancient woodland – no woodland in the eighteenth century within less than 1 km – 'Sch' displays no less than 8 AWP species, including *O. acetosella*, *M. perennis, C. majus, G. rivale* and *C. oppositifolium*.

In summary, these results highlight that there is no systematic distinction between probable ancient woodland and recent woodland sites of classes B and C. Besides the principal woodland habitat (or most likely the wetness gradient), the geographical location of the sites seems to account for part of the variations observed in plant assemblage. The results also indicate that a large number of AWP species could develop in recent woodland sites within a relatively short period of time, which would explain the regular occurrence of AWP in class B and class C sites.

4.6 Discussion

4.6.1 Cartographic assessment of the Ancient Woodland Inventory

4.6.1.1 Overestimation of the amount of ancient woodland in the study area

Important lessons can be learned from the cartographic assessment of the AWI. Firstly, the results show that the AWI seems largely to overestimate the amount of ancient woodland in the study area, when ancient woodland is defined as continuously wooded since at least 1750. In Area 2, the comparison between the AWI and the woodland cover reconstructed for T1 (1740-1799) indicates that 40% of the woodland considered as 'ancient' is likely to be pseudo-AW. In Area 3, the comparison of the AWI with the woodland cover reconstruction in T2 (1801-1833) shows similar results and the estimates indicate that at least 40% of the area considered as ancient woodland was probably not even woodland by the early nineteenth century.

It is likely that a large part of the pseudo-AW originates from the pronounced increase in woodland cover between T1 and T3 (c.1860). Indeed, Chapter 3 demonstrated that the woodland cover increased from 3.1% in T1 to 6.3% in T3 in Area 2, and from 4.7% in T2 to 7.6% in T3 in Area 3. Unsurprisingly, the inaccuracy of the AWI affects also the identification of PAWS sites. Moreover, considering that the woodland cover reconstructions for T1 and T2 do not represent the woodland cover as far back as 1750 – the official threshold to define woodland as 'ancient' in Scotland – the amount of pseudo-AW identified in the present study is likely to be an underestimate.

Secondly, it seems that most woodland of category 2a – identified as semi-natural from the First Edition OS maps only – is inaccurately considered as ancient. The amount of pseudo-AW might represent at least 60% of category 2a both in Area 2 and Area 3. Based on the assumption that the Roy map overlooked many woodland sites, the sites of category 2a began to be considered as ancient woodland during the revision of the AWI in the 1990s (Kupiec, 1997). These results tend to show that this assumption has led to incorrect identification of a relatively high amount of woodland as ‘ancient’. The inaccuracy of the AWI highlighted for category 2a is a key finding as it could well apply beyond the boundaries of the study area.

It was expected that less pseudo-AW would be identified when using as reference the woodland cover reconstruction in T2 than in T1, the former being later than the second. In addition, the reconstruction in T2 represents the woodland at a time when considerable amounts of woodland were already planted and it is certain that some plantations were not acknowledged as such on the estate plans (see Chapters 2 and 3). Despite these considerations, the amount of probable pseudo-AW identified using the woodland cover in T2 is only slightly lower than when using its counterpart in T1. A few explanations may help to understand this observation: 1) the results of the assessment are not directly comparable between T1 and T2 as the estimates were done on different areas of study (i.e. Area 2 for T1 and Area 3 for T2); 2) the woodland cover reconstruction being more planimetrically accurate in T2 than T1, it was possible to use with confidence a lower critical distance threshold to estimate the percentage of probable pseudo-AW; and 3) plantations may be more often acknowledged as such on estate plans from T2 than T1. If this last point were proven true, it would imply that, thanks to surveyors’ indications, estate plans from the early nineteenth century can help to identify more pseudo-AW than estate plans from the eighteenth century only.

Thirdly, the inventory tends to overlook the complex history of individual woodlands. Present-day woodland could include juxtaposed stands of different continuity classes and management histories within the same site. However, the Ancient Woodland Inventory does not consider the plantations around ‘ancient cores’ that were regularly planted between 1750 and 1860 (see Chapter 3). More generally, any change in the shape of the woodland boundaries over time is necessarily overlooked as ancient woodlands are perceived as stable environments in the inventory. Likewise, the inventory cannot integrate changes in woodland composition and structure such as the conversion of wood pastures to dense woodlands.

Over the last few years in the UK, other studies have begun to point out deficiencies in the AWI. In Scotland, Whittet et al. (2015) showed that about 50% of the sites thought to be post-1860 regenerations of woodlands depicted in the Roy’s sheets (i.e. category 3 in the AWI) appear, in fact, to have been open woodland in c.1860. These sites have, therefore, experienced longer woodland continuity than identified in the AWI. As for the present study, Stone and Williamson (2013) and subsequently Barnes and Williamson (2015, p.122-133), have argued that many woodland sites listed as ancient in Norfolk (England) actually have more recent origins than was previously thought. Thus, while the threshold date to define an ancient woodland in England is 1600 A.D., almost a fifth of the woodland sites listed in the AWI that were studied by Barnes and Williamson (2015, p.127) were found to be more recent (mostly eighteenth or nineteenth century).

Nevertheless, many of these sites shared features that are usually associated with ancient woodland, including the occurrence of ancient woodland indicator species (Stone and Williamson, 2013; Barnes and Williamson, 2015, p.131-133).

4.6.1.2 Using logistic regression models to identify pseudo-AW

The logistic regression models of woodland cover for T1 developed in Chapter 3 failed to identify a majority of pseudo-AW without misclassifying a large number of probable ancient woodland sites (i.e. false negatives). Nonetheless, some of the sites with the lowest probability of being wooded in T1 could be accurately identified as pseudo-AW with little risk of false negatives. In sum, the models were clearly able to distinguish better than randomly the pseudo-AW from the AW in T1.

By extension, these results imply that differences exist between the environmental characteristics of these two groups. Compared to probable ancient woodland, it was found, in general, that pseudo-AW are located on higher elevation, further away from the streams, on more gentle slope and perhaps on ground with different geographical aspects. While casting doubt on woodlands listed in the AWI for which the probability scores to be woodland in T1 are the lowest, the logistic regression models can be relevant for detecting some of the pseudo-AW sites in the study area.

In addition, the models could be used where estate plans do not completely cover the study area. They can determine, without historical cartographic evidence, which woodlands in the AWI are the least likely to be ancient. Nonetheless, it remains unsure to what extent each model can be applied outside the current study area, which is an important shortcoming of the method. This issue cannot be addressed without extending the coverage with estate plans to other areas of Scotland for further tests.

It is noteworthy that as some woodlands in T1 were certainly not identified as late eighteenth century plantations by estate surveyors, some ‘AW in T1’ cells (‘1’ cells) might share similar characteristics with the ‘pseudo-AW’ (‘0’ cells), which are also late eighteenth and early nineteenth century plantations. Similarities such as a location on more gentle slopes, higher elevations or greater distance from streams may explain that some ‘1’ cells are incorrectly classified as ‘0’ for a given decision threshold. In fact, some of the ‘1’ cells with the lowest probability scores could be woodland plantations not acknowledged as such on estate plans. Hence, models could also help identifying the woodlands of plantation origin depicted on eighteenth century estate plans that are incorrectly considered as ancient ‘of semi-natural origin’ in the inventory.

4.6.1.3 Accuracy and reliability of the woodland cover as depicted from the Roy map

Several studies have assessed the overall reliability and consistency of the Roy map (Whittington and Gibson, 1986; Nisbet, 2009). This assessment is crucial in deciding how the ‘Great map’ can be used for historical geography (Hewer, 2010). More particularly, Whittington and Gibson (1986) used a comparative approach involving contemporary estate plans of several areas in the Scottish Highlands and Lowlands. The authors focused their comparisons on place names and the depiction of agricultural lands, enclosure and settlements. They found regular discrepancies between the ‘Protracted Copy’, the ‘Fair Copy’ of the Roy map – this second version was produced after the original protraction and includes more details – and the estate plans. The largest source of discrepancy highlighted by the authors seems to concern the depiction of agricultural lands. In particular, the Fair Copy was thought, sometimes, to privilege aesthetic considerations at the expense of an accurate depiction (Whittington and Gibson, 1986). In addition, this copy occasionally indicates considerably more arable lands than on the estate plans (Whittington and Gibson, 1986).

Unfortunately, Whittington and Gibson (1986) have little to say about the reliability of the depiction of the woodland cover on the Roy map. As stressed by the authors (p.13), any study such as theirs is limited by the small number of contemporary estate plans usually available. In addition, many estates were likely to be depleted in woodland by the time of the survey. In the study area, a comparative approach was only made possible between the Roy map (1752-1755) – only one version exists for Southern Scotland (Whittington and Gibson, 1986, p.12) – and estate plans produced one or two decades later. Some examples of differences regarding the woodland cover between the Roy map and the estate plans are presented in Figure 4.6.

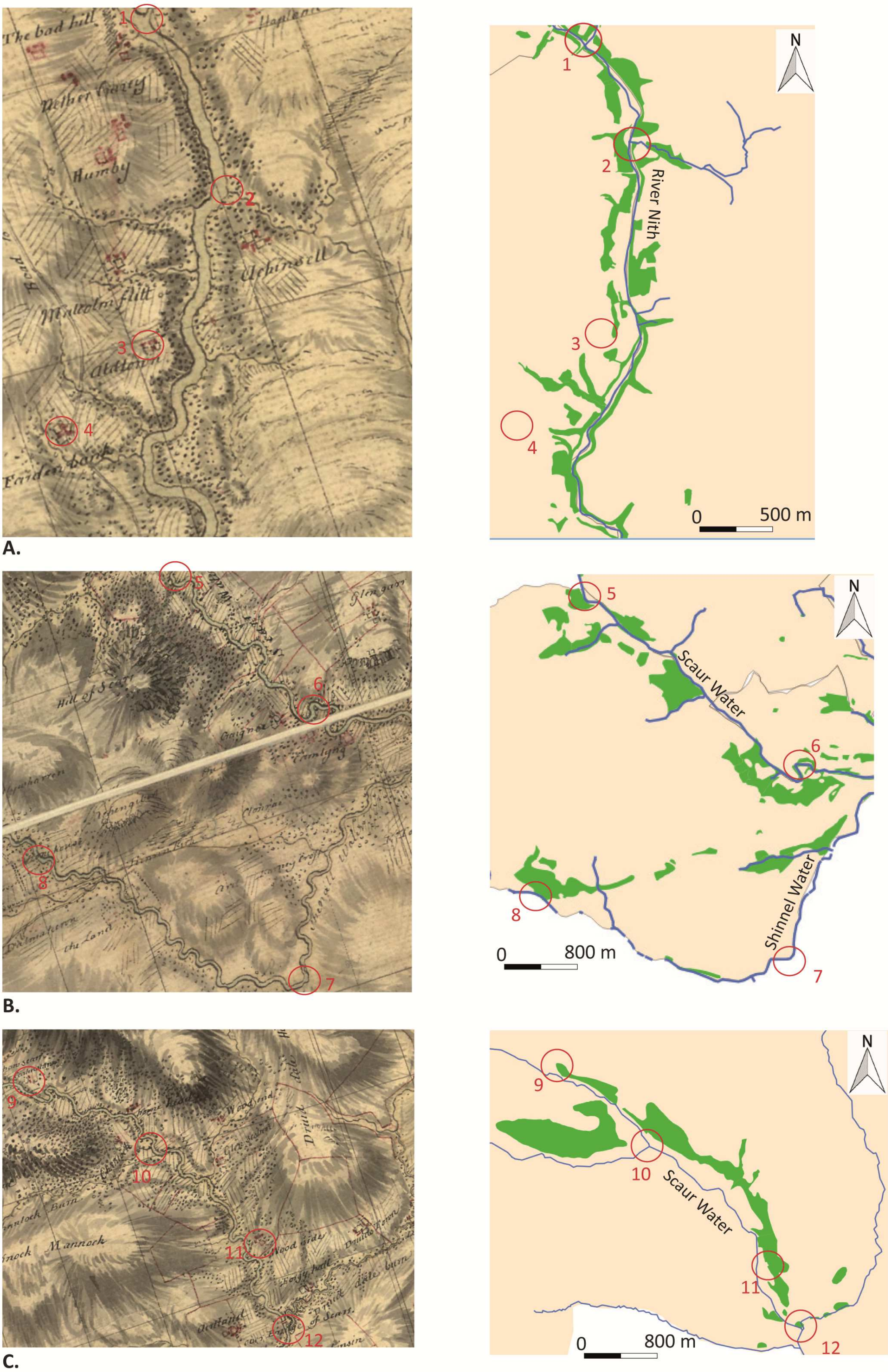


Figure 4.6 Comparison between the Roy map (left) and the woodland cover as depicted on eighteenth century estate plans (right) (legend and explanations after the second part).

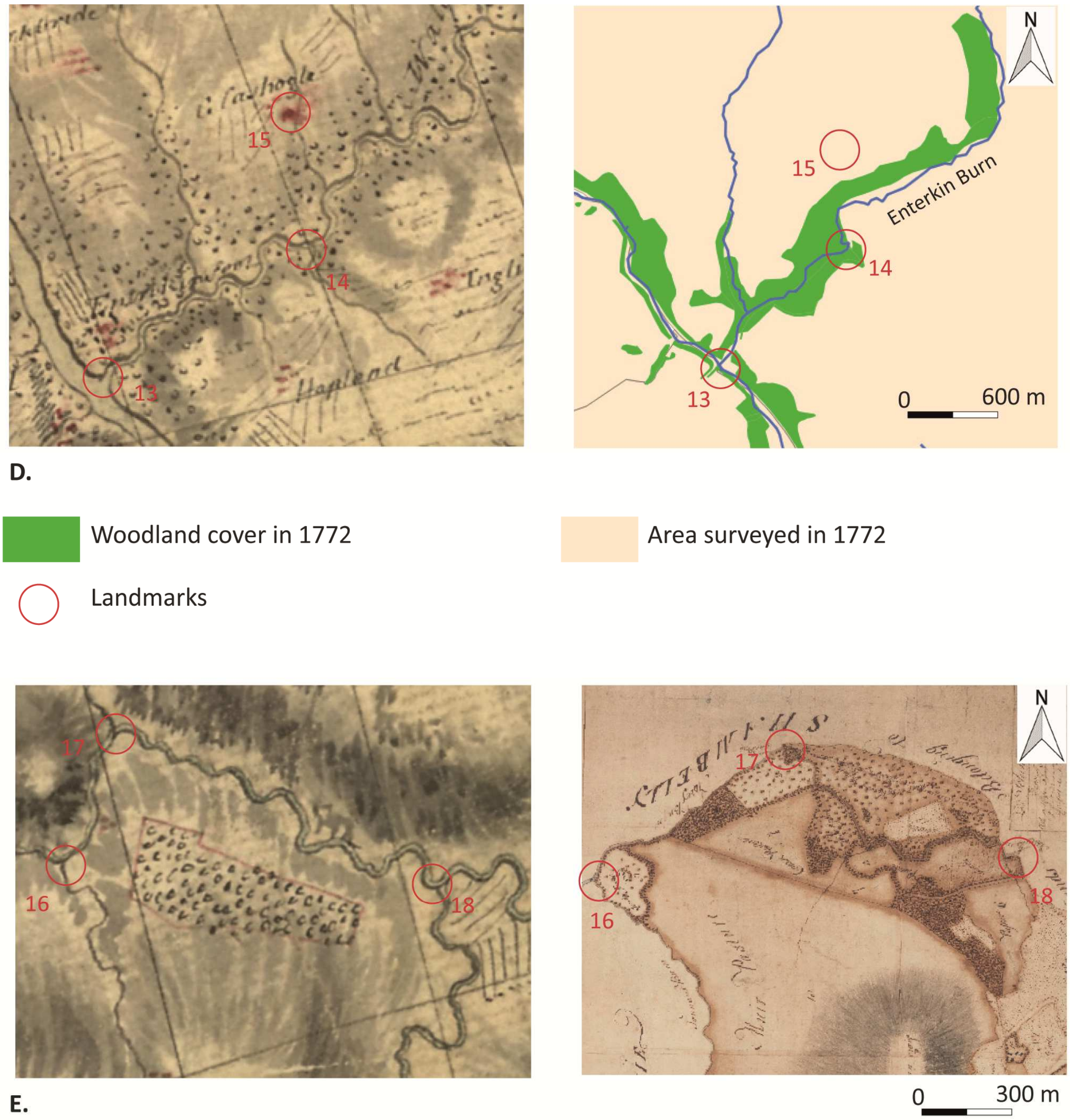


Figure 4.6 /continued Comparison between the Roy map and the woodland cover as depicted on eighteenth century estate plans. From **A.** to **D.**, the comparison is done using the woodland cover reconstructed from estate plans by J. Leslie dated 1772. In **E.** the comparison is done with an extract from an estate plan dated 1759 (Farm of Glen by John Tait). Courtesy of the NLS for the different subsets of the Roy map.

Along the River Nith, from Drumlanrig castle to Sanquhar, a continuous and thick band of woodland is depicted on the Roy map as is partly illustrated Figure 4.6A. This representation contrasts clearly with the relatively patchy woodland cover as depicted on the more detailed estate plans from 1772 and produced before enclosure. The same discrepancy applies along other watercourses such as Scaur Water and Shinnel Water (Figure 4.6B and C).

More local examples tend to confirm the observation that, in several instances, the Roy map might exaggerate the area covered with woodland. Part of Coshogle wood was mapped in 1763 by James Wells and the whole woodland was mapped again in 1772 by James Leslie. While the two estate surveyors show that the woodland area located south of Enterkin Burn was mostly unwooded pasture (Figure 4.6D), the Roy map depicts indifferently both sides of the burn as covered with woodland.

It seems unlikely that so much woodland could have been lost in one or two decades on Drumlanrig estates. Other evidence supports this contention. Three pre-Military Survey plans cover areas of Drumlanrig estates along the River Nith. Produced in the 1740's by a surveyor named Vernon, these plans seem considerably less detailed. They could not be georeferenced with the same level of accuracy as other estate plans and, therefore, they were left out for the woodland cover reconstructions. However, it is noteworthy that they show relatively little woodland. If the woodland cover on these plans is reliable, they certainly do not support the possibility that the woodland cover decreased so substantially between c.1750 and 1772.

