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# MODELLING ECOLOGICAL VALUES IN HETEROGENEOUS AND DYNAMIC LANDSCAPES WITH GEOSPATIAL DATA

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Cover picture: Bloody cranesbills (*Geranium sanguineum*) on Mälhamn island

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# ABSTRACT

Our surrounding landscape is in a constantly dynamic state, but recently the rate of changes and their effects on the environment have considerably increased. In terms of the impact on nature, this development has not been entirely positive, but has rather caused a decline in valuable species, habitats, and general biodiversity. Regardless of recognizing the problem and its high importance, plans and actions of how to stop the detrimental development are largely lacking. This partly originates from a lack of genuine will, but is also due to difficulties in detecting many valuable landscape components and their consequent neglect. To support knowledge extraction, various digital environmental data sources may be of substantial help, but only if all the relevant background factors are known and the data is processed in a suitable way.

This dissertation concentrates on detecting ecologically valuable landscape components by using geospatial data sources, and applies this knowledge to support spatial planning and management activities. In other words, the focus is on observing regionally valuable species, habitats, and biotopes with GIS and remote sensing data, using suitable methods for their analysis. Primary emphasis is given to the hemiboreal vegetation zone and the drastic decline in its semi-natural grasslands, which were created by a long trajectory of traditional grazing and management activities. However, the applied perspective is largely methodological, and allows for the application of the obtained results in various contexts. Models based on statistical dependencies and correlations of multiple variables, which are able to extract desired properties from a large mass of initial data, are emphasized in the dissertation. In addition, the papers included combine several data sets from different sources and dates together, with the aim of detecting a wider range of environmental characteristics, as well as pointing out their temporal dynamics.

The results of the dissertation emphasise the multidimensionality and dynamics of landscapes, which need to be understood in order to be able to recognise their ecologically valuable components. This not only requires knowledge about the emergence of these components and an understanding of the used data, but also the need to focus the observations on minute details that are able to indicate the existence of fragmented and partly overlapping landscape targets. In addition, this pinpoints the fact that most of the existing classifications are too generalised as such to provide all the required details, but they can be utilized at various steps along a longer processing chain. The dissertation also emphases the importance of landscape history as an important factor, which both creates and preserves ecological values, and which sets an essential standpoint for understanding the present landscape characteristics. The obtained results are significant both in terms of preserving semi-natural grasslands, as well as general methodological development, giving support to science-based framework in order to evaluate ecological values and guide spatial planning.

**Keywords:** Geospatial information, remote sensing, biodiversity, semi-natural grassland, modelling, nature management

# TIIVISTELMÄ

Ympäröivä maisemamme on alati muuttuvassa tilassa, mutta viime aikoina muutosten nopeus ja niiden vaikutukset ympäristöön ovat kasvaneet. Luontoarvojen kannalta kehitys ei ole ollut pelkästään myönteistä, vaan monin paikoin lajistollisesti arvokkaat elinympäristöt ovat vähentyneet ja yleinen luonnon monimuotoisuus on kaventunut. Vaikka ongelma ja sen laajuus on yleisesti tunnistettu, ovat suunnitelmat ja toimet negatiivisen kehityksen pysäyttämiseksi paljolti keskeneräisiä. Osaltaan tämä johtuu tahtotilan puutteesta, mutta myös siitä että monet arvokkaista maisemakomponenteista ovat hankalasti havaittavia ja puutteellisesti tunnettuja, jolloin niihin ei osata kohdistaa tarvittavaa huomiota. Tässä yhteydessä erilaiset ympäristöön liittyvät digitaaliset tietolähteet voivat auttaa tiedon kartuttamisessa mutta vain, jos tarvittavat taustatekijät tunnetaan ja aineistoja osataan käsitellä soveltuvalla tavalla.

Tässä väitöskirjassa keskitytään ekologisesti arvokkaiden maiseman ominaisuuksien tunnistamiseen geospatiaalisten aineistojen avulla, ja suositellaan käyttämään tätä tietoa aluesuunnittelun ja luonnonhoidon tarpeisiin. Tällä tarkoitetaan alueellisesti arvokkaiden lajien ja niiden elinympäristöjen havainnointia paikkatieto- ja kaukokartoitusaineistoja käyttäen, sekä tarkoitukseen sopivien analysointimenetelmien kehittämistä. Tutkimuksen kohteena on lounaissuomalainen maisema hemiboraalisessa kasvillisuusvyöhykkeessä, ja etenkin alueella esiintyvät arvokkaat perinnemaisemat, joilla pitkäkestoinen laidunnus ja hoitotoimenpiteet ovat luoneet monimuotoisen eliölajiston. Tutkimuksessa kehitetään yleistettäviä menetelmiä, ja saatuja tuloksia voidaan soveltaa myös laajempiin käyttötarkoituksiin. Tärkeässä osassa ovat erilaiset tilastollisiin tekijöihin ja muuttujien yhteisvaihteluun perustuvat mallinnusmenetelmät, joilla suuresta määrästä alkuperäisaineistoja erotetaan halutut ominaisuudet. Mallinnukset tehdään yhdistämällä useita maiseman ajallisia ja alueellisia muutoksia kuvaavia paikkatietoaineistoja.

Väitöskirjan tulokset osoittavat, että maiseman dynamiikan ymmärtäminen ja muutosten tulkinta on olennaista luontoarvoiltaan tärkeiden kohteiden löytämiseksi. Tämä vaatii tietoa tutkitun ilmiön syntymekanismeista ja tehtävään käytetyistä aineistoista, mutta usein myös havainnoinnin kohdistamista riittävän yksityiskohtaiseen vaihteluun jonka avulla pirstoutuneita ja osin päällekkäisiä maisemakomponentteja voidaan tunnistaa. Näiden syiden takia valmiiksi luokitellut aineistot ovat usein liian yleistettyjä soveltuakseen sellaisenaan pienialaisten maisemakohteiden löytämiseen, mutta niitä voidaan kuitenkin hyödyntää osana pidempää työketjua. Tutkimuksen tulokset tukevat sitä tulkintaa, että maiseman nykytilaa edeltävät muutokset ovat olennaisia ekologisia arvoja maisemassa säilyttäviä tekijöitä. Tästä syystä on erityisen tarpeellista tuntea maiseman menneisyys osana nykyistä maisemarakennetta. Saadut tulokset ovat merkittäviä niin perinnemaisemien säilyttämisen kuin maisemaekologisen tutkimuksen menetelmäkehityksenkin kannalta, ja ne tukevat paikkatietoon ja tieteelliseen tutkimukseen perustuvaa luonnonsuojelua ja aluesuunnittelua.

**Avainsanat:** Paikkatieto, kaukokartoitus, biodiversiteetti, perinnemaisema, mallinnus, luonnonhoito

# ACKNOWLEDGEMENTS

This chapter is quite in the beginning of this book but it also ends a relatively long episode in my life. It has been the time of many joyful happenings as well as disappointments, but fortunately the latter ones did not happen too often. Instead of troubles, I remember all the positive things like learning something new every day, hearing encouraging words from those people who themselves had been in my position for decades ago, or having outdoor lunches on sunny fieldtrips. I am happy to have reached this point and achieving the target I've been focusing on for the last years, but simultaneously somewhat sad that it's all done now. Definitely, if someone would ask me, I would do it all again.

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I feel that I have been lucky to do my postgraduate studies at the Department of Geography and Geology, University of Turku, where we have been having absolutely wonderful working community. Everyone there has, of course, been contributing to the spirit but I would like to specifically mention a few persons. Nora, we shared an office room for a long time and you were the person who helped me a lot in my early career. We also attended several international conferences together, which were much nicer to travel with you. More recently, during the time when I was finalizing my dissertation, Hanna L. is a person who deserves special acknowledgements. In the course of those busy weeks I had millions of questions related to the dissertation process, and I honestly don't know if I would have been able to find all the answers in time without your help. Furthermore, I want to thank Annukka, Kirsi, Leena and Sari of your efforts related to administrative (and many other) issues; everything went as smoothly as it was possible (and if not, it was not your fault). I am not going to provide a comprehensive list of all the other contributing colleagues here as there would be a considerable risk of forgetting someone important, but generally I want to thank all the doctoral students as well as everyone else at the department – you have made my postgraduate time to be unforgettable. In particular, those restless discussions during the coffee breaks and lunch hours were necessary counterpoints to the demanding scientific work. There were also many important persons outside the department who helped me with my dissertation such as Helle Skånes, Maija Mussaari, Jyrki Lehtinen, and many others – thank you!

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This has been a long road, and I would not have been able to do it by myself, or only with help of my academic colleagues. Indeed, I want to address my humble gratitude to my parents, who have always supported me and been willing to understand my choices, even if they would have appeared to be irrational at times. I also want to thank all my friends who managed to offer me enjoyable moments outside of university, without needing to discuss absolutely anything about academic issues. And Winnie, my wife, you have been having a special privilege to see the whole process at a close distance. It has not always been easy, for either of us, but without you many days would have been much darker.

A fully done dissertation is not the end of the road, but it is just the beginning of a new section. Nevertheless, it is a good time to stop for a moment, see the track behind with all the up- and downhills, and take a look at the surrounding landscape. Next steps from now on remain somewhat unknown, but own visions and hard work will lead the way to new challenges.

# CONTENTS

# LIST OF ORIGINAL PUBLICATIONS

This thesis consists of a summary and the following four original papers. The papers are referred to in the text by their Roman numerals:

**I** Pitkänen T.P., Skånes H., Käyhkö N., 2015. Detecting subpixel deciduous components to complement traditional land cover classifications in Southwest Finland. International Journal of Applied Earth Observation and Geoinformation 42, 97–105.

**II** Pitkänen T.P., Käyhkö N., 2016. Reducing classification error of grassland overgrowth by combing low-density lidar data with multitemporal satellite images and orthophotos. Submitted manuscript.

**III** Pitkänen T.P., Kumpulainen J., Lehtinen J., Sihvonen M., Käyhkö, N., 2016. Landscape history improves detection of marginal habitats on semi-natural grasslands. Science of the Total Environment 539, 359–369.

**IV** Pitkänen T.P., Mussaari M., Käyhkö N., 2014. Assessing Restoration Potential of Semi-natural Grasslands by Landscape Change Trajectories. Environmental Management 53, 739–756.

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# 1. INTRODUCTION

Ecological values in the surrounding landscape relate primarily to the existence and arrangement of living organisms. Their abundance and variation can be reflected through the concept of *biodiversity*, referring to species, genetic, ecosystem and landscape diversity in an area, which further affect the state and stability of the environment (Laurila-Pant et al. 2015; Swingland 2001). Recently, biodiversity has been significantly declining due to rapid changes driven by socioeconomic, political, technological, natural and cultural forces (Bürgi et al. 2004). If measured by species loss, it is estimated that the current extinction rate is up to 1,000 times higher compared to the 'natural' pre-human time and likely to accelerate unless immediate efforts are taken (Ceballos et al. 2015; De Vos et al. 2015). This detrimental development is widely acknowledged and may ultimately concern our survival (Cardinale et al. 2012; Hooper et al. 2012), but efficient evidence-based strategies to halt these losses are largely lacking (Sutherland et al. 2015). Partially, this is derived from a lack of true will due to the anthropocentric perspective on biodiversity, viewing its value primarily through the satisfaction of human needs while failing to recognize the real costs related to landscape modifications (Randall 1991; Reid et al. 2005; Straton 2006). Concepts such as ecosystem services, landscape services and environmental services have been developed to provide better opportunities to link ecology and economy (Daily et al. 2000; Schägner et al. 2013; Termorshuizen and Opdam 2009), but these ideas must also be translated into practical actions in order to improve landscape resilience, quality, and diversity. Further, this also requires confirmed knowledge on where ecologically important habitats contemporarily exist in the landscape, how have they emerged and changed over time, and what possible threats may affect their future development.