A comparison was also possible between the Roy map and an estate plan from 1759 by John Tait covering the 'farm of Glen', along the New Abbey Pow (Figure 4.6E). The results of the comparison contrast with previous observations. In this instance, while the estate survey was done less than eight years after the Military Survey, the Roy map shows considerably lower tree cover, omitting much woodland and open woodland. This observation suggests that the representation of the woodland cover in this area is inaccurate. More generally, this example shows also that the depiction does not seem consistent across the study area. Unfortunately, for the rest of the study area, the lack of contemporary estate plans, the discontinuous coverage and the low amount of woodland during the eighteenth century restricted even more the possibility of pursuing a comparative approach.

The small scale of the Roy map could partly account for the inaccurate depiction of the woodland cover compared to that in estate plans. General Roy himself stated that the survey is "a magnificent military sketch, [rather] than a very accurate map of the country" (Roy, 1785, p.387). It is also noteworthy that the Military Survey was achieved with surveying instruments such as the circumferentor, which is considered of lower accuracy (Whittington and Gibson, 1986, p.11; Fleet et al., 2011). According to Whittington and Gibson (1986, p.11), this choice denotes the will by General Roy and his survey teams to favour speed, and certainly economy, at the expense of higher accuracy. This compromise is easily understood considering that most of Scotland was to be mapped in only a few years. The challenge to survey steep and rough areas – such as riversides – may have also increased the influence of time constraints on the final quality of the survey.

Other considerations such as the aesthetic value of the Roy map and the rather unclear symbology may further account for some of the discrepancies between the Roy map and estate plans. Do the black dots drawn on the map represent dense tree cover only? Are bushes, open woodland – or other area covered with scattered trees – represented in a similar manner? As the surveying books used by the military surveyors have disappeared (Whittington and Gibson, 1986, p.11), it remains challenging to interpret the woodland related features represented on the map.

Most importantly for this study, it is not possible to identify the boundaries of the woodland and to georeference the Roy map with accuracy. Therefore, a comparison of the latter with the highly detailed and accurate First Edition OS might have led to some confusion about the temporal continuity of several woods. This issue might account for the incorrect inclusion of many recent woodland sites into the Scottish Ancient Woodland Inventory.

4.6.1.4 Implications for the study of the Scottish woodland history

Based on estimates derived from the Roy map, Smout et al. (2005, p.388) assumed that the woodland area covered about 9% of the Scottish landscape by the mid-eighteenth century. However, the estimates calculated in Chapter 3 indicated that the coverage was close to 3% by T1. Therefore, it seems clear that Smout et al.'s estimates do not apply to Nithsdale and Annandale.

The present chapter introduces additional elements that suggest that, beyond the boundaries of the study area, Smout et al. (2005) might have overestimated the woodland cover from c.1750. Indeed, Smout et al.'s estimates are based on the assumption that the Roy map might have overlooked half of the woodland cover (2005, pp.61-64). Conversely, in the study area, it has been shown that this map might, overall, exaggerate the woodland extent. Added woodland that never existed in a military map was initially considered as unlikely by the authors because 'the surveyors would have found this irresponsible' (Smout et al., 2005, p.61). Indeed, it is intriguing that a map with military purposes did not depict woodland cover with great care given the strategic character of this feature. However, as underlined by Whittington and Gibson (1986, p.9), the initial objectives of the map might have been changed as the risk of another Jacobite rising was fading, which was the case by the time this part of Scotland was surveyed.

Thus far, it is not possible to conclude whether the Roy map tends either to under- or over-estimate the amount of woodland in Scotland. Discrepancies in the depiction of the land-cover between the Protracted Copy and Fair Copy in North Scotland have already been highlighted (Whittington and Gibson, 1986). Differences in consistency in the depiction of woodland cover may well exist between and within the Scottish Highlands and Lowlands. In any case, observations from the study area indicate that the generalisation that the Roy map overlooks much of the woodland cover cannot be extended to the study area, at least.

In addition, Smout et al.'s (2005) estimates relied on figures provided by the AWI (2005, pp.61-62). The authors accepted the assumption that the woodlands of category 2a are ancient – based on their shape and characters – and that these sites might have been overlooked in the Roy map (Smout et al., 2005). On the contrary, this present study has shown, in the study area at least, that the AWI was highly inaccurate in including much woodland that is post-1750. This inaccuracy concerns particularly the woodland of category 2a.

4.6.2 Plant species composition in woodlands with different habitat continuities

The assessment of the AWI indicates that the latter seems largely to overestimate the extent of ancient woodland in the study area. As the mapping of ancient woodland is not accurate, it is legitimate to ask if this finding has a broader impact on the study of ancient woodland. The inaccuracy of the AWI suggests that any study investigating the effects of continuity on the woodland ecological properties might need to find other evidence of continuity.

Recent research has suggested that ancient woodlands can be partly identified through distinctive plant communities and particularly the occurrence of vascular plant species indicative of longer continuity (AWP species) (Peterken and Game, 1984; Rose, 1999; Hermy, 2015). These plants are believed to be an efficient tool for identifying ancient woodland sites where there is a lack of historical sources (Hermy et al., 1999; Wright and Rotherham, 2011; Rotherham, 2011; Schmidt et al., 2014). The reconstruction of past woodland cover and changes from very detailed historical estate maps offered an excellent opportunity to test whether the study area‘s woodlands of different continuity classes display distinct plant communities.

4.6.2.1 Assessment of the indicator species of ancient woodland in the study area

Regarding AWP species, the results of the vegetation survey indicate that: 1) the frequency of occurrence of nine species was statistically significantly higher ($p < 0.05$) in probable ancient woodland (class A) than woodland plantations from the eighteenth century or later (classes B and C); 2) only wild garlic (*Allium ursinum*) and bush vetch (*Vicia sepium)* occurring in at least three sites are associated exclusively with class A sites. Most species that occurred significantly more often in sites of class A remained relatively common in recent woodland plantations (e.g. dog’s mercury was found in 21% of class B and C sites); and 3) many well-known indicator species of Scottish ancient woodland listed by Crawford (2009) are common in non-ancient woodland sites. For instance, yellow pimpernel (*Lysimachia nemorum*), wood sorrel (*Oxalis acetosella*), bluebell (*Hyacinthoides non-scripta*) and enchanter's-nightshade (*Circaea lutetiana*) were identified in 58% to 83% of the non-ancient woodland sites.

As already discussed by several authors (Rose, 1999; Crawford, 2009; Rotherham, 2011), AWP species cannot be used individually to identify ancient woodlands as, most likely, none of these species grow exclusively in ancient woodland habitats. For that matter, it has been instead suggested that the score of AWP species per woodland should be considered (Rose, 1999; Crawford, 2009). While the species richness in this study does not vary significantly between the different continuity classes of woodland, there are indeed statistically significantly more AWP species in probable ancient woodland than in the woodland plantations. Moreover, most of the 'rare' species known as AWP (occurrence < 2) are found in class A sites.

Nonetheless these observations should be tempered by the consideration that eight class B sites (of 18 sites, i.e. 44%) display more than 10 AWP species and up to 14 AWP species. These sites have more AWP species than between about 25% and 35% of the study area's ancient woodland sites. These results suggest that no clear distinction can be systematically made between ancient and non-ancient woodland based on AWP species. Even though ancient woodland sites are more likely to provide habitats to a larger number of AWP species, it seems that using them as an evidence to identify woodland with longer continuity is prone to a relatively high risk of errors. On the other hand, these results indicate that recent woodland can have high ecological value in providing habitats to many valuable species known to be associated with ancient woodland.

The nature and score of AWP species are also inherent to various factors that are not necessarily related to continuity. Soil properties, and particularly pH, are particularly known to influence greatly the number of AWP species (Crawford, 2009; Rotherham, 2011). The list of indicator species that serves as reference is obviously another point to consider. As this list is known to differ from a region to another, and to an unknown extent, the score of AWP cannot be compared between regions and used uniformly in Scotland. For a given region, identifying indicator species of ancient woodland to draw up an efficient list is, in itself, challenging. Such task requires the survey of a considerable number of woodland for which the continuity is well established. As we have seen through the assessment of the AWI, it seems unlikely, in Scotland, that the ready-made AWI can be used efficiently for that purpose. When the time comes to draw up a list, clear criteria to include a species are needed. Using a large list may be equivalent to compare species richness instead of focusing on the characters that are thought to make the diversity of ancient woodland sites unique. A list that is too short increases the risk to lend too much importance to individual species that are not confined to ancient woodland. In the latter case, the identification of ancient woodland would rely on a very few evidence only.

When evaluating if a site is ancient, several authors have also stressed the fact that the size of woodland should be considered along with the score of AWP species (Crawford, 2009; Rotherham, 2011). Indeed, more AWP species are expected to be found in large ancient woodland sites. But what boundaries are we considering? In the study area, the woodland cover is often composed of juxtaposed stands of different continuity classes (Chapter 3 and Chapter 4). Is category 'ancient woodland' only the area covered by an 'ancient core'? Are later plantations surrounding the ancient cores included in the same category? This consideration reflects a practical issue to the approach of considering woodland size to determine if a wood is rich in AWP species as the size may vary considerably depending on the boundaries that are considered. Moreover, the ancient boundaries are challenging to determine without accurate historical mapping such as estate plans.

4.6.2.2 The probable role of the local landscape context in the present-day distribution of ancient woodland indicator species

In the present study, it is noticeable that most 'recent woodland' sites have experienced a continuity of 100 to 250 years. The results of this study may indicate that this lapse of time was sufficient for many non-ancient woodland sites to acquire characters attributed to ancient woodland. This hypothesis was partly verified by the fact that the sites of class B or C located near ancient woodland sites seem to be particularly rich in AWP species. It is likely that ancient woodland sites have served as 'reservoir' from which these species have colonised more recent woodland (as known from studies such as Brunet and Von Oheimb, 1998). Therefore, the local landscape context could be proven very important to explain the occurrence of AWP species in more recent woodland and make the identification of ancient woodland sites even more challenging.

Although less rich in AWP species, a very recent plantation (< 50 years, 'Pin3') juxtaposed to probable ancient woodland was covered with well-known AWP species, such as wood speedwell (*Veronica montana*), barren strawberry (*Potentilla sterilis*), yellow pimpernel (*Lysimachia nemorum*) and dog's mercury (*Mercurialis perennis*). This observation suggests that these species may have been able to move rapidly to colonise this plantation – probably 100 to 150 m in less than 50 years to reach the plot if they colonised directly from the nearest ancient woodland. Likewise, planted between 1772 and 1820, three woodland sites (i.e. 'Cle1', 'Cle3' and 'Cle4') displayed 10, 13 and 14 AWP species, respectively, making them very similar to the probable ancient woodland located within less than 500 m ('Cle2', 14 AWP species). These sites are categorised erroneously as 'ancient' in the AWI but these errors would be difficult to notice based on vegetation surveys. In general, the strong similarities in plant assemblage that occasionally exist between woodland sites of different continuity but relatively close to each other should lead us to the conclusion that the inaccuracy of the AWI can remain un-noticed in the field.

Despite the considerations above regarding the importance of the connectivity between recent and ancient woodlands, the occurrence of 8 AWP species in one small (< 4ha) and rather isolated plantation established between 1820 and 1860 remains intriguing (site 'Sch'). This site contained species such as wood sorrel (*Oxalis acetosella*), dog's mercury (*Mercurialis perennis*), water avens (*Geum rivale*) and pignut (*Conopodium majus*). Other landscape elements may have served as refuges for these AWP species before they colonised this site. For instance, ditches and hedges have been pointed out by Barnes and Williamson (2015) as areas where some AWP species can survive outside woodland; scattered trees and bushes in pasture could also provide more habitats (Wulf, 2004). A detailed study of life-history traits of these plants (e.g. Hermy et al., 1999;

Bellemare et al., 2002; Wulf, 2003) could help to understand in further detail the distribution patterns of AWP species in recent woodland and the mechanisms that have operated to conclude on the potential of each species to colonise woodland according to different ecological and non-ecological factors.

4.6.2.3 The role of past land-use and present-day environmental conditions on plant species composition

The results of the DCA indicate that there is no clear distinction in plant assemblage between sites of different continuity classes. In addition, the grouping on the DCA ordination of probable ancient woodland sites along the first DCA axis seem to relate more to the fact that these sites are distinct from woodland with higher level of ground wetness. Indeed after removing the 10 sites categorised as 'Wet woodland' (NWSS, 2014), the position of probable ancient woodland do not indicate anymore difference between probable ancient and recent woodlands. Moreover, the plant composition of probable ancient woodland sites categorised as 'Wet woodland' is more similar to recent 'Wet woodlands' than the other probable ancient woodland sites. In sum, it seems that the wetness gradient of the ground may be responsible for blurring further the distinction between ancient and recent woodland. Unsurprisingly, soil pH was also very important to structure plant communities (as discussed, for instance, by Crawford, 2009; and Rotherham, 2011).

Different considerations may account for the fact that the plant composition does not differ significantly between woodland sites of different continuity classes. Firstly, a chief issue is the challenge to ascertain that the woodlands in class A are indeed ancient woodland and not eighteenth century plantations that were not acknowledged as such on estate plans. It is, therefore, possible that a few sites considered as 'probable ancient' may be post-1750. However, in all cases the woodland sites of class A have longer continuity than woodland sites of classes B and C. Moreover, this uncertainty does not call into question the high occurrence of ancient woodland indicator species in several recent woodland sites.

Secondly, although all the sites that were surveyed are currently native woodland, it is not possible to determine whether this had always been the case or if substantial historical changes affected the dominant habitats at some point of their history. It is likely that some present-day native woodland sites were mixed or coniferous woodland when they were recorded on historical plans. Such changes may have affected the environmental conditions on the long-term and influenced the current botanical characteristics of these sites. On that matter, it is noteworthy that coniferous trees, although very scarce, were recorded in 16 woodland sites, including 5 sites of class A (see Appendix E). This observation indicates that these probable ancient woodland sites underwent the plantation of non-native tree species in their recent history. Likewise, 18 woodland sites, including 3 sites of class A, were depicted as mixed woodland on the First Edition OS 25-inch to the mile maps. Unfortunately, as these maps do not cover a large part the study area, it was not possible to determine how the fact that a site was broadleaved, coniferous or mixed in c.1860 has contributed to structure its present-day floristic composition.

Therefore, old past land cover and land use, not always identifiable from estate plans, may explain the differences within and between the different continuity classes. The case of Lochwood (SSSI) can support this idea. Covered with pollard trees over 400 years old, this site is known to be a former wood pasture partly converted into mixed woodland in its recent history (SNH, 2008). The woodland history of this SSSI may account for the fact that it contains a plant community that is very distinct from all the other ancient woodland sites. It is also noteworthy that despite its very long continuity, Lochwood does not display a particularly rich community of AWP species, with 12 species (the median for class A sites was 13 species). Intensive historical grazing and/or unsuitable light conditions – the canopy has remained relatively open – may account for the absence of woodland specialist species that fit to shaded conditions and that are vulnerable to grazing. In sum, as past management may overrule the effect of continuity, it seems relevant to integrate woodland history as much as possible when considering continuity.

Thirdly, in previous studies comparing the vegetation between ancient and recent woodland, the recent woodland sites were mostly secondary woodlands established on former arable lands (e.g. Bellemare et al., 2002; Flinn and Vellend, 2005; Sciama et al., 2009). The effect of former agricultural land-use may have long-term persistence on soil properties (Bellemare et al., 2002; Flinn and Vellend, 2005). Changes in soil properties may favour the establishment of competitive species while hampering the establishment of several woodland specialist species (Honnay et al., 1998; De Keersmaeker et al., 2004; Flinn and Vellend, 2005; Fraterrigo et al., 2006). Thus, a high degree of soil disturbance, as expected on former arable lands, can alter the flora and lead recent woodlands to have distinct plant communities from ancient woodlands (Flinn and Vellend, 2005). In contrast, almost the totality of the woodland plantations surveyed in the present study was established on former pasture; only one site (i.e. 'Ecc') was on former cropland. Former pasture is likely to have a lower impact than former arable lands on soil properties (Koerner et al., 1997; Wulf, 2004). A study by Koerner et al. (1997) already showed stronger similarities in soil properties and vegetation between woodland with longer continuity and more recent woodland on former pasture. Furthermore, in the Prignitz (Germany), Wulf (2004) showed that recent woodland sites developing on former grasslands display a larger number of woodland species than those developing on former arable lands. The author discusses how some woodland species such as *Anemone nemorosa* and *Carex remota* – recognised as AWP species in Scotland (Crawford, 2009) – can survive in niches in pastures and meadows. In summary, the different historical land uses of recent woodland sites may explain why the distinction between ancient and recent woodland seems to be much more evident in other studies, for which afforestation occurred mostly on arable lands, than in the present one. This consideration should lead us to reiterate Rotherham's hypothesis (2011) that indicator species may actually grow preferentially on soils with historically lower disturbance. If this assumption is proven true, then the concept of indicator species may be less relevant in areas where recent woodland has mostly grown on former pasture.

It is noteworthy that in the case of 'Rah2' – a site of class B with 10 AWP species –, a further 4 AWP species including dog's mercury (*Mercurialis perennis*), wood anemone (*Anemone nemorosa*), pignut (*Conopodium majus*) and yellow pimpernel (*Lysimachia nemorum*) have been identified only at the edge of the woodland. As they were not inside the woodland, their occurrence was not considered for this site. However, it would be of interest to understand why these species have not established themselves inside the woodland. Is this evidence of recruitment limitation or do these species only need more time to move into the woodland? Repeated observations of this kind and long-time monitoring may help to address questions related to the ability of plant species to colonise new woodland over time and the role of present-day ecological conditions.

4.6.3 Final considerations

The present study shows that: 1) the Ancient Woodland Inventory is largely inaccurate; 2) as such, the inventory cannot identify the historical boundaries of ancient woodlands that have been dynamic over the last centuries; and 3) the plant communities of ancient woodland sites – particularly the species known as AWP species – are not systematically distinct from those of recent woodland. As a result, these observations should question our understanding and definition of ancient woodland as a distinct category. A similar statement was made by Stone and Williamson (2013) and subsequently Barnes and Williamson (2015, pp.157-158) from studies in Norfolk (England).

However, rather than undermining the ecological importance of woodland with longer continuity, this study points out the ecological value of woodlands not currently included in the 'ancient woodland' category. Therefore, the present results should not be understood as a pretext to dismiss conservation measures applied to woodland sites with longer continuity. On the contrary, these measures seem worth being extended to a larger woodland area than the woodland currently defined as 'ancient'.

Adopting a more recent threshold date or integrating any native woodland adjacent or located in the surrounding area of ancient woodland are different options to consider. They are supported by a few motives: 1) the relevance of extending the conservation status to some recent woodland of classes B and C is suggested by the ecological value of several of these sites that is regularly as high as those of ancient woodland. Although these sites are not ancient, most of them have already experienced a relatively long-history (> 100-150 years), a lapse of time that was sufficient for many plant species to establish themselves in these woodlands; 2) this study revealed that the boundaries of probable ancient woodland sites cannot be identified accurately from the Roy map or the First Edition OS maps. This issue has already led the AWI to integrate much woodland that is not ancient according to the official definition for Scotland; 3) the 'cut-off' date to define ancient woodland is, in any case, arbitrary and there is no consistency between countries, nor any known threshold that marks particular changes in woodland ecological features. This date varies from 1600 (England and Wales, Goldberg et al., 2007), to c.1775 in Belgium (Honnay et al., 1998), c.1780 in Germany (Wulf, 2003) or early nineteenth century in France (Dupouey et al., 2002b). A threshold date that is later than 1750 could be more convenient as based on more reliable historical sources and criteria. On the other hand, a later cut-off date could undermine the importance of identifying and protecting in priority woodland sites with the longest continuity, if the latter are indeed of considerably higher ecological value.

The fact that the AWI integrates much recent woodland is perhaps not an issue for conservation measures. However, it seems certain that it can affect any research study that relies on this inventory to investigate the ecological differences between ancient woodland and more recent woodland sites. In the past, this inaccuracy may have led to incorrectly consider several plant species as indicator species of ancient woodland (although some of these species may be indeed associated with relatively longer continuity). In turn, the occurrence of many AWP species in 'pseudo-AW' may lead to a circular problem where it becomes difficult to disentangle what species are indicators of ancient woodland and what woodland is ancient. *In fine*, widespread errors in the inventory could lead research studies to undermine the real importance of woodland continuity. Naming the AWI 'provisional' may not be enough to warn researchers and other woodland experts of the pitfall of using this inventory as reference for antiquity. No final inventory – i.e. exempt of error – is likely to be released in the future.

As the aim of the field survey was to determine if distinct flora can be perceived between woodlands of different continuity classes, the present work did not tackle other field evidence that can indicate if a wood is ancient. This evidence is often associated with the cultural value of ancient woodland that enhances the importance of these sites. For instance, in England, archaeological features, such as walls and banks, can provide additional evidence of ancient woodland (Glaves et al., 2009b, Rotherham, 2011). While the relevance of this approach can be efficient, these features are unfortunately not always apparent and can be also misleading (Stone and Williamson, 2013: Barnes and Williamson, 2015). The occurrence of veteran trees and old coppice trees are other factors to consider (Glaves et al., 2009b; Rotherham, 2011) but, once again, this evidence is not irrefutable to indicate long continuity. Veteran trees can precede the establishment of woodland and, in the present study, coppice trees were found in nine recent woodland sites (i.e. 38%) (Appendix E).

4.7 Conclusion

In the study area, the present chapter shows that a large area of woodland identified as 'ancient' in the Scottish Ancient Woodland Inventory (AWI) might be plantations from the late eighteenth to mid-nineteenth century. The inaccuracy of the AWI seems to concern to a greater extent the ancient woodland identified exclusively from the First Edition OS maps (i.e. category 2a). Estimates were produced while considering the uncertainty associated with the planimetric accuracy of estate plans. In addition, the AWI classification seems to consider ancient woodlands as stable features and overlooks the complexity of woodlands' differing historical trajectories. For instance, it does not take into consideration the woodland plantations adjacent to ancient woodland that frequently occurred between c.1750 and 1860 (Chapter 3).

Overall, the logistic regression models of past woodland cover developed in Chapter 3 do not allow an accurate identification of the 'pseudo-ancient woodland' in the AWI. However, these models remain able to distinguish better than randomly the pseudo-AW from the probable ancient woodland using a probabilistic approach. The pseudo-AW sites can be identified based on their environmental characters that contrast with ancient or probable ancient woodland (e.g. higher elevation, lower slope steepness and further away from streams).

It appears that the substantial discrepancy between the AWI and the evidence of the woodland continuity provided by estate plans result in part from the inaccuracy of the Roy map. Examples of comparison with estate plans indicated that the sheets covering Nithsdale and Annandale might, overall, exaggerate the amount of woodland cover. This observation contrasts with the current belief that, on the contrary, the Roy map tends to overlook a large amount of woodland. Used in conjunction with the very accurate First Edition OS maps, the raw depiction of the woodland cover on the Roy map might have led to an overestimate of the amount of ancient woodland for the Scottish AWI – the 'Great Map' was convenient to use for the AWI as it covers the whole Scotland. Therefore, it is likely that the lessons from the cartographic assessment of the AWI and the Roy map can be applied outside the study area. In addition, the inaccuracy and inconsistency of the Roy map as stressed in this Chapter should prompt caution in using this historical source to study woodland history in Scotland.

The vegetation survey of 41 woodland sites shows that probable ancient woodlands identified from estate plans are likely to exhibit more plant species associated with ancient woodland. Nonetheless, a large number of recent woodlands should be also recognised for their high ecological value as their vegetation can share much similarity with those of ancient woodlands. In addition, the regular occurrence of many ancient woodland indicator species in non-ancient woodland habitats highlights the risk of incorrectly recognising recent woodland sites as 'ancient' without other evidence of antiquity. In that regard, the use of the AWI to identify ancient woodland sites can bring additional misleading evidence. Ultimately, these errors can impact the accuracy of studies that aim to investigate the effect of habitats continuity in the ecology of woodland.

Through several cases studies, historical estate plans proved to be a unique and valuable complementary resource for ecological studies of woodland habitats. These detailed cartographic records can help to investigate the ecological importance of woodland continuity with regards to other biological and non-biological factors and to understand the distribution patterns of plant species. This chapter demonstrates how rapidly several plants known as indicator species of ancient woodland are able to establish themselves in new woodlands and, thus, to contribute to blurring the distinction between ancient and recent woodland habitats. Estate plans can help further to assess how past land-use and landscape context may contribute to shape the ecological characteristics of present-day woodland. A better understanding of these mechanisms is crucial in adopting suitable strategies to conserve habitats of high ecological value inside and outside ancient woodlands.

Chapter 5

Conclusion

5.1 Introduction

Historical maps have been used in various countries for investigating past changes in woodland cover and for assessing their long-lasting implications (e.g. Wilson, 2005; De Keersmaeker et al., 2014, 2015; Bergès et al., 2016; Loran et al., 2016). They have also helped to identify ancient woodland sites for woodland conservation purposes (Goldberg et al., 2007) and to better understand the ecological importance of woodland continuity (e.g. Wulf, 2003; Schmidt et al., 2014). In Scotland, the earliest detailed topographic maps covering large parts of the country, namely the Roy map (c.1750) and the county maps, do not have the level of detail, accuracy and reliability of the First Edition OS maps (c.1860) (Chapters 1, 2 and 4). The potential of these small-scale pre-OS maps is therefore limited to providing evidence of the woodland cover global extent and character prior to c.1860. Consequently, little is known about the environmental legacy of relatively recent changes and the history of the ancient woodland sites compiled in the Scottish Ancient Woodland Inventory – an important tool for woodland conservation (Goldberg et al., 2007).

The integration of estate plans in a GIS was found to be efficient means to address this gap and to provide a unique time perspective concerning past woodland cover distribution, character and changes. At first sight, it appeared challenging to combine the information of hundreds of plans varying in form, dates of production, and by different mapmakers. Nonetheless, the consistency in the depiction, accuracy and reliability of estate plans enabled spatially explicit reconstructions of the woodland cover extent for two time series prior to c.1860. These reconstructions were possible using 352 estate plans covering a total of 107,700 ha in the historic counties of Dumfriesshire and Kirkcudbrightshire.

In addition, this PhD has demonstrated how the careful study of historical estate plans can provide detailed spatio-temporal evidence of the changes that have occurred since the mid-eighteenth century. Hence, this study has highlighted how the present-day woodland cover has progressively emerged from past human actions, including deforestation, plantation and management practices. In addition, historical written archives offered a complementary insight into the spatial analyses concerning historical tree composition and some of the processes that led to changes in past woodland cover.

As well as throwing new light on the woodland history of these last 200-250 years in the study area, this interdisciplinary PhD research has provided valuable information for the conservation of present-day woodland. In particular, this study revealed, and quantified to what extent, the Scottish Ancient Woodland Inventory is inaccurate. By extension, it examined the reliability of the historical cartographic sources that acted as the basis for the Scottish Ancient Woodland Inventory, and thus proceeded to a critical assessment of the methods to compile ancient woodland sites. Furthermore, the higher planimetric accuracy of estate plans compared to other contemporary cartographic sources enabled the accurate identification of case study sites for comparison of the plant communities between probable ancient woodland and later plantations (i.e. 'recent woodland'). The results question our perception of ancient woodland as areas definable in the landscape and as a category of distinctive ecological character. In doing so, this study challenges in many ways the different criteria that are currently considered as essential to defining 'ancient woodland'.

By reassessing our current belief concerning past woodland cover extent and changes and by questioning our perception of ancient woodland, the implications of this research are assumed to extend beyond the boundaries of the study area. This work also highlights the considerable value of estate plans for studies that aim to reconstruct and investigate past landscape changes at historical periods when cartographic evidence was scarce or considerably less detailed.

This concluding chapter summarises the key findings for each of the aims laid out in Chapter 1, namely: 1) reconstructing historical woodland cover in the study area at different time periods from the second half of the eighteenth century; 2) characterising the long-term changes in woodland and assessing their legacy on the distribution and characteristics of present-day woodland; and 3) proceeding to a critical assessment of the criteria to define ancient woodland as a distinct ecological category and identifying the implications for conservation planning. In addition, this chapter presents potential research directions and the wider contribution to research.

5.2 Key findings

Aim 1. *Reconstructing historical woodland cover in the study area at different time periods from the second half of the eighteenth century*

Based on the study of 352 estate plans, the GIS-method presented in Chapter 2 allowed the spatially explicit reconstruction of the woodland cover for two time series, namely T1 (1740-1799) and T2 (1801-1833). The woodland reconstructions for each time series do not represent a snapshot of the woodland cover at a single point in time; they are a composite of data compiled from estate plans drawn at different dates. As such, the woodland cover reconstructions for T1 and T2 are dominated by data prior to c.1775 and after c.1815, respectively. Altogether, the estate plans cover a total area of about 107,700 ha in Dumfries and Galloway and the two time series cover a common area of 41,980 ha. The range of information provided by the plans concerning woodland cover was recorded into the GIS geospatial database for each site and categorised afterwards into woodland vegetation classes and management types.

The conceptual framework by Leyk et al. (2005) allowed uncertainties to be identified and assessed. These uncertainties are associated with the challenge of working on a large number and variety of plans (i.e. production-oriented uncertainty, transformation-oriented uncertainty and application-oriented uncertainty). Uncertainties occurred at different points from the estate plans production to their practical use for research on woodland cover changes. Such assessment was necessary: 1) to determine the accuracy and reliability of the reconstructions; 2) to explore the comparability of data extracted from estate plans, First Edition OS maps (i.e. T3, c.1860) and the modern woodland inventories; and 3) to integrate and mitigate these uncertainties while addressing the different research objectives.

While being faithful to the surveyors' original work, the reconstruction methods were efficient in compensating for or mitigating deformations and inaccuracies at several stages of the process, including land survey, map production, storage, digitisation and vectorisation of the plans. The planimetric accuracy of the woodland reconstructions for T1 and T2 – the median of the Root Mean Square Error (RMSE) was 17 and 11 m, respectively – seemed appropriate for a comparison with the First Edition OS plans (i.e. T3, c.1860) and modern data (i.e. T4, 2014). While the mapmakers used a relatively similar range of scales, a better understanding of their conventions to depict and name woodland enhanced the comparability of the plans. The possibility to compare the woodland reconstructions for T1 and T2 with the woodland cover in T3 and T4 enabled the study of past changes with a very detailed spatio-temporal resolution. The study of woodland trajectories and the calculation of the perimeter-area ratio (PAR) on the trajectory patches confirmed the global consistency, and thus the reliability, of the depiction of woodland cover between the different time series.

Some uncertainties remained. In most cases, there was insufficient information concerning woodland to categorise woodland data into vegetation classes and management types; the plantations were, for instance, not always acknowledged as such. In addition, the study of the plans revealed occasional ambiguity (e.g. meaning of 'bushy wood' and 'natural woodland') and vagueness in the depiction of the woodland (e.g. 'woodland' and 'bushes' could not be always distinguished). Despite these uncertainties, the level of reliability and accuracy of the estate plans, and thus the woodland reconstructions, proved to be sufficient to investigate the long-term changes in woodland cover.

DAMP's (*Dumfries Archival Mapping Project*) contribution was essential in providing access to privately-owned estate plans that had been unavailable to researchers. The success of this collaboration illustrates the considerable benefit to be derived from working closely with local community groups.

Aim 2. *Characterising the long-term changes in woodland and assessing their legacy on the distribution and characteristics of present-day woodland*

The results of the quantitative analysis showed a marked and consistent growth in woodland cover during the eighteenth and nineteenth centuries. While the woodland covered about 3% of the study area in T1, it increased to 4.5% in T2, and to between 6.5 and 8.5% in T3. When considering the evidence of plantation provided by the estate surveyors, it was possible to determine that the lowest coverage in the study area occurred, at the latest, sometime in the mid-eighteenth century with a generous estimate of 2.5% of woodland coverage. However, it is not possible to determine to what extent the results of the quantitative study in the study area apply to the rest of Scotland.

The results of the woodland metrics, change detection analysis and trajectory analysis brought further insights into the long-term woodland dynamics. The increase of the woodland cover took place through the occurrence of small clustered woodland patches alongside some plantations of much larger sizes. Despite the expansion of the woodland cover and occasional large plantations, the mean size of the woodland sites declined over time and their compactness decreased. In addition, the net gain of woodland hides important relative – or 'gross' – woodland loss over the eighteenth and nineteenth centuries. These woodland dynamics of loss and gain (i.e. absolute changes) accelerated during the first half of the nineteenth century. A consequence is that a maximum of only 21% of ancient woodland of semi-natural origins was estimated extant by c.1860 in the area covered by eighteenth century estate plans (Area 2, section 3.3.2). These results underline how the present-day woodland cover has been progressively shaped by plantations and clearance at different spatio-temporal rates.

The trajectory analysis enabled the tracking, mapping and categorising of the various historical trajectories of present-day broadleaved woodland since the eighteenth century. An important outcome was to show that this woodland can be composed of several juxtaposed sections of woodland stands of different ages. Consequently, some probable ancient woodland cores are now integrated into a matrix of relatively recent woodland plantations. Strong ecological implications can therefore be expected from this change in woodland connectivity on the spread of woodland species. Landscape context and history could partly explain the distribution patterns of vascular plant species on the field as discussed for aim 3.

The modelling approach using binary logistic regression allowed a better understanding of past woodland distribution and changes in relation to landscape physical contexts, thereby revealing the importance of several drivers (i.e. explanatory variables). Slope steepness, elevation and distance to the nearest streams were found to be dominant over time and for a large part of the study area. In addition, the results provide an insight into the effects of aspect of the slope and soil conditions – even though the importance of both variables differed according to the estates and the period of study. Contrasting observations over time and space within the study area might reflect both different environmental constraints and varying practices in establishing woodland. The woodland expansion between T1 and T2 took place near pre-existing woodland in T1, while the patterns of woodland expansion seem to have radically changed from the first half of the nineteenth century. During that period, the woodland expansion no longer tended to occur near pre-existing woodland and previous drivers failed to explain the patterns of this expansion. It is noteworthy that the closer proximity with ancient woodland of the eighteenth and early nineteenth century woodland may have enhanced their current ecological value compared to later plantations. The woodland species may have been able to colonise more easily the early plantations, located near ancient woodland, than the later plantations, on higher elevations and more isolated from pre-existing woodland cover (see aim 3).

Using the models of past woodland distribution for T1, it was possible to produce spatially explicit probability maps of past woodland cover that were adapted according to the region of study. These models should be considered as exploratory methods and can be improved after integrating other variables of importance to explain past woodland cover (e.g. distance to the roads, population, local needs, etc.). The possibility of producing spatially explicit probability maps remains relevant to locating: 1) areas where the models do not explain accurately past woodland distribution – and that can, in turn, help to improve the models; 2) the very early plantations not identified as such on the estate plans; and 3) the woodland listed in the Ancient Woodland Inventory which are the most likely to be plantations rather than ancient woodland (see aim 3).

Unfortunately, despite a few exceptions, the estate plans did not provide much evidence concerning the woodland tree species composition. A consequence is that changes in tree composition, when they occurred, cannot be identified from estate plans. The First Edition OS and other historical sources including the Statistical Accounts of Scotland (1791-1845) proved useful in partly overcoming this limitation. The different sources confirmed that plantations of mixed woodland formed a large part of the woodland cover by the late eighteenth century in the study area. In addition, variations in the species planted occurred between estates according to local preferences.

A better understanding of past practices for planting woodland is particularly relevant as plantations of non-native tree species do not necessary support the same biodiversity as native woodland (Brockerhoff, 2008; Pedley et al., 2014; Wilson, 2015). In sum, historical references contributed to understanding how present-day woodland character may have progressively emerged from past human management. In addition, these documents provided further information regarding the reasons that encouraged planting woodland and the interest of practices such as mixing broadleaved and coniferous. Evidence from archives also indicated that the temporal resolution of the mapping reconstruction from estate plans may still underestimate the magnitude of past woodland changes (see Muller and Carruthers, 2017, Appendix D). Finally, while highlighting past changes, this study provided fresh opportunities to examine some of the long-lasting ecological implications on present-day woodland ecosystems.