One of the particularly biodiversity-rich and threatened habitat types are the hemiboreal semi-natural grasslands in northern Europe, where numerous species have become regionally or even globally threatened. This indicates substantial risks for future extinction which must be taken seriously (Rassi et al. 2010). Reasons for the detrimental development have been land use changes that have replaced the previously natural or semi-natural areas, and habitat degradation due to altered management regimes (Foley et al. 2005). In particular, the development of agricultural technology and changed socio-economic circumstances have led to the abandonment of traditional cultivation and grazing techniques, which used to support the co-existence of numerous species better than the present, largely monofunctional agricultural landscape (Strijker 2005). Since existing vegetation is the product of long-term interactions between biotic, abiotic, and anthropogenic factors, many of the semi-natural grassland species have been able to exist in potentially suboptimal habitat conditions for an extended period of time (Cousins and Eriksson 2008; Kuussaari et al. 2009). This however may have caused an *extinction debt* – a situation where species patterns are not fully supported any longer by the landscape structure, thus becoming vulnerable to extinction and posing challenges for biodiversity conservation (Bommarco et al. 2014; Helm et al. 2006; Kuussaari et al. 2009). While the existence and prevalence of an extinction debt is a debated issue (Cousins 2009; Öster et al. 2007), the problem is that our tools to observe, understand, and monitor such phenomena are limited. In reality, this means that preserving only the remaining habitat fragments may not be enough to support the long-term existence of these semi-natural grasslands.

Practical conservation efforts start from the detection of existing and potential habitat patches, and ensuring their favourable status. Extensive fieldwork-based campaigns are generally not a feasible option for collecting habitat information, and there is a need to find solutions, which help in identifying the focused species or habitats with relatively high accuracy and low demand on resources. The important prerequisites for this are a solid understanding of the targeted species' autoecology and distribution, as well as an ability to recognise the focused habitats among the more robust and expressive landscape characteristics. Nowadays, geospatial data derived from remote sensing and other map materials, collated within Geographic Information Systems (GIS), have established an essential role. Specifically, remote sensing can detect vegetated surfaces at high resolution using readily accessible data, whereas GIS provides a spatially referenced system for managing, visualizing, and analysing these data (Goodchild 1994; Goodchild and Case 2001; Xie et al. 2008). However, distinguishing characteristics related to ecologically important targets requires combination of several data sources and their advanced geoprocessing. As ecological values are built up from unique spatio-temporal nature-human dynamics, unravelling their subsequent traces in the contemporary landscape requires materials and observations over a relatively long span. This is a challenge in detecting ecologically valuable semi-natural grasslands, as their presently existing pattern is known to be influenced by the historical distribution and previous land use regimes (Cousins et al. 2007; Lindborg and Eriksson 2004; Skånes 1996).

This dissertation aims at developing methods to detect ecological values in highly heterogeneous and dynamic landscapes of south-western Finland. Focusing on semi-natural grasslands and using geospatial modelling techniques, the thesis establishes sophisticated evaluations of these important habitat components and their networks in the contemporary landscape. The detailed objectives of this dissertation are:

1. To identify the potentialities and restrictions of using existing geospatial data in mapping semi-natural grasslands;
2. To develop semi-automatic geospatial modelling methods, which allow detection of ecologically valuable grassland components in fragmented and dynamic landscapes; and
3. To discuss how these geospatial approaches can provide contextually smart solutions for improved management and conservation of semi-natural grasslands.

The thesis consists of a synopsis and four papers, henceforth referred to with roman numerals I-IV. The papers are presented with more details in Chapter 4.1.

# 2. THEORETICAL AND CONCEPTUAL BACKGROUND

## 2.1 Landscape and its components

*Landscape* creates an important framework for this thesis and belongs to the key concepts of modern geography. Etymologically the root form of the word "landscape" originated in Germanic languages and referred initially to a region of the environment with an emphasis on land reclamation and creation (Antrop 2013). In the scientific literature, Alexander von Humboldt in the early 19th century was regarded as the first person who specifically mentioned landscape when describing the physical appearance and structure of the land (Haber 2004). According to Humboldt's concept, landscape was principally to be defined through its visual and aesthetical constructions, which supported the wholeness of nature, and could not be separated from its physical characteristics (Bunkse 1981; Cosgrove 1985; Haber 2004). For Carl Sauer, who continued to develop the concept, landscape was an area made up of a distinct association of forms that included both physical and cultural phenomena (Agnew et al. 2003: 300; Sauer 1925). His definition stressed the fact that people were not only tied to their natural and physical environment, but had a possibility to change and shape it (Wylie 2007: 22). These views were also challenging contemporary studies of environmental determinism (Solot 1986) and provided support for a more holistic interpretation of landscape. Specifically in Finland, J.G. Granö had an important influence on the definition of landscape through his book *Reine Geographie*, published in 1929 in German and followed by a Finnish translation one year later. Granö's vision of landscape emphasized and further developed the German tradition, interpreting landscape principally as a product of human perception. Granö separated proximate and distant fields of visions, the latter of which was primarily perceived through the visual sense and acted as a synonym for a landscape (Buttimer 2010; Granö 1930: 17-18). In addition, Granö pinpointed the importance of landscape-derived explanation in geography as a tool to understand, classify, and delineate spatially organized phenomena (Granö 1930: 22).

More recently, landscape conceptualization has evolved to favour larger and more comprehensive entities that combine both spatial and visual characteristics (Naveh and Lieberman 1994: 4). It is, however, noteworthy that the vaguer English language version of *landscape* does not exactly correspond to its initial German counterpart *Landschaft*. The distinctively dualistic meaning that connected the surrounding environment to its definable regions, though not denoting a specifically bounded territory, has been dissipated in the translation (Cosgrove 2006; Granö 1998; Hartshorne 1939: 169). This shift is reflected in the definition provided by Antrop (2000a), which respects the preceding visual approaches by referring to landscape as a product of the perceivable environment, but mentions that landscape should be seen as a holistic, relativistic, and dynamic entity that is not tied to any territorial unit. Stemming partly from the linguistic shift from *Landschaft* to *landscape,* as well as the natural evolution of the scientific paradigms, the concept of landscape has been adapted and defined in various fields. For example, in human geography it may signify a system of social constructions (Duncan 1990: 17), or a non-representational entity defined by a combination of space, time, and experience (Thrift 2008: 19). In addition, the idea of landscape has been merged with more operative approaches such as in the case of landscape ecology, applying the initial theme towards an ecological interface with respect to its heterogeneous components, patterns and processes, various spatial scales, occurred changes, and anthropogenic influence (Wu 2013). Indeed, rather than having a single and absolute definition for what a landscape is, it has become a term that on the one hand has been formed in the course of history, while on the other hand can be redefined depending on the discipline, purpose, tools, and application of the observer. As stated by Hartshorne in the 1930s, but which still applies today, the concept of landscape has retained is importance in the field of geography. However there will always be a continuous and inevitable debate concerning its definition which arise from various critics, and is reflected in both major as well as minor respects (Hartshorne 1939: 158).

In this thesis, landscape is viewed as heterogeneous, hierarchical, and multiscaled entity, which has a transdisciplinary character, according to the characterizations of landscape ecology and landscape science (Antrop 2000b; Wu 2013). Biotic and abiotic landscape features and their trajectories are central considerations, but human agents are seen as a modern basis for the existence of semi-natural grasslands. Furthermore, in accordance with Granö’s ideas, landscape is considered as a framework to understand spatial phenomena in an organized manner, thus providing a concept to tie together a variety of its distinct but interdependent components. The important terms that are used in the thesis to distinguish certain landscape components from the ecological perspective are *biotope* and *habitat*. Of these concepts, biotope is understood to be a larger community- or population-related region of the environment that hosts a number of organisms, whereas habitat relates primarily to a place where a certain organism or species currently exists, or could be realistically expected to be found (Allaby 2010; Whittaker et al. 1973). These concepts do not form a fully nested hierarchy but rather they partially overlap and are often confused in common language, which has also created critical views of their correct definitions and usage (Mitchell 2005; Udvardy 1959). For semi-natural grasslands, however, a moderate level of confusion should be allowed, as delineating exact habitat units may prove to be an impossible task given their intrinsically heterogeneous appearance. In addition, landscape components distinguished in this dissertation are related both to existing characteristics and future potentialities. Therefore they do not fully satisfy the relatively static habitat definition but are closer to denoting favourable biotope conditions.

## 2.2 Landscape as a complex, dynamic and holistic system

Landscapes can be seen as systems that are characterized by high complexity in space and time, thus requiring detailed and case-sensitive approaches for their interpretation (Tscharntke et al. 2012; Waldhardt 2003). To respond to these requirements from the perspective of semi-natural grasslands, landscape should be interpreted as interplay of spatial, temporal, and cultural dimensions (Fig. 1). Of these three, spatial dimension relates primarily to the horizontal patterns that can be detected in the landscape. These patterns however operate at various resolutions and spatial levels, and therefore the focus should not be placed only on the coarse and abrupt variations. Instead, a hierarchical approach distinguishing small, transitional and fragmented components as an essential part of the landscape diversity should be adopted (Noss 1990). This is an important aspect since semi-natural grasslands are intrinsically heterogeneous habitats, and their abandonment is followed by a gradual succession to secondary forest (Johansson et al. 2008; Rocchini et al. 2006), thus emphasizing the need to see beyond robust landscape structures to detect their current state and potential trajectories.

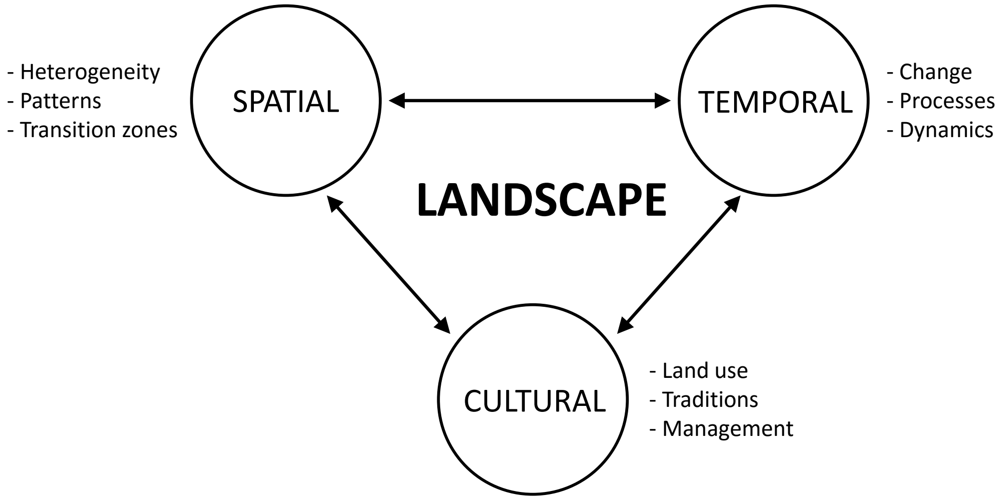

**Figure 1.** Schematic illustration of a holistic landscape approach and three key dimensions.

Distinguishing and understanding ecological values based on a present landscape i.e. using only the spatial dimension, will often lead to unsatisfactory results, because knowledge of the previous drivers and processes along the temporal continuum is essential as well (Ewers et al. 2013). These two dimensions are, however, closely linked since patterns like shape, size, and spatial arrangement of patches of vegetation in the landscape often result from previous ecological processes that have generated them (Rocchini et al. 2006). In the geospatial context, these considerations lead to the notion that a single data source may not be sufficiently detailed to capture fully this landscape heterogeneity, therefore, approaches are required that integrate data from different sources, scales, and temporal phases. Particularly important for semi-natural grasslands are favourable long-term dynamics and a lack of detrimental changes, which create preconditions for the targeted landscape characteristics. In this respect, landscape should be seen a holistic interplay of various components that should not be interpreted only based on the prevailing patterns, but also involving the temporal continuum and processes that are fundamentally linked.