Aim 3. *A critical assessment of the criteria to define ancient woodland as a distinct ecological category and implications for conservation planning*

The long woodland continuity and distinct ecological characteristics are important criteria for the recognition of ancient woodland sites and their integration in conservation planning (Goldberg et al., 2007). Through a better assessment of woodland history in the study area (aim 2) this research sheds new light on the history of the sites compiled in the Scottish Ancient Woodland Inventory (AWI). It has also challenged the idea that these sites can be recognised based on their plant assemblage. Ultimately, this study calls into question the recognition of ancient woodland as a distinct category and proves to have relevant implications for woodland conservation.

Assessing the Scottish Ancient Woodland Inventory

A large area of woodland recognised as ‘ancient’ in the Scottish AWI was not wooded during the first time series (T1, 1740-1799) or even the second time series (T2, 1801-1833). This woodland being not recorded on estate plans is likely to be of more recent origin than expected. The amount of ‘pseudo-ancient woodland’ (pseudo-AW) was found to reach at least 40% of the woodland compiled in the AWI for the area covered by eighteenth century plans. The identification of ‘ancient woodland’ based on the interpretation of the First Edition OS maps only (category 2a) appears less reliable than the interpretation based on the Roy map (category 1a). Nonetheless, at least 30% of the ancient woodland identified from the Roy map was also found to be pseudo-AW. These results can be explained by the relatively low level of reliability and accuracy of the Roy map as illustrated by local comparisons with estate plans.

This study questions the methodology used to draw up the Scottish AWI. By showing that the largest inaccuracy concerns the woodland of category 2a, this research does not support the current assumption that has led to all the native woodland depicted on the First Edition OS maps being considered as 'ancient' (Kupiec, 1997). By extension, it seems wrong to consider that the woodland of category 2a was more likely to be overlooked during the Roy mapping, despite the inaccuracy of the latter (Kupiec, 1997). Moreover, as the boundaries of the woodland cover changed between c.1750 and c.1860 on account of the numerous plantations and clearances that occurred during that period (aim 2), it seems inaccurate today to define the boundaries of ancient woodland based on those depicted on the First Edition OS maps. The Roy map lacking in detail and being partly unreliable, it appears difficult to identify the exact boundaries of the ancient woodland using either the Roy map and/or First Edition OS maps.

In sum, while ancient woodland is part of a matrix of woodland plantations of different continuity (aim 2), it appears that the AWI incorrectly considers these sites as stable features in the landscape. It is also noteworthy that historical management practices such as the trend of planting mixed woodland may have led to substantial changes in the woodland composition and structure of ancient woodland sites. They are additional reasons that should lead us to dismiss the perception of ancient woodland sites as stable features over time.

The logistic regression models developed in Chapter 3 (and discussed for aim 2) proved to be able to distinguish better than randomly the pseudo-AW from the probable ancient woodland. This probabilistic approach takes advantage of the fact that the environmental characters of many pseudo-AW sites (e.g. elevation, slope steepness and distance from streams) seem to contrast with ancient or probable ancient woodland. In the future, this approach may be proved useful to identify more accurately true ancient woodland sites for research studies or conservation purposes where historical evidence is missing.

Assessing the importance of woodland continuity on plant communities

Eighteenth century estate plans are unique for identifying case study sites to determine whether ancient woodland sites are ecologically distinct from 'recent woodland'. Contrary to the Roy map and First Edition OS maps, these plans provide a better idea of the real boundaries of ancient woodland, thereby allowing the categorisation of woodland sites into different continuity classes for ecological studies (e.g. probable ancient woodland, eighteenth century plantations, and late nineteenth century plantations).

The botanical survey of 41 native woodland sites of different continuity classes led to the identification of 149 vascular plant species. The sites could be identified from the trajectory analysis (see aim 2). Although probable ancient woodlands are likely to exhibit more plant species associated with ancient woodland (AWP species), several recent woodland sites are very similar in plant community to those of ancient woodlands. For instance, up to 14 AWP species and 12 AWP species were found in pre- and post-First Edition OS plantations, respectively. The occurrence of many of these species in non-ancient woodland habitats highlights how rapidly they can actually establish themselves in recent woodlands. These species include some of those regularly reported as ancient woodland indicators such as dog's mercury (*Mercurialis perennis*), wood anemone (*Anemone nemorosa*), pignut (*Conopodium majus*), wood sorrel (*Oxalis acetosella*), bluebell (*Hyacinthoides non-scripta*), wild strawberry (*Fragaria vesca*) and yellow pimpernel (*Lysimachia nemorum*) (listed as AWP species in Scotland by Crawford, 2009). This ability to thrive in recent woodlands contributes to blurring the distinction between woodland habitats of different continuities. Moreover, the differences in plant assemblages observed between woodland sites could result less from continuity than distinct environmental conditions such as soil's wetness and acidity, levels of grazing, tree composition and the woodland structure inherited from past management.

As the eighteenth and nineteenth century's woodland plantations seem to have grown mostly on former pasture, it is possible that the historically lower disturbance of these soils (e.g. lack of plowing) did not preclude the recruitment process of AWP species. These conditions contrast to other studies for which recent woodland occurred on former arable lands (e.g. Bellemare et al., 2002; Flinn and Vellend, 2005; Sciama et al., 2009). In addition, the dispersal of AWP species may have been enhanced by local context such as good connectivity between ancient and recent woodland as illustrated by the proximity of late eighteenth or early nineteenth centuries plantations to ancient woodland (see aim 2) – the ancient woodland acting as reservoir of species to recent plantations (e.g. Brunet and Von Oheimb, 1998; Barnes and Williamson, 2015). Some of the AWP species recorded in recent woodland may have also spread from non-woodland refuge areas (e.g. ditches and hedges) where environmental conditions – for instance, relatively humid, shaded, and low grazing – would have already provided suitable habitats for these species long before tree plantations occurred (Wulf, 2004; Barnes and Williamson, 2015). In any case, this study has shown that several AWP species have established themselves in recent woodland more rapidly than previously claimed. The strong similarities in plant communities between woodland sites of different continuities suggest also that the inaccuracy of the AWI might remain un-noticed in the field. In addition, these results demonstrate that ancient woodland sites are not alone in providing habitats to valuable species.

To summarise, this study shows that: 1) the AWI is largely inaccurate; 2) the AWI cannot identify the historical boundaries of ancient woodlands; and 3) the plant communities of ancient woodland sites – in particular ancient woodland indicator species – are not systematically distinct from those of recent woodland. These observations should not only challenge our understanding and definition of ancient woodland as a distinct category, they also suggest that depending on the landscape context (i.e. connectivity to ancient woodland but also presence of hedges and ditches as refuge areas), environmental conditions (e.g. pH, wetness) and woodland history (e.g. past land-use, past management), relatively recent plantations could deserve the same recognition as ancient woodland for conservation. In other words, with respect to vascular plants, it can be worth extending conservation interest to a larger woodland area than to ancient woodland. As this study focuses on vascular plants only, further research based on estate plans and considering other taxonomic groups (i.e. invertebrates, lichens, bryophytes, mammals, etc.) can also prove relevant to provide more inclusive guidance for woodland conservation.

5.3 Potential research directions

Since the end of data collection for this project, DAMP has already been able to collate hundreds of supplementary historical estate plans that should considerably extend the historical mapping coverage in Scotland. The availability of these plans increases the horizon of possibilities. The most important task would be to extend the region of study and proceed to a similar pattern of analyses in order to assess to what extent the current results can apply to the rest of Scotland. Moreover, while this research does not cover in detail the period after c.1860, similar analyses for the period c.1860-2014 to those undertaken here could also enhance our understanding of the most recent changes, their causes and consequences. Finally, the findings of this PhD can serve as a basis for potential research directions that can be considered for historical and ecological perspectives. Some of them are introduced in this section.

5.3.1 Factors that influence the accuracy of the historical woodland cover reconstructions

It is likely that imprecisions are introduced at each stage of the reconstruction, including data collection by estate surveyors, plans' drawing, storage, digitisation, georeferencing and vectorisation. In a Master's study (MSc), Bates tried to determine the influence of several factors on the accuracy of georeferenced estate plans – particularly the digitising method, the distance surveyed by the surveyor and height (Bates, 2014). While the study by Bates (2014) was constrained by the limited number of estate plans available, the very large set collated during this PhD offers more opportunities for extensive investigation. Such assessment can be relevant for various reasons such as improving practices of storage, digitisation methods and data integration into GIS. The latter involves improving the mosaicking of estate plans for local georeferencing and choosing the most adequate transformation. In addition, identifying where the plans are perhaps less accurate (e.g. steep slope, lands on higher elevation or along the water network) could help in better assessing the quality of the woodland reconstructions – planimetric accuracy and reliability – depending on the landscape properties. For instance, Bates (2014) on pre-OS estate plans and Loran et al. (2016) on the Siegfried Map (nineteenth century, Switzerland) found that historical maps' accuracy tends to decrease as the slope increases. Integrating how the planimetric accuracy of the historical woodland cover reconstruction varies over space can serve to identify with better precision what site is ‘ancient’ or ‘pseudo-ancient’ woodland during the process of comparison with the Ancient Woodland Inventory.

Chapter 2 discusses the limitations of using the RMSE as an indicator of the reconstructions’ planimetric accuracy. The availability of many plans would allow testing and implementing other metrics that better reflect this characterisation. The mean absolute error that gives a similar weight to each control point’s residual error (Chai and Draxler, 2014) can be considered first to supplement the RMSE. Another metric of interest to implement would give higher weight to control point’s residual error near any area of particular interest – such as woodland – and also penalise georeferencing based on few or unevenly distributed control points.

5.3.2 Historical drivers of past woodland cover and changes

The logistic regression methods were presented as exploratory to understand some of the drivers of past woodland cover distribution and changes (aim 2). These models can also help in better identifying present day woodland sites that are likely to be early plantation – when evidence from eighteenth century estate plans is missing – and ‘pseudo ancient-woodland’ sites in the Scottish Ancient Woodland Inventory (aim 3). The models could be improved in testing other explanatory variables that may be of interest, including topographic wetness index (Beven and Kirkby, 1979), wind indices (Boehner and Antonic, 2009) or solar radiation (Hofierka and Suri, 2002). In addition, a larger study area – as now possible from the new estate plans digitised by DAMP – would allow assessing more accurately the performance, and thus relevance, of the models when applied to other regions of study.

Assessing in more detail non-biophysical drivers can be also relevant. For instance, Loran et al. (2017) used a modelling approach including socio-economic factors such as population size, farms and cattle data census to better understand the forest expansion in Switzerland since 1850. For this research, wood-demanding industries, population, and distance to the nearest roads are some of the drivers that may have contributed to determine the location and amount of woodland plantations. Although some of this data remains more challenging to collect from historical maps or archives – in particular for the first time series (T1, 1740-1799) – some valuable information such as population census is available in the Statistical Accounts of Scotland (1791-1845). Integrating this data could be a first step to assessing local needs in wood and better calibrating the different models which, thus far, tend to overestimate the amount of woodland.

Finally, the results from Chapter 3 indicate that despite net woodland gain over time, a substantial amount of woodland was lost between each time series. The logistic regression models could be used to identify where the woodland disappeared from, into what land-cover/land-use type the former woodland was converted, and thus reveal some of the drivers that led to these changes.

5.3.3 Abilities of the so-called 'ancient woodland indicator species' to colonise recent woodland and processes

Further research is needed to assess the role of the different factors that are likely to shape the plant distribution patterns. These factors can be difficult to disentangle and are closely related. Notably, they may include the landscape context, past land-cover/land-use, current woodland structure, soil chemistry and the level of grazing in each woodland site (Chapter 4); it is noteworthy that the Native Woodland Survey of Scotland already provides information on the latter (NWSS, 2014). A comprehensive assessment of these factors would enhance our understanding of the processes that made the plant's dispersal and recruitment effective and, thus, contribute to better designing conservation strategies.

Firstly, it would be of interest to systematically identify the former land-cover/land-use where the eighteenth and nineteenth century plantations have grown. As discussed in Chapter 4, past land-cover/land-use influences the level of historical disturbance of the soils that, in turn, might enhance or hamper the recruitment of plant species (Honnay et al., 1998; De Keersmaeker et al., 2004; Flinn and Vellend, 2005; Fraterrigo et al., 2006). They may have also provided environmental niches where woodland plant species can survive outside woodlands (Wulf, 2004; Barnes and Williamson, 2015). The vectorisation of the whole land-cover/land-use from historical estate plans is therefore recommended. It is notable that such data can also be of interest for landscape historians aiming to study long-term landscape changes, besides woodland cover.

Secondly, the study of *plant functional traits* can be undertaken from the plant surveys carried out for this research. These traits can be morphological, physiological and phenological features (Pérez-Harguindeguy et al., 2013). Notably, they determine plants' ecological strategies, response to environmental constraints and their influence on ecosystem properties (Pérez-Harguindeguy et al., 2013). Several studies have shown interest in plant traits in order to determine if the plants associated with ancient woodland share biological characteristics that determine their colonisation capacities (i.e. dispersal and recruitment) (e.g. Verheyen et al., 2003; Hermy and Verheyen, 2007; Kimberley et al., 2013). In the UK, Kimberley et al. (2013) demonstrated that several traits associated with AWP species reflect poor dispersal capabilities (i.e. short, perennial species and a high seed weight). Plant traits can thus be relevant to understanding how some of the AWP species have successfully established themselves in recent woodland of the study area – in some cases in less than 100 years, as shown in Chapter 4 – and to determine whether these plants can survive in refuge areas outside woodland. Plant traits can also reflect the plant response to environmental disturbances such as historical land-use and grazing pressure (Diaz et al, 1999; Verheyen et al., 2003). In sum, an in-depth study of the traits of the plant species identified in the study area could highlight some of the conditions and processes that did or did not make the dispersal and recruitment effective. In addition, this approach can provide a better understanding of the potential resilience of woodland to future disturbances (Kimberley et al., 2013).

As well as providing an insight into the remnant influence of historical land-use on woodland ecosystems in different historical and environmental contexts, such a study can provide valuable information for diverse woodland sites, including degree of vulnerability, potential of woodland species to spread, and potential for restoration. This information could be integrated into management and conservation programs.

5.3.4 Identifying potential areas suitable for native woodland expansion

The Scottish Government encourages the expansion of native woodland and the development of the forest habitat networks to mitigate habitats fragmentation (Forestry Commission, 2009b; Wilson, 2015). This measure aims to enhance the movement of species to increase the resilience of population and alleviate the impact of future disturbances such as climate change (Forestry Commission, 2009b). In this regard, woodland models can assist in identifying the potential suitable areas for planting new woodland and enhancing natural regeneration (SNH, 2004; Forestry Commission, 2009b; Gkaraveli et al., 2004). In Wales, Gkaraveli et al. (2004) established a methodology to determine priority areas in Snowdonia National Park after having weighed different ecological criteria and including distance to the nearest ancient woodland. Using a related modelling approach, the Forestry Commission Scotland (2009b) has also implemented *potential native woodland network* maps to guide the woodland expansion. While including climatic and soil information, this model gives priority to areas adjacent to existing ancient and native woodland (i.e. ‘core area’). The identification of a network of ‘potential expansion zones’ aims to improve the ecological connection to core areas and thus allows the expansion of species known as ‘slow’ and ‘moderate’ colonisers. The model also encourages *ex nihilo* the creation of new woodland where the native cover is low (Forestry Commission, 2009b).

Lessons learned from this PhD and future research can considerably improve the identification of the most suitable areas for the expansion of native woodland. This PhD shows that past woodland cover reconstructions from estate plans can help in identifying more accurately than the Scottish Ancient Woodland Inventory what sites are likely to be ancient semi-natural woodland (ASNW) and plantation on ancient woodland sites (PAWS). In using these reconstructions, it should be possible to better target potential suitable areas for native woodland expansion, namely the areas adjacent to ‘true’ ASNW and the PAWS for conversion into native woodland. Furthermore, current models could integrate valuable historical data from estate plans such as past land-use. The latter can be crucial as it may have a long-lasting influence on the ability of species to colonise new woodland (Koerner et al., 1997; Honnay et al., 1998; Flinn and Vellend, 2005; Fraterrigo et al., 2006; Plue et al. 2008; Fichtner et al., 2014). For instance, priority could be given to former pastures over former arable lands (Chapter 4; see also Wulf, 2004). Finally, current models could integrate the location of past woodland cover. The latter can be important if residual populations of lost woodland could survive in the landscape. Woodland specialist species who found refuge in diverse elements of the landscape (e.g. ditches, edges) near lost woodland could spread again to the newly created native woodland (Barnes and Williamson, 2015).

5.4 Contribution to research

This PhD research provides new information that adds to a wider-knowledge base. Firstly, to the author’s knowledge, this study is the first that assesses the spatio-temporal comparability of estate plans at the landscape scale. In doing so, the results highlight the potential of combining hundreds of estate plans into a GIS to reconstruct past landscape and investigate historical changes at periods of time when little evidence is available.

Secondly, while acknowledging the different domains of uncertainties related to the use of estate plans, the GIS-based methodology includes valuable suggestions to georeferencing estate plans, integrating their historical cartographic data into a homogeneous database and studying landscape changes using a range of complementary geospatial analyses. This approach can serve as a basis in the future to integrating data from the hundreds of estate plans that have been recently copied by DAMP and covering other regions of Scotland. Apart from woodland, this approach can also apply to studies focusing on other aspects of the historical landscape and wishing to take advantage of the invaluable source of information provided by estate plans. Such studies can be of interest for different research areas such as landscape history, archaeology and ecology.

Thirdly, some key findings improve considerably our understanding of past woodland cover and changes prior to the First Edition OS maps. Interestingly, the estimates of the woodland cover are considerably lower for the study area than those by Smout et al. (2005) for Scotland. They also differ from the assumption that the minimum coverage in Scotland occurred in the early twentieth century and that the woodland cover experienced little change over the nineteenth century (Smout et al., 2005). Moreover, it appears here that a small portion of ancient woodland was extant by c.1860 (i.e. less than 21%), which contrasts with the current assumption that at least 50% of the woodland cover in Scotland was semi-natural ancient woodland (Anderson, 1967; Pryor and Smith, 2002; Smout et al., 2005).