Creation and existence of the contemporary semi-natural grasslands, however, depends essentially on anthropogenic activities and thus cannot be understood without the cultural dimension. While some commentators situate humankind apart from nature, insisting on a radical discontinuity between humans and the rest of the natural world (Spretnak 1999: 66), it is a more common perspective in geography to regard humans and their management of the landscape as integral to landscape development, resulting in both increased and decreased ecological values. This view is close to the concept of a total human ecosystem, which integrates humans into their total environment (Naveh 2000). In addition, when focusing on the holistic interpretation, landscape is a complex human-nature realization where its total outcome is always more than the sum of its respective parts (Antrop 2006). This is an essential point of view for semi-natural grasslands, which basically consist of natural elements that through patterns and abundance have been modified by anthropogenic activities.

This holistic concept gives a framework for perceiving and understanding landscape on a theoretical level, but in practice ecologically important landscape components need to be evaluated through proxies and estimates such as occurrence of easily distinguishable species (Caro 2010). This tends to cause inaccuracies and generally leads to the necessity of considering a broader range of environmental conditions, which are known to support the existence of these values according to the best of our knowledge. In addition, some of the landscape values may indicate promising possibilities rather than existing conditions. For semi-natural grasslands, an example could be dormant seeds which have accumulated in the soil but may not be viable to grow at present habitat conditions. If previous conditions would be restored, they could possibly germinate again and therefore enhance habitat connectivity (Auffret and Cousins 2011; Rudnick et al. 2012). Recognizing these prospects is an important issue, and should be regarded as a part of the landscape's future potential. However, management supporting the increase of ecological values needs to be well-planned and targeted according to regional landscape characteristics (Whittingham et al. 2007). This also reflects views discussed by Vitousek et al. (1997), pinpointing the fact that increased human dominance is causing rapid changes to Earth's ecosystems, and consequently we cannot escape our responsibility to maintain and manage our environment in order to keep it diverse and functional. Thus, a complex but structured perception of the landscape is more important than ever, or we will overlook important components that are essential for various ecosystem functions.

## 2.3 Key geospatial concepts

Smart and combined use of geospatial data forms an essential foundation for this thesis for the detection, measurement, and analysis of the dynamic dimensions of the holistic landscape. In general, *Geospatial data* refers to spatially organized and georeferenced information of the Earth phenomena (Macário et al. 2009).

Various geospatial data sources were used in this dissertation: earth observation data, fieldwork-based findings, and various existing contemporary and historical map materials.

Unfortunately geospatial data sources always reflect the landscape in an incomplete way – either by focusing on a limited range of environmental variation, or by generalizing the perceived complexity into logical and comprehensible units (Weibel and Dutton 1999). Geospatial information involves subjective decisions and often requires satisfaction of defined societal norms. Consequently, data does not intrinsically capture the holistic image of the landscape, but should rather be seen as a collection of resources used to arrange heterogeneous environmental components into an understandable form depending on the selected dimension. In addition to the early definitions of landscape, geospatial information may contain a range of features that cannot be derived from our visual senses. These features may help us to understand the existing landscape patterns from entirely new perspectives, and provide important aspects for holistic landscape interpretation. However, as initially emphasized by Sauer (1925), elements that are of anthropogenic origin are an integral part of the geospatial landscape in a fundamental way, and cannot be fully separated from “natural” counterparts.

Spatial and temporal landscape dimensions can be organized through two key concepts of *pattern* and *process* (Shao and Wu 2008; Wu and Hobbs 2002). Pattern refers primarily to structural components such as shape, size and spatial arrangement, which arise from complex interactions between physical, biological, and social forces (Farina 2008; Turner 1989). Analysis of patterns requires simplification of this inherent landscape heterogeneity into simplified models represented by raster pixels, points, linear networks, continuous surfaces or categorical patches (McGarigal 2006). During the last decades, various geospatial data sources have gained great importance in observing the landscape patterns, providing tools for a better understanding of their scattered components, and connecting patterns to processes (Nagendra et al. 2004; Shao and Wu 2008). Linkages between patterns and processes are generally firm but complex: some patterns are created by certain processes, but other processes depend on or are limited by patterns (Bell 2012: 16; Schröder and Seppelt 2006). Processes can be understood as the interaction of different objects in an environment, and classified to be either exogenous or endogenous, but their exact meaning varies considerably between applications (Schröder and Seppelt 2006). Processes or their consequent geographical realities are often simplified and represented as models, which help to formalize and develop theories about how patterns and processes interact (Goodchild 1992; Turner et al. 2001: 67). Creating models that indicate dependencies between the patterns and processes occurring on semi-natural grasslands is one of the core issues discussed in this dissertation.

Further important concepts that support pattern definition are *scale*, *extent* and *resolution*, which are partially overlapping. Scale, for example, can denote the spatial context where geographical phenomena occur; this can vary from a single point to the entire globe and beyond (Meentemeyer 1989) or alternatively may point out the temporal range applied in the study (Turner 1990). Scale can also be used to describe the magnitude or size of the study units (*e.g.* “small scale variation”), referring to concepts such as the size of the smallest observable element (or grain), extent, lag or cartographic ratio (Wu 2004). Alternatively it can be used to emphasize the regional focus of the study as applied in “landscape scale” (de Vries et al. 2012; Elkin et al. 2012; Phillips et al. 2003). In this context, landscape scale would generally be understood as a cluster of interacting ecosystems which are repeated in a similar form for a few kilometres or more (Forman and Godron 1986: 11). In addition, scale can signify the accuracy of the vector format in terms of its initial construction, with a potential further specification of being a *nominal* scale. Compared to scale, the definition of extent is relatively simple as it normally denotes the used study region or a certain measurable area (Meentemeyer 1989; Turner et al. 1989), and often expressed as an absolute figure. Resolution, in turn, can be used in spatial (element size), spectral (ability to define distinct spectral ranges) as well as in temporal (frequency of observations) meanings (Lausch and Herzog 2002), but most often it is applied to describe the pixel size of a raster such as those found in satellite images. In this dissertation, the term scale has variable meanings, which vary with the study context, extent denotes a certain areal coverage, and resolution is generally used to indicate the accuracy of pixel-constructed data.

## 2.4 Mapping of spatial patterns

When mapping landscape patterns and related processes, it is essential to understand the characteristics and production processes of the used geospatial data. Furthermore, in the context of semi-natural grasslands, the applied data should be able to assist in the detection of both larger biotope networks as well as its smaller and partially overlapping components, which vary in space and time. This poses challenges for recognizing the patterns of interest, and extracting the essential information from the total landscape variation.

In this dissertation, remote sensing imagery and existing maps are fundamental sources of information in detecting both contemporary as well as past landscape characteristics. Of these two, remote sensing acquisitions can be considered *primary data*, i.e. being direct measurements, which are usually the first link of the processing chain that potentially ends with highly transformed output products (Lillesand et al. 2015: 488). Such transformation would include: georectification, preprocessing procedures, analysis, and production of maps or other final material that indicate the pattern of interest (Song et al. 2001). Whilst processing primary data is time-consuming with many stages where errors can be introduced and compounded, it does provide the end-user with near-complete control over the outputs, which in turn can be tailored to the research question of interest. However, since spatial patterns are usually scale dependent, distinguishing the desired phenomena requires that spatial and spectral resolution, as well as the extents of the data are suitable (Lam and Quattrochi 1992; Saura and Martinez-Millan 2001; Shao and Wu 2008). For heterogeneous semi-natural grasslands, relatively high spatial resolution is normally needed to enable the detection of fine-scale and partially mixed vegetation targets.

*Secondary data sources*, such as processed geospatial data layers in GIS or existing map sheets are generally easier to implement and suitable for identifying patches that are relatively homogeneous and exhibiting abrupt transitions to adjacent areas (Gustafson 1998). This is often the case for areas of high anthropogenic influence such as urban features, infrastructures or cultivated fields, but such abrupt class borders can include a large number of subjective decisions or be misleading in a landscape characterised by transition zones, or ecotones (Arnot and Fisher 2007; Brown 1998; Hansen et al. 1988; Küchler 2012). Therefore, there are a few additional important considerations that must be addressed. Firstly, class units are apparently homogeneous and supposed to minimize their within-unit variation but in reality, all maps should be seen simply as generalisations that emphasise the selected themes while suppressing the unimportant properties (Foody 2002; Weibel 1997: 101). For example, widely used CORINE classification (Anon. 2000) defines broad-leaved forest as being characterised by a vegetation formation that is composed principally of trees with mainly a predominance of broad-leaved species having at least 30% crown coverage, and satisfying the minimum mapping unit of 25 ha (Bossard et al. 2000: 67). To put this definition in another way, if we see a certain patch from above, it must be large enough to avoid amalgamation into neighbouring entities, up to 70% of land cover types other than trees may be visible, and almost half of the trees do not need to belong to broad-leaved species; however, it is still possible to call it a broad-leaved forest. Secondly, it is important to recognise the intended use of the classification, which provides important hints of the emphasised characteristics and suitability for specifying the patterns of interest. One important delineation is whether the data indicates *land cover* i.e. its biophysical attributes, or *land use,* which expresses the intents or transformations by human action, thus providing a socioeconomic portrait of the landscape (Lambin et al. 2001; NRC 1999: 304). These categories are also often mixed, causing difficulties for their exact interpretation and intended separation. Thirdly, even if we are convinced that our class definitions and level of generalisation is suitable for the observed pattern, attention must be paid to the comparability of different data sets in the case of their integration. This concern is closely related to conceptual spaces, ontology and the semantics of the classification, i.e. to what degree do different class definitions match each other, and what solutions to deal with potential mismatches are needed (Ahlqvist 2004; 2005). Semantic diversity and plasticity can occur both in space, as exemplified by different concepts of “forest” by Björk and Skånes (2015), as well as in time, when apparently similar classes have dissimilar interpretation at different moments (Comber et al. 2004).

When the considerations above are applied to the mapping of semi-natural grassland patterns, primary data would normally provide more details on spatial landscape dimension and potentially indicate its previous and ongoing processes. However, it omits confirmed information on the cultural dimension (e.g. land use). Furthermore, primary data sources do not have a long historical span or their availability is highly limited, which makes it impossible to use them for interpreting extended retrospective trajectories. And finally, processing primary data sources is tedious and requires considerable amount of contextual knowledge, thus making their use unfeasible in many circumstances. One solution for smarter usage of secondary data is to recognise patterns using fuzzy characterisation. A fuzzy concept stands for insertion of multiple membership values for the same entity or boundary line, and can help to take a substantial step towards the detection of actual, naturally organised patterns. Fuzzy approaches are capable of representing mixed, imprecise or vaguely known data (Fisher 2001; Salski 1992; Wang and Hall 1996), which otherwise would be impossible to incorporate into conventional classifications. Even fuzziness must be based on finite and predefined categories, but recognising their overlapping mixtures with specified membership values helps to overcome the most severe limitations related to exclusive classes and abrupt borderlines. A fuzzy approach has also been adopted in this dissertation as an integral strategy to describe elements of semi-natural landscape patterns.

## 2.5 Landscape modelling

*Landscape modelling*, in this thesis, refers to smart and combined use of several geospatial data sources, resulting in the identification of landscape characteristics that support the existence of semi-natural grasslands. A generic geographical interpretation for a “model” is to recognise it as an idealised and structured representation of real phenomena (Warf 2010) with varying scales and targets. Fundamentally, models have a highly selective attitude to information, where less important signals are eliminated to emphasise selected, relevant or interesting aspects (Haggett and Chorley 1970: 23). In the landscape context, models basically describe how structured observations vary from random realisations and how different environmental objects interact (Schröder and Seppelt 2006). These can also be extended to include the cultural dimension through anthropogenic effects and consequent dynamics, leading to the recognition of the strong coupling between human agents and their surrounding environment (Werner and McNamara 2007). As exemplifications for landscape ecology, Sklar and Costanza (1991) define models as being mainly used for (1) quantitatively describing spatial landscape level phenomena; (2) predicting the temporal evolution of landscapes; and (3) integrating between and among spatial and temporal scales. These definitions are close to the themes discussed in this dissertation: the models are based on landscape observations and applied to simplify complex structures into spatially separable components. In addition, patterns and processes, the temporal dynamics and the natural as well as anthropogenic factors as recognized as integral parts of the targeted landscape system.