Although it is not yet possible to determine to what extent the trends observed in the study area apply to the rest of Scotland, this PhD casts doubt on the methods and assumptions that may have led previous research to overestimate the amount of past woodland cover for the whole Scotland. For instance, this research has demonstrated how the Roy map can largely overestimate the amount of woodland, and not only omit some sites as found previously for other areas of Scotland (e.g. see

Smout et al., 2005). The lack of consistency in the depiction of the woodland cover by Roy's surveyors should therefore preclude any extrapolation based on local observations as has been done in the past. This research also shows that the First Edition OS maps may depict a more comprehensive woodland cover than argued previously. Moreover, in demonstrating that the current methodology to draw up the Scottish AWI suffers from various inaccuracies and uncertainties, the present research shows that this inventory should not be considered as a reliable source to study woodland history.

Finally, this research reveals how estate plans can provide unique case studies for research projects that examine the importance of woodland continuity and that aim to better understand the distribution patterns of woodland species. More particularly, the identification of case study sites from estate plans can clarify the potential of using ancient woodland indicator species to identify ancient woodland sites and, if needed, refine the local lists. It can also help in examining the ability of woodland species to colonise new woodland and investigating in greater detail the ecological importance of local landscape context and past land-use. In sum, further interdisciplinary research projects linking history and ecology are needed to provide adequate guidance for woodland conservation.

Appendices

Appendix A – List of historical estate plans

Surveyor(s)	Title	Date	Note	Source	Reference
Black, John	Plan of the lands of Ach'nfranka, Whiteyard, Slacks and Moatt lying in the Parish of Lochrooton and Stewarty of Kirkcudbright belonging to James Guthrie	1758		NLS	Acc.7883/8/53
Brown, J	Plan of the estate of Auchenfranka in the Parish of Lochrutton and Stewarty of Kirkcudbright	1814		NLS	Acc.7883/8/47
Cowan, Samuel	Plan of the estate of Maxwelton, belonging to Sir Robert Laurie. (Vignette of bridge over Cairn Water)	1814		NRS	RHP34654
Cowan, Samuel	Plan of farm of Ellisland, Dumfriesshire	1817		NRS	RHP142480
Crawford, William	Plan of part of the Barony of Tinwald	1817		NLS	Acc.14419/1
Crawford, William	Plan of the Estate of Dalswinton	1817		NLS	Signet.s.53
Crawford, William	Plan of the parish of Morton	1820		Private	RHP37502
Crawford, William	Reduced sketch plan of the lands of Penfillan, the property of the Duke of Buccleuch,	1825		Private	RHP37853
Crawford, William	Plan of the farms of Barndinnoch, Fardingjames, Kirkbride and Breco, with key to contents.	1825		Private	RHP37720
Crawford, William	Plan of farms of Porterstown, Penmurtie and Beuchan	1825		Private	RHP37693
Crawford, William	Plan of the lands of Cunningholm, belonging to the Duke of Buccleuch	1825		Private	RHP37863
Crawford, William	Plan of the parish of Sanquhar, the property of the Duke of Buccleuch and Queensberry, with key to contents.	1831		Private	RHP37807
Crawford, William	Plan of the parish of Durisdeer	1820-1825		Private	RHP37667
Crawford, William	Plan of the farms of Templand, Blawplain, and Morton Holm.	1825?		Private	RHP37518
Crawford, William and David	Plans of Part of the Barony of Tinwald, Dumfriesshire	1812		NRS	RHP114
Crawford, William and David	Plan of the Barony of Mousewald	1812		NRS	RHP113
Crawford, William and David	Plan of the estates of Carthat and Rockhallhead, Lochmaben, Dumfriesshire	1812		NRS	RHP115
Crawford, William and David	Plan of farms belonging to the Duke of Buccleuch, including Drumlanrig Castle	1820		Private	RHP37542

Surveyor(s)	Title	Date	Note	Source	Reference
Dunbar, William	Plan of the Estate of Hills in the Parish of Lochrutton and Stewarty of Kirkcudbright	1775		Private	-
Dunbar, William	Plan of the Fir Wood at New Abby belonging to William Stewart Esquire of Shambelly	1787		Dumfries Museum	-
Forrest, William	Plan of the estate of Netherwood, Dumfriesshire	1806		NRS	RHP3592/1
Jardine, James	A plan of the Estate of Crawfordtown	1806	With later additions	Ewart Library	-
Jardine, James	A plan of Newton-Aird	1807		Dumfries Museum	-
Jardine, James	Plan of Breken-Side	1808		Dumfries Museum	-
Jardine, James	Plan of Pennyland - part of the Estate of Dalswinton belonging to P. Miller Esqr	1809		Private	-
Jardine, James	Plan of Cress-Well lying in the parish of Dumfries belonging to R. Jardine Esqr	1809		Ewart Library	-
Ker, Henry	Plan of the lands of Auchenhaestnene	1820		Private	RHP37647
Lauder, John and Udny, Joseph	Plan of farms in the parishes of Johnstone, Kirkpatrick-Juxta and Dumfries	c.1790		Private	RHP10054
Leslie, (James?)	Plans of the Southside of the Barony of Sanquhar	1764-1766	24 plans	Private	RHP 38137
Leslie, (John or Hamilton)	Plan of the farms of Craigbeck and Crofthead	1768		Private	RHP37546
Leslie, Hamilton	Plan of the Estate of Eliock	1767		Private	-
Leslie, Hamilton	Plan of Blaze (Bleise) Commonty under process of division, with scheme of division	1768	Reduction plan (Udny)	Private	RHP83389/7
Leslie, Hamilton	Plan of Wamphray Muir Common, with scheme of division	1768	Reduction plan (Udny)	Private	RHP83389/8
Leslie, Hamilton	Plan of Commonty of Dundorran, with scheme of division	1768	Reduction plan (Udny)	Private	RHP83389/9
Leslie, James	Plans of the Barony of Drumlanrig, Vol.1, Durisdeer	1772	48 plans	Private	RHP38134
Leslie, James	Plans of the Barony of Drumlanrig, Vol.2, Penpont, Tynron and Keir	1772	51 plans	Private	RHP38135
Leslie, James	Plans of the Barony of Drumlanrig, Vol.3, Morton and Closeburn	1772	40 plans	Private	RHP38136
Leslie, John	Plan of part of the grounds belonging to the Duke of Queensberry.	1765		Private	RHP37753
Lewars, John	Plan of the Lands of Midglen	1795		Private	-
Lewars, John	Plan Of The Farm Of New Mains Of Tinwald, Dumfriesshire	1799		NRS	RHP30
Lewars, John	Plan of the estate of Eccles, belonging to John Bushby Maitland, with key to contents	1801		Private	RHP37840
Lewars, John	Plan of Craig	1814		Private	RHP92617
Lewars, John	Plan of Little Auchenfad	1814		Private	RHP92612
Lewars, John	Plan of Martingarth	1814		Private	RHP92616

Surveyor(s)	Title	Date	Note	Source	Reference
Lewars, John	Plan of Woodside	1814		Private	RHP92618
Lewars, John	Plan of Gibbonhill	1814		Private	RHP92622
Lewars, John	Plan of Airds	1814		Private	RHP92624
Lewars, John	Plan of Whitehill	1814		Private	RHP92615
Lewars, John	Plan of Loshes and Cat Aik	1814		Private	RHP92613
Lewars, John	Plan of Kirkconnell Flow	1814		Private	RHP92621
Lewars, John	Plan of Meikle Auchenfad	1814		Private	RHP92611
Lewars, John	Plan of Mill hill	1814		Private	RHP92614
Lewars, John	Plan of the farm of Kirkland of Kirkmichael, Dumfriesshire	1814		NRS	RHP216
Lewars, John	Plan of Kirkconnell Mains	1814	Photocopy by NRS	NRS	RHP92620
Lewars, John	Plan of Maxwellbank	1814	Photocopy by NRS	NRS	RHP92623
Lewars, John / Wells, James	Plan of the farm of Whinnyhill [Copied by Lewars from survey by Wells]	1791		Private	RHP92625
McCartney, William	Volume of maps of the several Farms in the Estate of Dalswinton	1768	14 plans	Private	-
McCartney, William	A plan of the Lands of Airds	1782		Private	RHP92609
McCartney, William	A plan of the lands of Blackwood	1783		Private	-
McCartney, William	A plan of the Lands of Barbech	1784		Dumfries Museum	-
McCartney, William	Plan of farm of Ellisland, Dumfriesshire	1787		NRS	RHP142479
McCartney, William	Plan of Auldgirth (Draft version)	18th century (1783?)		Private	-
McCartney, William- Bell, John	Plan of the Estate of Killylung, Dumfriesshire [Copy by Bell - original by McCartney]	1787		NRS	RHP323/2
Morrison, John	A plan of the lands of Blackwood. The property of W. Copland Esqr of Collistoun	1804		Private	-
Morrison, John	A plan of the lands of Clauchries Cairns and Aulgirths. The property of W. Copland Esqr of Collistoun	1804		Private	-
Morrison, John	Youngfield, the property of G. Young Esq	1819		Ewart Library	-
Mounsey, William	Plan of estate of Terregles, the property of Marmaduke Constable Maxwell. (Vignette of [Terregles House] and ruins of Lincluden (Linclouden) College)	1810		NRS	RHP30165
Mounsey, William	A Plan of the Loch Rutton Estate comprending the property in Loch Rutton and Urr parishes in the Stewarty of Kirkcudbright belonging to Marmalade Constable Maxwell	1815		NLS	Acc.7932/06
Richmond, James or Tait, John	Plan of the Park farm	1767		NRS	RHP5384
Shepherd, Alexander	Plan of the lands of Holehouse and Gardenholm	1767		Private	RHP10096

Surveyor(s)	Title	Date	Note	Source	Reference
Shepherd, Alexander	Plan of Bearholm, Milton, Murthat and Palaceknowe	1767		Private	RHP10094
Shepherd, Alexander	Plan of Stiddrigs (Stidrigs) and Banks, Upper and Nether Plewlands, Park and Haig, North and South Borland, Inglestone (Inglestoun) and Barntimpen, with table of contents: [late 18th century]	Late 18th		Private	RHP8338/4
Stitt, H	Plan of Brooklands	1822		Dumfries Museum	-
Stitt, H	Plan of the lands of Strathmilligan	1825		Private	RHP37578
Stitt, H	Plan of Crairiepark, Eliock estate, Dumfriesshire	1833		NRS	RHP141259
Tait, James	Plan of fifteen merkland and town of Moffat	1759	Reduction plan (Udny, 1778)	Private	RHP83387/8
Tait, James	Plan of farms on part of the estate of Annandale	1759		Private	RHP10091
Tait, James	Plan of farms of Akieknow and Tathknow, with table of contents	1759	Reduction plan (Udny)	Private	RHP83389/1
Tait, James	Plan of the common of Moffat	1760		NLS	MS.27850
Tait, James	Plan of farms of Raecleugh, Ericstane (Erriocstane), Greenhill, Auldhousehill, Meikle Holmside, Blacklaw, Holehouse, Gardenholm and Craiks Craig	1767	Reduction plan (Udny, 1779)	Private	RHP83387/5
Tait, James	Plan of the Cuthbertrig, part of the estate of Annandale	1771		Private	RHP10100
Tait, James	Plan of farms of Leithenhall and Laverhay together with estate of Poldean, with table of contents: 1773	1773	Reduction plan (Udny)	Private	RHP83389/3
Tait, James	Plan of farm of Kirkhill as now possessed comprehending Howgill, Cleughside and Staffenbigging with their shares of the Commonty of Blaze (Bleise), Middlerigg, Pleaknow, comprehending also the mill, mill lands and glebe of Wamphray	1773	Reduction plan (Udny)	Private	RHP83389/4
Tait, James	Lochmaben	1786		NRS	RHP13490
Tait, James	Plan [of] Castle Mains of Lochmaben, in Annandale	1788		NLS	Acc.11419 M3
Tait, James	Plan of farms of Fingland, Helbeckhill, Hazlebank, Cammock and Cacrabank with their shares of Cammock and Blaze (Bleise) Commons	1773?	Reduction plan (Udny)	Private	RHP83389/5
Tait, James	Plan of farm of Broomhill	Mid-18th		Private	RHP83391/7
Tait, John	Plan of the Lands of Auchengran	1759		Dumfries Museum	-
Tait, John	Farm of Glen	1759		Ewart Library	-
Tait, John	Plan of the farms of Shambelly, Townhead, Wanfoord, Clachruheads, and Barlay	1759		Dumfries Museum	-
Tait, John	A plan of Broomhills Common	1766		NRS	RHP5

Surveyor(s)	Title	Date	Note	Source	Reference
Tait, John	Plan of the Estate of Killylung, Dumfriesshire	1768	Damaged - half of plan is missing	NRS	RHP323/1
Tait, John	Plan of Kirkconnell Mains belonging to James Maxwell of Kirkconnell	1782		Private	RHP92603
Tait, John	Plan of Greenmerse Farm	1782		Private	RHP92604
Tait, John	Plan of the farm of Carse belonging to Charles Stewart of Shambelly	1759?	Pre-1772	Dumfries Museum	F5
Tait, John	Part of plan of farms of Bogside (Bogueside) and Miln	18th century (1759? 1782?)	Damaged.	Private	RHP92644
Tait, John	Plan of the lands of Butterwhat, Dalton, Dumfriesshire	c.1756		NRS	RHP1744
Tait, John	Plan of the farms of Corsua and Moat	c.1765		Private	RHP10024
Tait, John and Gillon, John	Plan of the farm of Kirkhill, Dalton, Dumfriesshire	c.1756		NRS	RHP1743
Tennoch, William	Plan of the farms of Carrifran, Polmoody, Capplegill, etc. on Moffat Water, Dumfrieshire	1767	Reduction plan (Udny)	Private	RHP10181
Tennoch, William	Plan of farms of Rivox, Mosshope (Mossop) and Middlegill	18th		Private	RHP83387/7
Tennoch, William	Plan of farm of Polmoody	18th		Private	RHP83387/1
Tennoch, William	Plan of farm of Capplegill and Carrifran (Carriferan)	18th		Private	RHP83387/2
Tennoch, William	Plan of the plantation on the Gallowhill and the strip on the Captain's Fauld	Late 18th		Private	RHP83387/3
Udny, Joseph	Plan of that part of Earl of Hopetoun's estate of Wamphray called the Inside of Wamphray together with adjoining farms belonging to Marquis of Annandale:	1775	Reduction plan (Udny)	Private	RHP83389/2
Udny, Joseph	Plan of Clarefoot and Archbank	1778		Private	RHP83387/4
Udny, Joseph	Plan of part of the farms of Raehills, Crunzierton and Mollens	1781		Private	RHP10032
Udny, Joseph	Plan of grounds of the farms of Mollins and Raehills	1782		Private	RHP10035
Udny, Joseph	Plan of the farm of Lochbrow	1782		Private	RHP10033
Udny, Joseph	Plan of the farms of Kinnelhall and Kinnelholm	1782		Private	RHP10036
Udny, Joseph	Plan of lands in the parish of Johnstone, Dumfriesshire	1783		Private	RHP10037
Udny, Joseph	Plan of the farms of Raehills, Crunzierton and part of Mollin	1785		Private	RHP10041
Udny, Joseph	Plan of the farm of Kinnelhead	1785		Private	RHP10108
Udny, Joseph	Plan of the upper part of the parish of Johnstone	1786		Private	RHP10047
Udny, Joseph	Plan of the under part of the parish of Kirkpatrick-Juxta lying between the River of Annan and Kinnel Water	1786		Private	RHP10109

Surveyor(s)	Title	Date	Note	Source	Reference
Udny, Joseph	Plan of South and North Boreland, Park and Haig	1786		Private	RHP10046
Udny, Joseph	Plan of the Rainrig Common, lying in the Parish of Johnstone and shire of Dumfries	1791		NLS	MS.10490 4
Udny, Joseph	Plan of Moffat Mill lands	1792		Private	RHP10168
Udny, Joseph	Plan of the House, Offices, and Policy of Raehills	1793		Private	RHP10056
Udny, Joseph	Plan of the farm of Skemrighead (Skimrighead), Millhill, Nether Cleuchbrae (Cleughbrae) and Kirkhill	1813		Private	RHP10066
Udny, Joseph	Plan of the farms of Corsua and Mote (Moat)	1813		Private	RHP10070
Udny, Joseph	Plan of the farms of Beastockrig and Righead	1813		Private	RHP10065
Udny, Joseph	Plan of the farms of Kinnelhall and Kinnelknock	1813		Private	RHP10069
Udny, Joseph	Plan of the farms of Lochbrow, Oakbank, Panlands, Chemes and Yett	1813		Private	RHP10068
Udny, Joseph	Plan of the farms of Annanbank, Roods, Auchindinnings and Over and Middle Cleuchbrae (Cleughbrae)	1813		Private	RHP10060
Udny, Joseph	Plan of the farms of Chapel, Johnstonecleuch (Cleugh), Springwells and Greigsland	1813		Private	RHP10063
Udny, Joseph	Plan of the farms of Woodend and Cleuchheads (Cleughheads)	1813		Private	RHP10062
Udny, Joseph	Plan of the farms of Williamson and Hazelbank	1813		Private	RHP10061
Udny, Joseph	Plan of Blackburn, Goodhope, Cow Park and Kinnel Water	1813		Private	RHP10064
Udny, Joseph	Plan of the farm of Kirkbank and the schoolmaster's possession and glebe	1813		Private	RHP10067
Udny, Joseph	Plan of Marchbank and Biggarts, lying in the parish of Kirkpatrick-Juxta	1813		Private	RHP10115
Udny, Joseph	Plan of the farms of Upper Murthat and [Newfarm] (the Common Farm)	1813		Private	RHP10116
Udny, Joseph	Plan of the farms of Bearholm and Milton	1813		Private	RHP10117
Udny, Joseph	Plan of the farm of Kinnelhall	1816		Private	RHP10073
Udny, Joseph	Plan of the Upper Crooks, showing the new channel of the River Annan	1820		Private	RHP10186
Udny, Joseph	Plan of the farms of Milton, Palaceknowe, Kirktown and Redbrae	1823		Private	RHP10127
Udny, Joseph	Plan of the farms of Kinnelhead and Whiteholm	1823		Private	RHP10122
Udny, Joseph	Plan of the farm of Chapel	1827		Private	RHP10128