Models can work either on a conceptual or operational level. In this thesis, Figure 1 represents a conceptual landscape model which helps in targeting the discovery and description of the essential components for habitat delineation and spatial planning (Fischer et al. 2004; Fries et al. 1998; Sanderson et al. 2002). Models are however predominantly discussed on operational level, focusing on quantitative dependencies between environmental variables which are described by statistics. These models normally include phases of formulation, parameterisation and verification, with the subsequent steps of analysis, validation, and prediction (Pearson et al. 1999). An important operational application presented in the thesis is species distribution modelling, relating the geographical distribution of species or communities to their environmental conditions in a static and probabilistic way (Guisan and Zimmermann 2000). Recently, species distribution modelling applications have been facilitated by developments in statistics and information technology, thus making them capable of establishing better links between the field-based information with extensive amount of GIS-derived environmental layers (Elith and Leathwick 2009). Increased supply of environmental data has also expanded the use of species distribution models, but simultaneously resulted in the emergence of applications that are initialised without a solid and realistic ecological base (Austin 2007; Elith and Graham 2009). Hence, a careful consideration of the environmental conditions, used variables, and representativeness of the species data is required to ensure successful modelling. From the perspective of semi-natural grasslands, it is fundamental that all the landscape dimensions are included in the modelling approach to gain realistic results.

A common deficiency in many landscape-related models is their focus on the currently observable characteristics without properly perceiving the landscape's dynamism. Firstly, this may obscure the interpretations of present environmental relationships as they are highly affected by the previous trajectories (Käyhkö and Skånes 2006). The historical legacy is especially obvious when the models deal with the distribution of plant species on semi-natural grasslands, exhibiting slow responses to landscape changes and lacking an immediate ability to search for an alternative habitat (Burel 1993; Helm et al. 2006; Orians and Wittenberger 1991). Incorporating historical knowledge into models is not straightforward since we can mostly only observe the past landscape phases through snapshots at irregular intervals, with differing accuracies, semantic characteristics, and often poor documentation (Kienast 1993; Vuorela et al. 2002). However, it may offer us the only way to explain patterns that otherwise appear to be irregular, random or biased. Secondly, when models are projected to provide data for the future, altering conditions may affect the accuracy of the results. A fixed time horizon easily leads to neglecting the long-term dynamics of human-environmental systems, and prevents estimation of alternative future environments via different scenarios (Veldkamp and Verburg 2004; Verburg et al. 2006). Scenario-based modelling can be used for topics where rate and direction of changes can be estimated, such as predicting the potential effects of changing climate conditions on ecosystem properties and landscape configuration (Nuñez et al. 2013; Opdam and Wascher 2004; Prentice et al. 1993). However, scenarios can also be based on qualitative expert-based evaluations, as exemplified in the dissertation paper IV. Such evaluations and their consequent results are constructed through subjective but well-founded decisions, which are also able to project potential anthropogenic modifications into the future.

# 3. STUDY AREA

## 3.1 General characteristics of the study area

The empirical work of this thesis was done in south-western Finland, in three study locations between 21-24°E and 60-61°N (Fig. 2). The region is located at the northern edge of the hemiboreal zone, which is characterized by boreal influences, such as the commonly found podsolic soils and a dominance of coniferous trees, as well as existence of temperate vegetation like Penduncalate oak (*Quercus robur*) (Ahti et al. 1968: 190-191). Penduncalate oak is also important as a keystone species that houses a large diversity of other species, and has consequently a high conservation value in the region (Alanen and Osara 1986). Due to historical reasons and continuous long-term management activities, particularly extensive oak forests are to be found on the island of Ruissalo (Mäkitalo 2006). In terms of larger habitats with high ecological values, the traditionally managed grasslands and their transition zones to woodland vegetation are one of the most important. These habitats are commonly called semi-natural grasslands and characterised by low nutrient levels, but a high diversity of perennial grasses, belonging to one of the most biodiversity rich habitats in the hemiboreal areas of Europe (Hansson et al. 2000; Pykälä 2003).