Surveyor(s)	Title	Date	Note	Source	Reference
Udny, Joseph	Plan of the farm of Lochenhead and part of Whiteholm	1823?		Private	RHP10126
Udny, Joseph	Plan of the Lands of Cragie-Burn lyeing in the Parish of Moffat and County of Dumfries, the property of Colonel Charles Maitland of Maitlandfield.	1816		NLS	Acc.3524
Udny, Joseph ; Riddell, Richard	Plan of the Lands of Kinharvie lying in the parish of Newabbey and County of Galloway belonging to Robert Riddel	1793		NLS	Acc.7932/03
Udny, Joseph?	Plan of the Annandale estate, Moffat	1807		Private	RHP10176
Unattributed	Plan of Commonty of Cammock as now divided, with table of contents	1776	Reduction plan (Udny)	Private	RHP83389/6
Unattributed	Plan of Lawridding farm	1800		NRS	RHP140403
Unattributed	Plan of Lawridding farm	1822		NRS	RHP140404
Unattributed	Plan of estate of Netherwood	Late 18th		NRS	RHP88858
Unattributed	Plan of the Estate of Dalswinton	First half 19th		Private	-
Vernon, E	Plan of the estate of The Craigs	1740		Private	RHP37541
Vernon, E	Plan of 'Several Mealings or Tennements in Kirkconnel Parish and in the Barony of Sanquar'	1740		Private	RHP37534
Vernon, E	Plan of Morton Muir	1742		Private	RHP37533
Vernon, E	Plan of New Dalgarnock, Thornhill and The Lought	1742		Private	RHP37535
Vernon, E	Plan of the estate of Tibbers	1742		Private	RHP37537
Vernon, E	Plan of the north-west part of the estate of Tibbers	1743		Private	RHP37532
Vernon, E	Plan of Castlehill and the surrounding area	1743		Private	RHP37529
Vernon, E	Plan of Auchincell and adjacent lands	1743		Private	RHP37751
Wells, James	A particular plan of the mining liberated by the Duke of Queensberry to Messrs Crawfurds and Company of Wanlockhead.	1756		Private	RHP37555
Wells, James	Plan of the farms of Tibbers and Newhouse	1758		Private	RHP37652
Wells, James	[Plan of part of Durisdeer]	1763	Damaged - no title	Private	-
Wells, James	Plan of the estate of Eccles	1765		NRS	RHP810
Wells, James	Plan of the farms of Overholm, Blawplain (Blaplain), Cunning Holm and Kirkbog	1765		Private	RHP37717
Wells, James	A Plan of the East Side of Kirkgunzeon Barony	1774	Additions 1782 & 1805	NLS	Acc.7932/04
Wells, James	Plan and Survey of the Barony of Caerlaverock	1776		History Centre of Hull	U DDEV/75/1
Wells, James	Plans of the Commonty called Fell of Preston and parish of Kirkbean, Kirkcudbrightshire	1776		NRS	RHP13/2
Wells, James	[plan of] the estate of Amisfield the property of Charles Charteris Esqr:	1778		NLS	Acc.14419/2

Surveyor(s)	Title	Date	Note	Source	Reference
Wells, James	The Farm of Auchengieth - the property of Robt. Brown	1779		Ewart Library	-
Wells, James	The Upper College Mains of Lin cluden - The College of Lincluden and the Land adjoining which belongs to Willm Maxwell Constable Esqr - Corbelly Hill	1785	Three plans on the same item	Ewart Library	-
Wells, James	A Plan of Part of the Estate of Dalswinton	1786		Private	-
Wells, James	Plan of Kirkconnell Estate	1786		Private	RHP92606
Wells, James	Plan of Greenmerse Farm	1787		Private	RHP92605
Wells, James	Plan of Carcoside and Knockinstob	1787		Private	RHP37670
Wells, James	Plan of part of Estate of Mabie	1790	Original in two pieces	Private	RHP92601
Wells, James	Plan of Farm of Crooks	1790		Private	RHP92602
Wells, James	Plan of the farm of Airds	1791		Private	RHP92608
Wells, James	A Plan of the Barony of Lochrutton	1774-1775		NLS	Acc.7932/05
Wells, James	Part of plan of farm of Woodside	1786 or 1791	Photocopy by NRS	NRS	RHP92645
Whiteford, James	Plan of the lands of Holm	1806		Private	RHP37752
Wood, John	Plan of the Towns of Dumfries and Maxwelltown from actual survey	1819		NRS	RHP13044/12

Appendix B – Extract of the woodland cover reconstruction for the south part of the study area

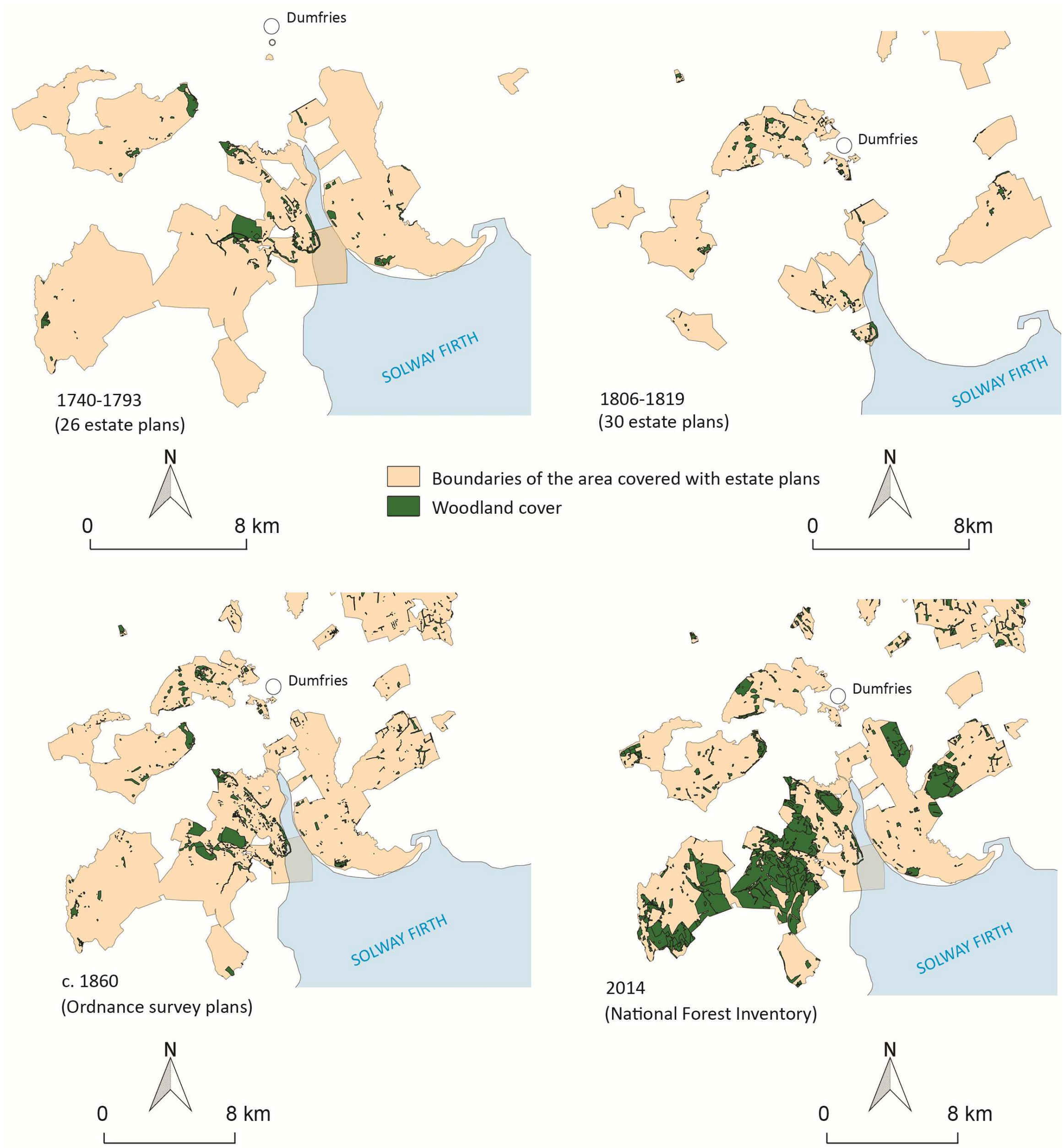


Figure B1. Woodland cover reconstruction for 1740-1793, 1806-1819, c. 1860 and 2014 in part of the parishes of New Abbey, Kirkgunzeon, Terregles, Dumfries, Caerlaverock and Tinwald. Data for 2014 are extracted from the National Forest Inventory (NFI, 2014). Polygons for which Category was 'Non-Woodland' in the NFI geodatabase were left out.

Appendix C – Variability in spatial distribution of the different woodland vegetation classes in T1 (1740-1799)

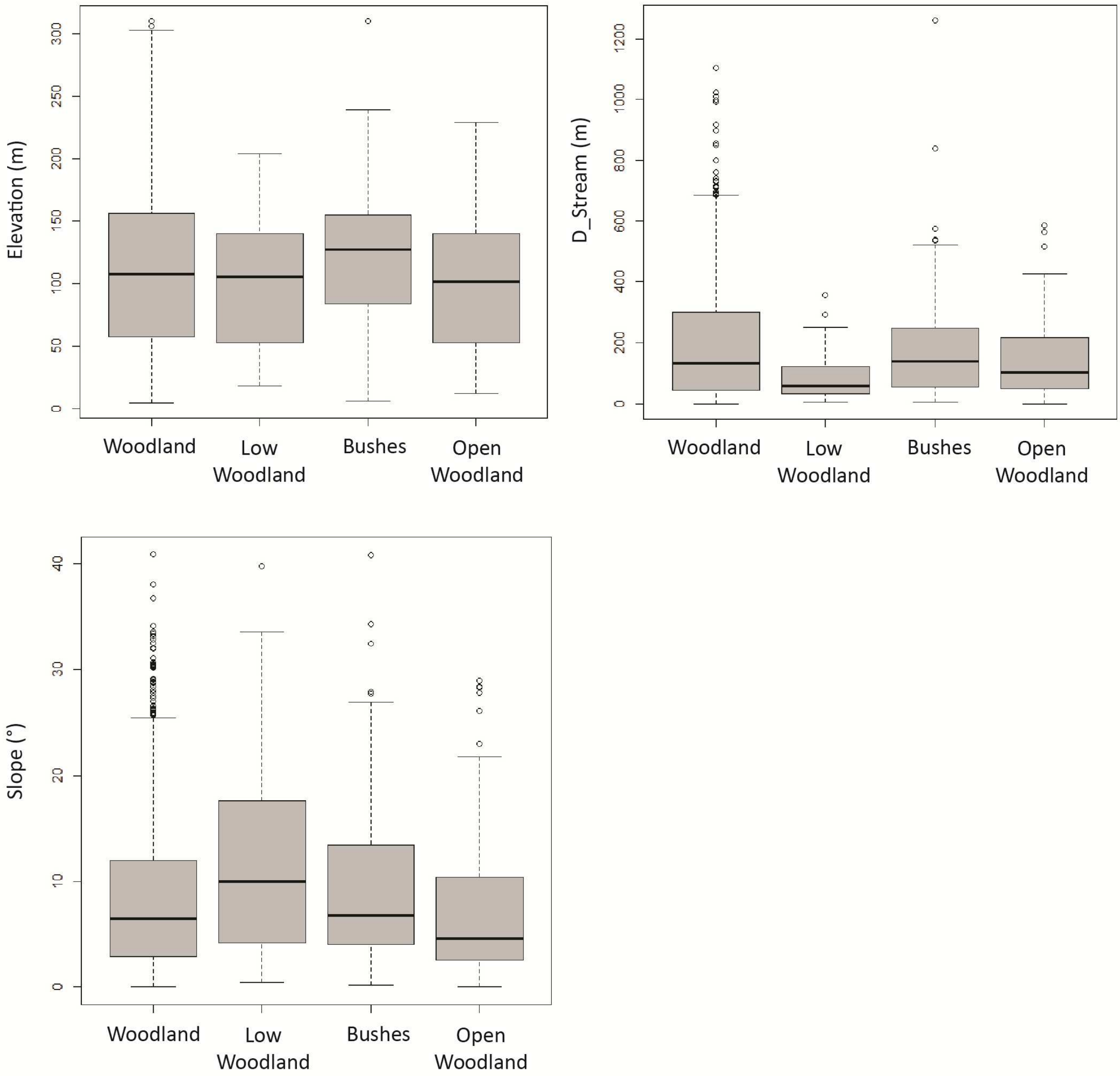


Figure C1. Boxplots of the elevation (m), slope (°) and distance to the nearest stream (m) in Area 1 for the different woodland vegetation classes in T1.

Appendix D – What ruefu' chance has twin'd ye o' your stately trees? - Historical maps and a poetic chronicle of Drumlanrig Woods

Publication by Muller T. and Carruthers G. (2017) in *Scottish Local History*, Vol. 98, 23-29.

What ruefu' chance has twin'd ye o' your stately trees?

Historical Maps and a Poetic Chronicle of Drumlanrig Woods

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Already infamous for his lax moral standards and nicknamed 'Old Q' in his last years, William Douglas, 4th Duke of Queensberry, saw his reputation tarnished further after he decided to strip woodlands in the estates around Drumlanrig Castle (Dumfriesshire) and Neidpath Castle (Peebleshire). These events happened sometime in the late eighteenth or early nineteenth century and inspired a poetic production directed against the Duke entitled 'Verses on the Destruction of the Woods near Drumlanrig', which was once attributed to Robert Burns. The date and authorship of the verses have long remained unclear but they contributed to making the fate of these woodlands widely known. They have often also been appropriated by nineteenth century writers wishing to express their scorn for the Duke. Supported by recently digitised historical estate maps that have been compared with written archives, this article is intended to bring new elements to bear on the circumstances of the extensive cutting-down of woodlands that is said to have occurred on William Douglas's lands while he was Duke of Queensberry.

'Verses on the Destruction of Woods near Drumlanrig' and their Authorship

The poem is believed to have been published first in the *Scots Magazine* of February 1803.[1] By way of introduction the text claims that the lines were written 'on a window shutter of a small country Inn, in Dumfriesshire, supposed to be by R. Burns'. They begin as follows:

As on the banks o' wandering Nith,
Ae smiling simmer morn I stray'd,
And traced its boniehowes and haughs,
Where linties sang and lammies play'd,
I sat me down upon a craig,
And drank my fill o' fancy's dream,
When from the eddying deep below,
Up rose the genius of the stream

During an encounter with 'the genius of the stream', the poet learns that the banks of the river were once covered with beautiful woodlands composed of beech, elm and oak, before some event stripped the area of its trees and left the ground bare: 'and scarce a stinted birk [birch] is left'.
In response to the poet's enquiry about the reasons behind this sudden change, the genius begins its diatribe and concludes with a bitter reference to the Duke of Queensberry:

The worm that gnaw'd my bonie trees,
That reptile wears a ducal crown.

The verses refer to the fate of the woodland once lying on the banks of the river Nith, near Drumlanrig Castle. It is believed that the 4th Duke of Queensberry decided to cut down the woodland and sell all trees fit to be sold in order to raise money for a dowry for the Countess of Yarmouth.[2] To explain this initiative, authors from the nineteenth century also refer to the 'greedy Vandalism'[3] of Old Q or his will to annoy his future successors.[4]

Nineteenth century editions of the work of Robert Burns sometimes include this piece but others leave it out because of serious doubts regarding the authenticity of the attribution.[5] The antagonism of Robert Burns towards the Duke of Queensberry was well known and this certainly contributed to the confusion. Indeed, Burns satirized William Douglas in the following lines:[6]

All hail! Drumlanrig's haughty Grace,
Discarded remnant of a race
Once godlike-great in story;
Thy forbears' virtues all contrasted,
The very name of Douglas blasted,
Thine that inverted glory

However, in the Annual Burns Chronicle and Club Directory, 1919 (Fig.1), JC Ewing suggests that the 'Destruction' verses were actually the work of the lawyer, novelist, poet and dramatist, Henry Mackenzie.[7] To support his assertion, Ewing cites George A Aitken, editor of the third Aldine edition of Burns, who had printed the verses with a note: 'Cromek wrote to Creech that he was told they were really written by Mackenzie'.[8,9] Ewing also reports that this statement regarding the original authorship was repeated by editors Henley and Henderson in 1897. Finally, the most conclusive evidence brought by Ewing is a letter written by Mackenzie, dated 22 October 1802 to Dr James Currie – early biographer of Burns – in which Mackenzie is recognised as the author:

> … Having occasion last year to make a Journey thro' Nithsdale, accompany'd by my eldest Daughter, We could not but feel the sharpest regret, and some little resentment, at the miserable Devastation which the Banks of that beautiful River had suffered from the cutting down of the Trees with which they had been cloth'd. My daughter observ'd to me that if Burns were alive, it would afford an excellent Subject for the Feeling and Indignation of his Muse to work upon. Catching the Hint, I wrote, almost impromptu, the little Poem in

question, and read it next day at a Gentleman's House where we vizited, from the penciled Copy in my Note-Book, which I pretended to have taken from the Window-Shutter of a little Inn, whence I had actually copied some other Lines of Burns' in praise of a Young Lady, published by you in the Collection of his Works. Somebody, I really forget who, afterwards wrote out a Copy from my Book, and prefixed to it the fictitious Origin which I had assigned it …[10]

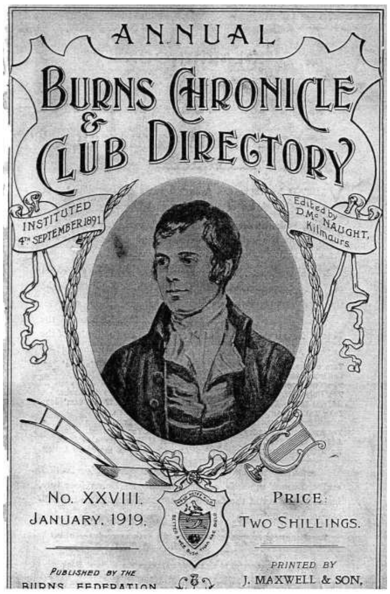

Fig.1 : Front cover of the Annual Burns Chronicle and Club Directory, No 28, January 1919

Evidence from Dorothy and William Wordsworth and Walter Scott

The woodland cover around Drumlanrig Castle has experienced substantial changes over the last centuries but various authors have commented especially on the so-called 'destruction' of the woods in the time of the 4th Duke of Queensberry. The negative reactions expressed during the nineteenth century show how the felling that inspired the 'Verses on the Destruction of Woods near Drumlanrig', and indeed the verses themselves, had a profound impact on the reputation of the Duke.

In 1803, the English poet William Wordsworth composed a heated sonnet that referred to the recent cutting-down of woodlands supposedly on the banks of the Tweed near Neidpath Castle.[11] It is not unlikely that the 'Verses' were a source of inspiration for Wordsworth's sonnet:

Degenerate Douglas! Oh the unworthy Lord!
(…)
A brotherhood of venerable Trees,
Leaving an ancient Dome, and towers like these,
Beggared and outraged! Many hearts deplored
The fate of those old trees: and oft with pain
(…)
And the green silent pastures, yet remain

In her diary, Dorothy Wordsworth, sister of William Wordsworth with whom she travelled through Scotland, wrote also in August 1803 about Drumlanrig Castle and the surrounding area:[12]

> The situation would be noble if the woods had been left standing; but they have been cut down not long ago, and the hills above and below the house are quite bare

However, while talking about the river Nith somewhere 'a mile and half from Drumlanrigg', she also mentions 'the banks woody', suggesting that, in 1803, not all of the woodland along the Nith had faced the destruction described in the 'Verses'. Further evidence of this is to be found elsewhere. Walter Scott, himself a keen planter of woodland, wrote about the Drumlanrig trees in his *Reliquiae Trotcosienses* (1831-2), although this was not published in full until 2004.[13] The work is a thinly fictionalised account of his home at Abbotsford. When discussing the making of Scottish furniture and 'the patriotic use of our own native wood'[14] Scott writes about his own furniture sourced from the woodland of the Duke of Queensberry:

> In this last subject, and apropos of the set of dining tables which are valuable in the eyes for more reasons than one; they were made of particular parts of the growth of certain very old oaks which had grown for ages and at length became stag-headed and half dead in the place where they originally grew in the old and noble park of Drumlanrig Castle. These trees were put up for sale by the late Duke of Queensberry, along with the more thriving plantations growing upon the domain around the castle, but no one being aware of the curious and valuable purposes to which they might be applied, they fetched low prices, and some of those who became purchasers did not even think it worth their while to cut them down, since the payment must have been a necessary consequence of concluding their bargain.
>
> So stood the matter when the Duke of Queensberry concluded an unusually long life and the bargain, so far as it respected these old trees, became in every respect forfeited. Mr Bullock, who chanced to be in attendance at Drumlanrig about the time, had no hesitation in giving it as his opinion that the progress of time had exactly brought these ancient oaks to the point of perfection when their wood would make the most beautiful furniture. The set of tables designed for the mansion we are talking of was accordingly taken in hand, and turned out most beautifully, so that it was one of the singular chances, that accident in this world will often bring a commodity to that purpose for which it is best adapted. A case also by Bullock out of the root of elm and yew trees which had grown in the woods of Rokeby completed the set of tables, forming a convenient and useful receptacle for the separate leaves of the original when they were not wanted for use.[15]

George Bullock (d.1818) was a house furnisher and designer in London. John Gibson Lockhart in his Memoirs of the Life of Sir Walter Scott writes that both castle and title were inherited by the Duke of Buccleuch in 1810, when, 'the parks and mountain slopes of Drumlanrig were almost denuded of tree'.[16]

Reports from Late Nineteeenth Century Authors

Some authors of the late nineteenth century had harsh words for the extensive clear-felling that supposedly took place on William Douglas's lands. For instance, CT Ramage wrote as follows in 1876:[17]

> During the greater part of last century the castle was surrounded by trees of great age … These woods, however, were doomed to destruction by the last Duke of Queensberry ('old Q'), it is believed to spite the noble family who were to succeed him, and at the beginning of this century they had nearly disappeared.

In the same text, the author mentions the survival of some trees that 'had escaped the hand of the destroyer' thanks to the intervention of the Earl of Dalkeith (future heir and Duke of Buccleuch) who would have bought the trees before they were chopped down. In addition, Ramage reports another version stating that the death of the Duke allowed the last trees to be saved, suggesting important felling until 1810:

> Even to the day of his death old Queensberry continued to destroy the woods on all his estates. The parish of Sanquhar to the present day shows the course he was pursuing.

In similar terms, James Brown's *History of Sanquhar* (1891), mentions a total clearance of the woods:[18]

> Towards the end of last century, this country-side was robbed of much of its natural beauty by the despicable policy of the last Duke of Queensberry … It does seem that the Duke had been animated by some such malicious, spiteful motive, for had the raising of money merely been his object, he would have confined the fell work of destruction to the enclosed woods and plantations, which were of some commercial value, whereas we find that not even the bonnie glens were spared … the banks of the Nith … had been thus disfigured to gratify an unworthy passion.

CT Ramage, James Brown and JR Robinson all refer to the 'Verses on the Destruction of Woods near Drumlanrig' in their publications, which illustrates the lasting influence of the poem throughout the nineteenth century, indeed for many decades after the event it describes. It also confirms that no precise date was known for this event as the 'Verses' are the only evidence mentioned by the authors and none of them seemed to know with certainty the year they were written or who the author was. According to Ramage:[19] 'They [the trees] were proceeding to be cut down before 1796, if the following poem, which is said to be by Burns, be genuine', while Brown wrote:[20] 'It is not unlikely that they were written, as has been supposed, by Burns, as he was given to scribbling down his effusions in such places'.

The Old Statistical Account of Scotland

In Dumfries and Galloway, the Statistical Accounts of Scotland provide little evidence of substantial woodland clearance in the estates belonging to the Duke of Queensberry. The reports in the *Old Statistical Account* (late eighteenth century) do not mention any felling in the parishes surrounding the river Nith near Drumlanrig Castle, namely Penpont (parish report published in 1791), Durisdeer (1792), Closeburn (1794) and Morton (1794). However, if the felling mentioned by the 'Verses' happened sometime during or after the year 1795, the lack of reference makes perfectly sense as the reports would have been published prior to it. The only written evidence of major felling on the lands of William Douglas in Dumfries and Galloway that is in the report covering the parish of Moffat, dated 1792:[21]

> ... There was another natural wood opposite to it, on the south side of Moffat water, belonging to his Grace the Duke of Queensberry; but it was lately cut down, and, being left uninclosed, is lost in future to the proprietor, and to the public.

The New Statistical Account of Scotland

While it describes in some detail the plantations of silver fir, spruce, scots pine, larch and oak that took place shortly after the death of Old Q, little is said in the *New Statistical Account* (1840s) about changes in the woodland cover that could be attributed to him. Despite that, the following extract suggests that substantial activity might have taken place. It concerns the parish of Tinwald:[22]

> A large portion of the parish was at one time covered with wood, the greater part of which was cut down by the last Duke of Queensberry; and now, except a quantity upon the estate of Amisfield, very little remains.

A further extract relates to the parish of Kirkconnel:[23]

> In the measurement of his Grace's property in this parish … that wood consists chiefly of brush and sproutings of trees formerly cut down, and is confined to the sides of deep ravines and the banks of the different rivers. The valuable part of the wood, many years ago, was set up to public sale by order of the late William Duke of Queensberry; and the purchasers were not required, by the articles of sale, to enclose the wood, so as to preserve the young shoots from being destroyed by the sheep or black cattle … there is not a single tree of any considerable value within that portion of this parish which originally belonged to his Grace.

In Sanquhar Parish, while referring to a cutting down 'about forty years ago' the following information is given:[24]

> A great part of the parish is destitute of plantations and uninclosed. Of the lands belonging to the Duke of Buccleuch and Queensberry, 282 acres are covered with natural wood, which

> are chiefly the banks of the streams. The trees are but small; they are merely shoots from the roots of large trees, cut down about forty years ago, and are chiefly oak, birch and hazel.

In conclusion, while the Statistical Accounts of Scotland do not refer to any major felling along the Nith as reported in the ‘Verses’, it is still possible to find evidence of important woodland loss on the lands of William Douglas. However, due to insufficient testimony, it appears that the written evidence cannot provide a precise idea of the extent to which the woodland was affected by major felling on the estates belonging to Old Q. It is not possible either from these reports to determine the precise location along the Nith where the felling mentioned in the ‘Verses’ occurred.

New Evidence from Historical Estate Maps

In 1810, at the age of 85, Old Q died without legitimate heir. The Castle of Drumlanrig and Dukedom passed to the Scotts of Buccleuch with an important collection of estate plans mostly dated between 1740 and 1772, before William Douglas became Duke of Queensberry. Shortly after his death, the estates of the new owners enjoyed a significant period of agricultural improvement when other surveyors were charged with mapping the lands of the Dukedom accurately. Consequently, the estates were mapped twice within a few decades. These plans are today well preserved in possession of the Duke of Buccleuch and Queensberry at Drumlanrig castle, and served for this study. Most of them depict in great detail the boundaries of past woodland cover and other land-cover types. Fortunately, this can help us to better appreciate the changes that occurred in the Dukedom during the late eighteenth and early nineteenth century.

In collaboration with the University of Glasgow and Dumfries Archival Mapping Project (DAMP), hundreds of these estate plans have been digitised. Using a Geographic Information Systems (GIS), modern mapping and aerial photographs, all historical maps of interest were georeferenced and assigned a coordinate system (Fig.2). Georeferencing allows the overlaying of different historical plans and modern data covering the same area. After vectorising all the woodland sites depicted on the georeferenced historical maps, it was possible to reconstruct past woodland extent and changes at different time slices and with an accuracy varying from 10 to 35 meters.

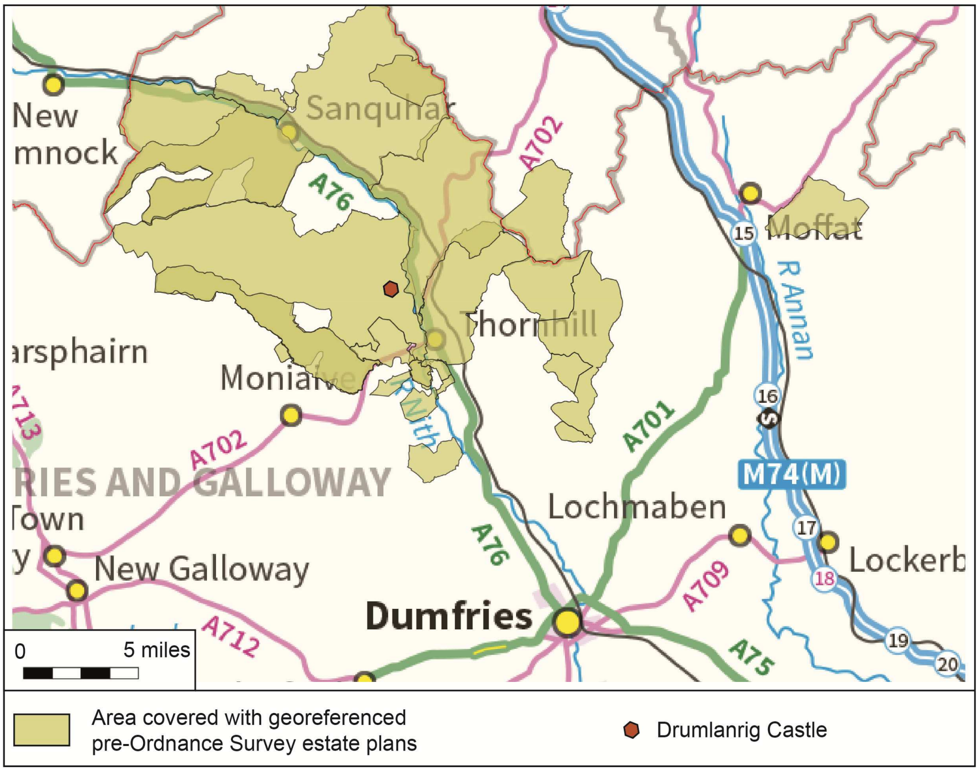

Fig.2: Area covered with georeferenced plans from the late eighteenth and early nineteenth centuries. This area corresponds to estates that once belonged to the 4th Duke of Queensberry. Background map: OS miniscale standard licenced under the Open Government Licence v3.0

Figure 3 shows a subset of the reconstruction of woodland cover changes between 1772 and 1820/1825, in the vicinity of Drumlanrig castle, where we assume that the destruction of the woodland mentioned in the 'Verses' took place. The reconstruction clearly highlights an area of woodland once lying along the river Nith that disappeared sometime between 1772 and 1820. The clear-cut would have occurred on a relatively flat area, over a mile of distance and located only 0.6 miles north-east of the castle. The sequence of relative plans shows that this part of the banks was indeed wooded in 1772 while it served for growing crops in 1820 (Fig.4). Further back in time, in 1763, a plan by J Wells confirms the previous existence of this woodland.

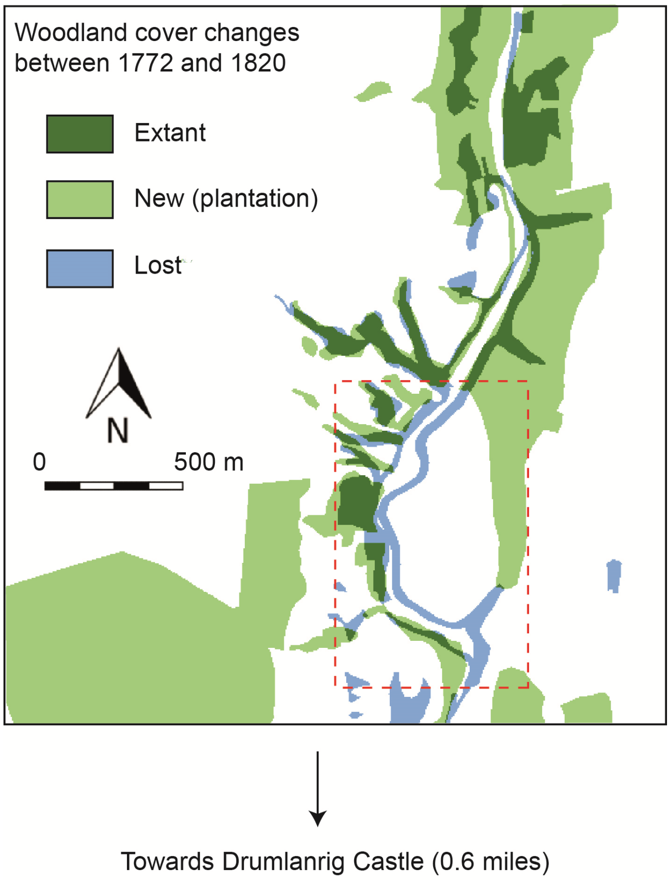

Fig.3: Reconstruction of the woodland cover changes between 1772 and 1820 along the river Nith near Drumlanrig Castle (spatial accuracy: c.30m). The blue band into the dashed rectangle corresponds to the proposed area for the lost woodland described in the 'Verses on the Destruction of Woods near Drumlanrig'.

In addition, another map by W Crawford suggests that this exact part of the wood along the Nith may have already disappeared by 1804, while the wooded banks further north and south were then extant (Fig.5). This map is the only existing one of the region that was made while Old Q was alive. If this wood was the one mentioned in the 'Verses', Crawford would have drawn it during the period of the tree felling or very few years afterwards. However, a closer look at this section seems to show that the mapmaker in fact drew some trees that are hardly perceptible today because of the faded nature of the symbols. Were they erased later or were they drawn originally like this? The rest of the map being well preserved, it seems unlikely that this particular portion is the only one that faced natural damage but it remains difficult to interpret Crawford's depiction. This map should also be studied with caution as Crawford drew it at a scale that cannot equal the level of detail and accuracy of the estate maps previously used. A mere coincidence would be surprising though and, in consequence, we can still hypothesise that this woodland ceased to exist sometime between 1772 and 1804.

A. B. C.

Fig.4: Subset of historical plans showing the woodland along the river Nith that disappeared sometime between 1772 and the early nineteenth century as mentioned in Fig.3:

A. Plan of part of Durisdeer by James Wells, 1763 (no National Records of Scotland reference number).

B. Plan of farm of Upper Enoch Park by James Leslie, 1772 (NRS RHP38134/24).

C. Plan of the parish of Durisdeer by William Crawford, 1820-1825 (NRS RHP37667). Courtesy of the Duke of Buccleuch and Queensberry.

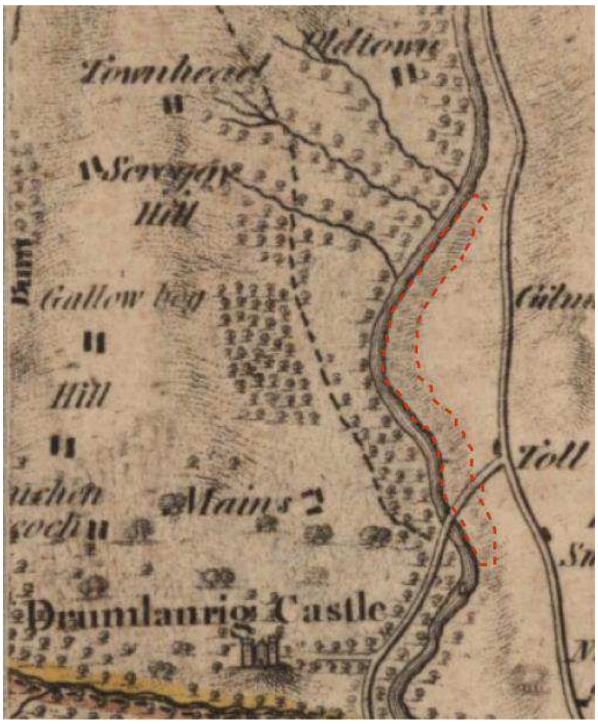

Fig.5: Subset of 'Map of Dumfries-shire' by William Crawford, 1804. Courtesy of the National Library of Scotland. The boundaries of the lost woodland shown in Fig.3 and Fig.4 are here in dashed red line. Faded tree symbols seem to represent this area. Was it to show that this wood was lost by 1804?

So, can this indeed be the area where the former woodland that inspired the 'Verses' once lay? It is the only strong mapping evidence for woodland loss on the estates of the 4th Duke of Queensberry. This woodland is known to have been located along the river Nith, as stated in the poem, and we could not find any similar example on the banks further north in the mapped area of the parishes of Sanquhar and Kirconnell.

Evidence from historical maps seems to confirm that important clear-felling happened along the Nith. However it seems difficult to understand the full extent of it. Indeed, the maps drawn in 1820 show that many large plantations were formed across the lands of the Duke of Buccleuch. It is not unlikely that among the sites said to have been denuded of their timbers by Old Q, some could have been planted again few years after the Buccleuch family succeeded him, as stated by Ramage:[25]

> The property came thus denuded of its beautiful clothing into the possession of Duke Henry of Buccleuch in 1810, and he at once began to replace what had been thus recklessly destroyed.

As a result, these plantations may have masked any important tree felling that happened during the time of Old Q and until his death in 1810.

Historical maps can also be viewed in the light of the eighteenth and nineteenth century writings. In the Statistical Account of 1792 for the parish of Moffat, the author exaggeratedly stated that Crofthead wood, lying on the lands of Old Q and left uninclosed, was 'lost in future to the proprietor, and to the public',[26] while the First Edition Ordnance Survey map shows that this wood was actually still extant in the mid-nineteenth century (Fig.6). The comparison of the First Edition OS with an estate map dated 1768 shows also very similar boundaries, which suggests that, even if denuded of its trees, this in fact did not signify the end of the wood.

Another example tends to show that some authors may have unfairly blamed Old Q for events that cannot possibly have been his fault. Ramage mentions that the Duke was responsible for cutting down the woodland on one of the banks of the Euchan Water in the parish of Sanquhar:[27]

> The cutting ended at his death, and at that time one side of the banks of the Yeochan (Euchan) was cleared, and the other had not been overtaken. The wood on the uncleared side still exists.

But estate plans from 1766 suggest that long before William Douglas became Duke only one of the two banks was wooded (Fig.7). It is then possible to assume that some authors exaggerated, whether deliberately or not, the damages caused by the Duke to the woodland cover. The 'Verses' and the scorn aroused by the Duke during his life might have easily influenced writers throughout the nineteenth century. Today, this makes it a challenge to assess the magnitude of the woodland loss during Old Q’s time.

Fig.6: Crofthead wood depicted in:

A. Subset of ‘A plan of Craigbeck and Crofhead’ by John Leslie, 1768 (boundaries of the woodland in dashed blue line, no NRS reference number). Courtesy of the Duke of Buccleuch and Queensberry

B. Ordnance Survey, first edition 1:10,560 (surveyed 1857-58). Courtesy of the National Library of Scotland. The two maps suggest that this woodland remained with very similar boundaries between 1768 and 1857-1858.

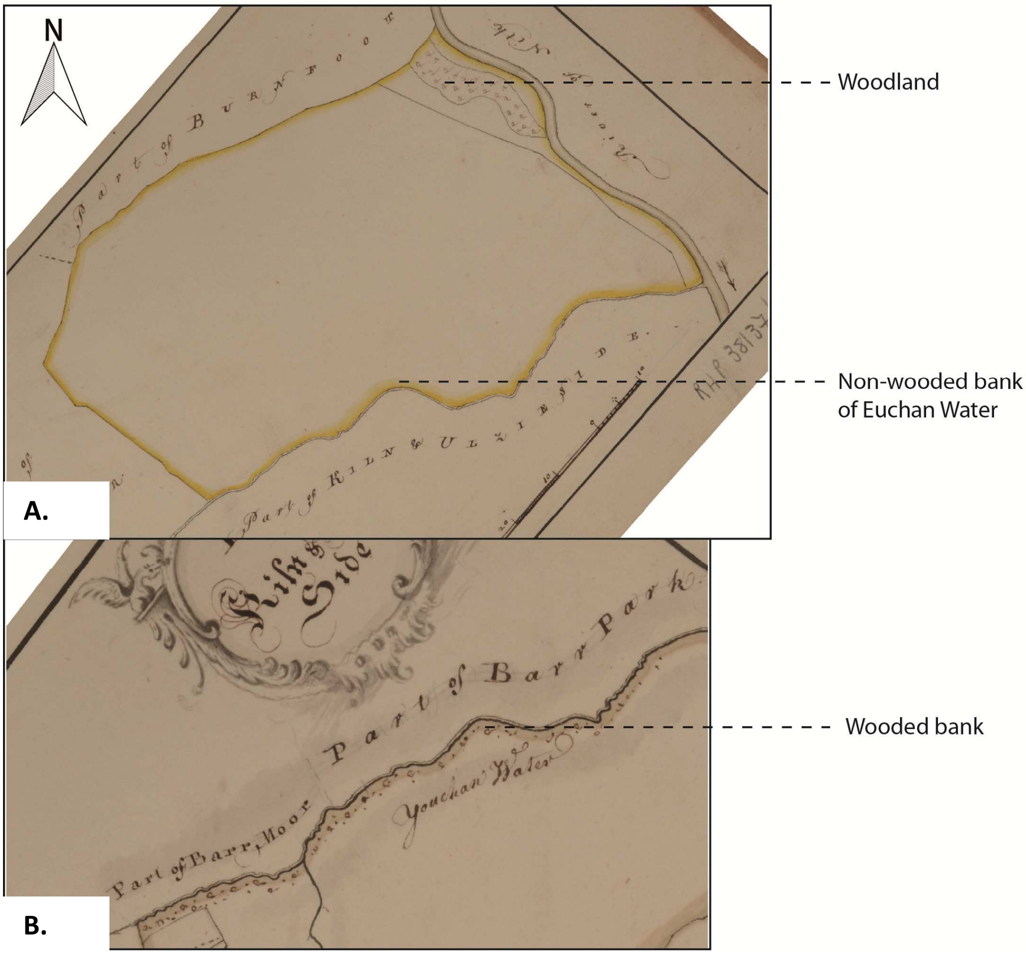

Fig.7: Farms in the parish of Sanquhar, subsets of maps by J. Leslie, 1766:

A. Plan of farm of Barr Park (NRS RHP38137/19).

B. Plan of farm of Kiln and Ulzie side (NRS RHP38137/23).

The two maps show that already in 1766 only one side of the banks was wooded. It suggests that Old Q cannot have been responsible for the cutting down of the woodland there. Courtesy of the Duke of Buccleuch and Queensberry.

Conclusion

Various historical documents support the evidence for dramatic changes in the woodland cover of the estates belonging to William Douglas while he was 4th Duke of Queensberry. Despite a few mentions in the parishes of Moffat, Tinwald, Sanquhar, Kirkconnell (Dumfriesshire) or to the banks of the river Tweed at Neidpath (Peebleshire), most of the sources refer primarily to the passionate ‘Verses on the Destruction of Woods near Drumlanrig’ that they attributed to Robert Burns. The study of estate maps from the eighteenth and nineteenth century allows us to identify a large area that was once wooded and certainly cut down sometime between 1772 and 1804. This woodland lay on the banks of the Nith near Drumlanrig Castle and could be the one described in the 'Verses'. However, the evidence available on historical maps is unable to confirm the extent of the cutting down of the estates of Old Q as many plantations were developed in the years following his death. Finally, a comparison of the maps against written archives suggests that it is likely that some authors exaggerated the results of the felling or mistakenly blamed the Duke for the loss of woodland for which he was not responsible.

Acknowledgements

The authors would like to thank the Duke of Buccleuch and Queensberry for providing the permission to reproduce extracts from estate maps. We would also like to thank the National Library of Scotland for permission to reproduce extracts from the 1st edition OS maps and 'Map of Dumfries-shire' by William Crawford, 1804.

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[19] Ramage, op cit, p.29.

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[21] Statistical Account of Scotland, Vol.2, Moffat parish,1792.

[22] New Statistical Account of Scotland, Vol.4 (1845), Tinwald and Trailflat parishes.

[23] New Statistical Account of Scotland, Vol.4 (1845), Kirkconnell parish.

[24] New Statistical Account of Scotland, Vol.9 (1845) Sanquhar parish.

[25] Ramage, op cit, p.29.

[26] Brown, op cit.

[27] Ramage, op cit, p.33.

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Appendix E – Additional data on the sample woodland sites for the plant survey

Explanations: *SSSI: Chanlockfoot (Bac1, Bac2), Coshogle wood (Cos), Lochwood (Low); ‘d-T1’: distance to the nearest woodland known in T1 (m); ‘Species richness’: total number of plant species; ‘AWP species’: total number of ancient woodland indicator plant species according to Crawford (2009) and the lists by local experts as in Table 4.6; ‘Coppice trees’: coppice stools (Y = ‘yes’); **‘**LULC in T1’: land-use/land-cover as depicted on estate plans T1.

Site code	Continuity class	pH	d-T1 (m)	Species richness	AWP species	Coppice trees	LULC in T1
Bac1*	A	4.2	-	48	24	Y	Wood
Bac2*	A	3.9	-	34	13	Y	Wood
Cos*	A	4.1	-	46	16		Wood
Eno	A	4.4	-	38	15		Wood
Mab	A	4.4	-	41	13		Wood
Hil*a*	A	4.3	-	35	11	Y	Wood
Hil*b*	A	3.7	-	19	6		Wood
Hil*c*	A	4.1	-	18	5	Y	Wood
Hil*d*	A	4	-	36	13	Y	Wood
Cle2	A	4.1	-	36	14	Y	Wood
Air2	A	4.5	-	46	11	Y	Wood
Mar	A	4	-	41	13		Wood
Low*	A	3.4	-	42	12		Wood
Cae1	A	3.9	-	41	9	Y	Wood
Tin	A	4.6	-	32	7		Wood Pasture
Pin1	A	4.2	-	41	15	Y	Wood
Pin2	A	4.5	-	37	15	Y	Wood
Mor	B	3.8	25	21	6	Y	Pasture
Sch	B	3.9	1132	23	8		Meadow
Ard	B	4.5	44	50	11	Y	Pasture
Cle1	B	4.1	30	30	10		Pasture
Cle3	B	4.6	81	35	14		Meadow
Cle4	B	4.5	32	35	13		Pasture
Ecc	B	3.9	2	23	3		Arable
Mof1	B	4.2	388	41	6	Y	Unkown
Mof2	B	4	411	12	3		Other
Gar1	B	3.7	1004	14	4		Pasture
Gar2	B	4.5	1176	40	9		Pasture
Lom	B	4.2	500	23	1		Loch
Mil	B	4.5	5	38	13		Unkown
Rah1	B	3.7	100	45	13		Unkown
Rah2	B	4.4	100	32	10		Pasture
Sha*a*	B	3.7	378	46	8	Y	Unkown
Sha*c*	B	4.6	35	35	10	Y	Pasture
Mon	B	4.7	3590	41	7	Y	Pasture
Dru	C	4.2	505	30	9		Pasture
Air1	C	3.8	5	39	8	Y	Other
Cae2	C	4.3	60	22	2		Meadow
Sha*b*	C	4.7	993	58	12	Y	Pasture
Lor	C	4.7	1653	24	2	Y	Pasture
Pin3	C	4.4	130	34	8		Pasture

Appendix F – List of plant species identified in the field and number of sites where each species was recorded per continuity class (Class A = 17 sites; Class B = 18 sites; Class C = 6 sites)

Plant species	Continuity Class		
	Class A (n = 17)	**Class B (n = 18)**	**Class C (n = 6)**
Abies alba	1	7	1
Acer pseudoplatanus	8	14	1
Aegopodium podagraria	0	1	0
Aesculus hippocastanum	1	1	0
Ajuga reptans	12	9	3
Allium ursinum	4	0	0
Alnus glutinosa	3	3	4
Anemone nemorosa	7	4	1
Angelica sylvestris	0	3	2
Anthoxanthum odoratum	8	5	2
Arrhenatherum elatius	6	3	3
Asplenium scolopendrium	1	0	0
Athyrium filix-femina	4	4	1
Betula sp.	9	10	2
Blechnum spicant	4	8	1
Brachypodium sylvaticum	1	0	0
Caltha palustris	0	1	2
Cardamine amara	2	0	0
Cardamine flexuosa	7	8	3
Carex pallescens	0	1	1
Carex remota	6	4	2
Carex sylvatica	6	2	0
Carpinus betulus	1	0	0
Ceratocapnos claviculata	5	2	0
Chamerion angustifolium	4	2	0
Chrysosplenium oppositifolium	9	12	3
Circaea alpina or *C. intermedia*	1	2	0
Circaea lutetiana	12	12	3
Cirsium palustre	2	4	3
Claytonia sibirica	6	3	2
Conopodium majus	8	6	2
Corylus avellana	17	12	3
Crataegus monogyna	10	6	5
Crepis paludosa	1	7	2
Dactylis glomerata	3	4	5
Dactylorhiza fuchsii	0	0	1
Dactylorhiza maculata	0	0	1
Deschampsia cespitosa	3	7	3
Deschampsia flexuosa	1	3	1
Digitalis purpurea	11	6	0
Dryopteris affinis	9	12	3
Dryopteris dilatata	15	16	6
Dryopteris filix-mas	5	5	3
Epilobium montanum	4	7	1

Plant species	**Continuity Class**		
	Class A (n = 17)	**Class B (n = 18)**	**Class C (n = 6)**
Equisetum palustre	0	0	1
Equisetum pratense	0	1	1
Equisetum sylvaticum	2	1	0
Fagus sylvatica	9	9	2
Festuca x Lolium hybrid	0	0	1
Ficaria verna	5	6	0
Filipendula ulmaria	7	8	3
Fragaria vesca	5	2	1
Fraxinus excelsior	11	15	5
Galeopsis tetrahit	4	1	2
Galium aparine	9	11	6
Galium odoratum	3	1	0
Galium palustre	4	7	5
Galium saxatile	3	2	0
Geranium robertianum	13	11	4
Geum rivale	0	3	0
Geum urbanum	9	13	4
Glechoma hederacea	0	2	0
Gymnocarpium dryopteris	2	1	0
Hedera helix	1	1	1
Holcus lanatus	1	4	2
Holcus mollis	3	2	0
Hyacinthoides non-scripta	17	16	4
Hypericum pulchrum	1	1	0
Ilex aquifolium	6	4	1
Impatiens glandulifera	1	0	0
Iris pseudacorus	1	2	2
Juncus conglomeratus	1	1	1
Juncus effusus	5	8	3
Juncus inflexus	0	1	0
Lamiastrum galeobdolon ssp. argentatum	0	1	0
Lapsana communis	3	0	0
Larix decidua	0	1	0
Lonicera periclymenum	9	8	3
Lotus pedunculatus	0	0	1
Luzula pilosa	3	3	0
Luzula sylvatica	2	3	0
Lysimachia nemorum	15	10	4
Malus sylvestris	0	0	1
Meconopsis cambrica	1	1	0
Melampyrum pratense	2	1	0
Melica uniflora	1	0	0
Mentha sp.	1	0	1

Plant species	Continuity Class		
	Class A (n = 17)	Class B (n = 18)	Class C (n = 6)
Mercurialis perennis	10	5	0
Milium effusum	2	0	0
Moehringia trinervia	1	3	0
Myosotis scorpioides	0	1	1
Myosotis secunda	0	0	2
Oenanthe crocata	3	2	0
Oreopteris limbosperma	1	1	0
Oxalis acetosella	15	15	4
Phegopteris connectilis	2	0	0
Picea abies	5	2	0
Poa trivialis	9	10	6
Polypodium vulgare	4	0	0
Polystichum aculeatum	1	0	0
Potentilla erecta	3	2	1
Potentilla sterilis	8	2	2
Primula vulgaris	7	3	1
Prunella vulgaris	0	1	1
Prunus avium	0	1	0
Prunus laurocerasus	1	0	0
Prunus padus	2	2	0
Prunus spinosa	0	1	0
Pteridium aquilinum	11	7	4
Quercus sp.	15	13	3
Ranunculus auricomus	2	0	0
Ranunculus repens	9	9	5
Rosa canina	1	1	0
Rubus fruticosus agg.	10	8	2
Rubus idaeus	1	6	0
Rubus saxatilis	15	9	3
Rumex acetosa	3	2	1
Rumex obtusifolius	7	4	2
Salix caprea	1	2	0
Salix cinerea	0	3	1
Sambucus nigra	2	0	1
Sanicula europaea	1	0	0
Scrophularia nodosa	2	2	0
Scutellaria galericulata	1	1	0
Senecio sp.	0	2	0
Silene dioica	12	10	3
Solanum dulcamara	2	0	1
Solidago virgaurea	1	0	0
Sorbus aucuparia	11	7	3
Stachys sylvatica	9	10	3
Stellaria holostea	10	8	4

Plant species	Continuity Class		
	Class A (n = 17)	**Class B (n = 18)**	**Class C (n = 6)**
Stellaria uliginosa	1	0	0
Succisa pratensis	0	0	1
Taraxacum spp.	0	2	0
Teucrium scorodonia	5	4	0
Tilia sp.	1	0	0
Ulex europaeus	0	1	0
Ulmus glabra	3	4	0
Urtica dioica	6	11	5
Urtica urens	0	1	0
Vaccinium myrtillus	1	2	0
Valeriana officinalis	1	3	2
Veronica beccabunga	0	1	1
Veronica chamaedrys	12	8	4
Veronica montana	6	0	2
Veronica officinalis	0	1	0
Veronica serpyllifolia	1	1	0
Vicia sepium	6	0	0
Viola riviana	11	12	1

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