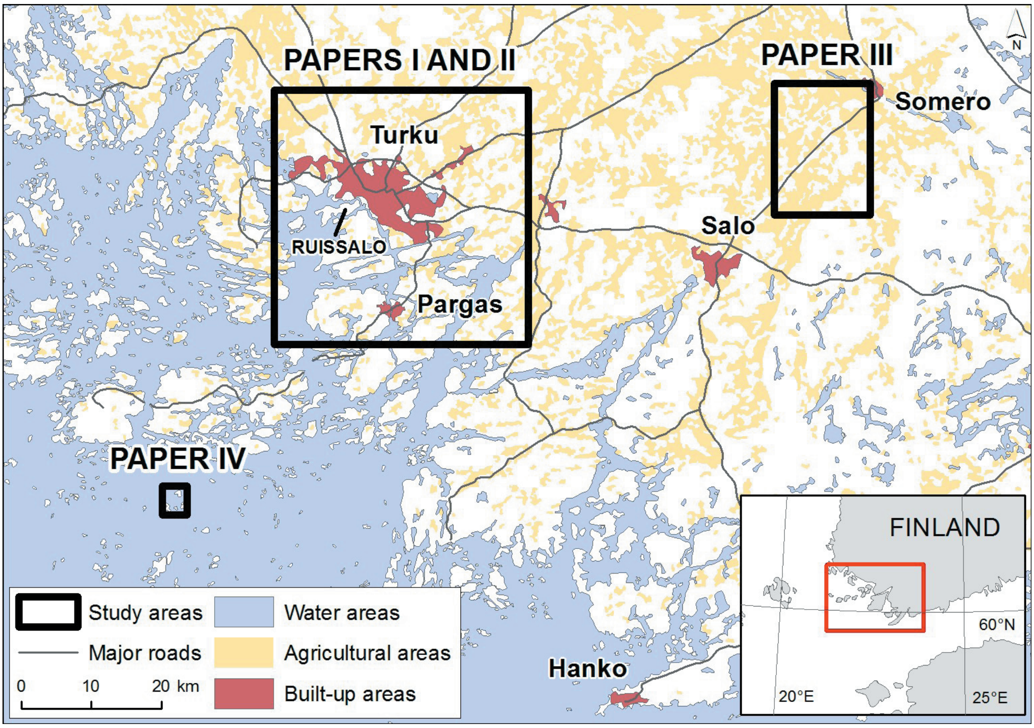

**Figure 2.** Study area and case study sites of the dissertation papers. National Land Survey of Finland, 2015.

The study region has high landscape heterogeneity, resulting from both natural and anthropogenic factors. Firstly, soil conditions vary considerably between the archipelago zone, characterised mainly by bedrock-dominated islands with relatively thin soils, and inland areas with more predominant clay and moraine deposits (Tikkanen 1994). Secondly, topographic conditions are affected by frequent bedrock outcrops, which generate an undulating terrain with a high degree of small-scale variation. Thirdly, due to historical reasons, accessibility, and differing environmental conditions the land use patterns have consequently been diversified into various forms and traditions within the area. These factors make the vegetation to consist predominantly of small patches with frequent transition zones, offering a suitable environment to develop and test various detection and mapping methods. This is particularly challenging for semi-natural grasslands which are fragmented and heterogeneous habitats, thus being often neglected in most approaches.

## 3.2 Semi-natural grasslands in hemiboreal landscapes

Given the recent decline in the ecologically important hemiboreal, semi-natural grasslands in Finland, these cultural landscapes form the focus of the study subject in the papers of this thesis (Fig. 3). Particular biodiversity values are associated with grasslands that have been purposely managed by grazing and/or mowing, but not intensively altered by fertilisation or drainage activities (Cousins and Eriksson 2001; Eriksson et al. 1995). During the long trajectory of management activities, this has resulted in a very high diversity of vascular plants (Cousins et al. 2007; Kull and Zobel 1991). However, their history extends to pre-agricultural time before the relatively late initiation of animal husbandry or management activities (Eriksson et al. 2005), which has created debate regarding their initial origin. Until recently, it was commonly thought that deciduous woodlands had dominated most of Central and Western Europe prior to human intervention, covering areas where trees in general were able to grow and leaving only minor spaces for more open habitats (Vera 2000: 1). Undoubtedly woodlands have been extensive, and the majority of the original forests have since been cleared (Peterken 1996: 34). However, based on the richness and abundance of grassland plants that require relatively open habitats, the total dominance of woodland vegetation has been questioned. Two principal ideas have been suggested to explain the more extensive and permanent existence of grasslands within the woodland matrix. Firstly, grasslands may have occupied a continuum of temporary habitats that were created by woodland disturbances, such as gap dynamics and wildfires, in combination with more permanent open patches on poor soils, shores, or floodplains (Bullock et al. 2011; Eriksson et al. 2005). Secondly, previously existing large herbivores such as wild ox, bison, and the wild horse may have had a major influence on the openness of the vegetation by browsing, grazing, trampling, and suppressing the growth of tree saplings (Eriksson et al. 2002; Svenning 2002; Vera 2000).

**Figure 3.** Contemporary semi-natural grassland area on Mälhamn island, part of paper IV study area.

There is not quite enough evidence to fully support the herbivore theory, but at least part of the semi-natural grassland species are virtually dependent on the existence of grazed habitats and cannot survive elsewhere (Kirby and Watkins 2015; Lindgren 2000: 28; Pykälä 2000). These drivers may also have been variable in different regions, and it is most likely that at least part of Europe may have been characterised by a dynamic landscape where a rhythm of tree and shrub regeneration were followed by an opening of the woodlands (Plieninger et al. 2015). Regardless of the initial origin of semi-natural grassland plants, it seems to be likely that the habitat continuum was partially replaced by scorching tactics and early animal husbandry in the Neolithic period, and later maintained by more extensive livestock grazing (Lindgren 2000: 28). These so called secondary grasslands were then managed with relatively similar systems for centuries or even millennia, until about the early decades of the 1900s (Erhardt and Thomas 1989). Management activities in the hemiboreal areas of Europe often included a combination of methods such as spring raking, grazing, mowing, intentional removal of woody plants, pollarding of scattered deciduous trees to provide winter fodder, and collecting of cattle dung for cultivated fields (Hansson et al. 2000; Jääskeläinen 2003; Kotiluoto 1998; Wahlman and Milberg 2002). Such management resulted in a negative nutrient balance by removing more nutrients than the growing plants or cattle dung would have provided (Vainio et al. 2001: 101). Further, this supported the co-existence of various relatively small-sized plant species and suppressed the extensive growth of tall grasses, thus maintaining high levels of biodiversity (Johansson et al. 2008). These traditionally managed semi-natural grasslands could be seen as a form of artificial habitats coincidentally providing environmental conditions which sustained many of the disturbance-adapted grassland species (Lindgren 2000).

Within the last century however, management activities and preferences in agriculture have faced drastic changes. In Europe, low intensity farming has been affected by rapid technical development, rationalisation of farming activities and intensified land use, driven by the changed relative prices between inputs and outputs (Baldock et al. 1994: 59; Hooftman and Bullock 2012; Strijker 2005). Today, grazed grasslands do still exist in the landscape but they are often artificially fertilised and characterised by high stocking rates, and dominated by a few productive forage species instead of high plant diversity (Isselstein et al. 2005). In the context of Finland, previous semi-natural grasslands were first largely converted to arable land and hay fields, and later also afforested and partly abandoned (Luoto et al. 2003). The semi-natural grasslands that remain today are only a small fraction of the coverage that used to be a century ago, and their habitat quality has been lowered partly due to lapsed management, and partly due to eutrophication (Pykälä 2000: 114; Vainio et al. 2001). In addition, the remaining semi-natural grassland patches are not only smaller but also considerably more fragmented and isolated in the landscape matrix compared to their previous extents (Johansson et al. 2008; Kiviniemi and Eriksson 2002). This can result in an extinction debt, which further leads to the notion that even if the current landscape conditions could be preserved exactly as they are now, the long-term existence of the contemporary species pool may not necessarily be secured. Further, while management of the existing semi-natural grasslands is essential, active restoration of deteriorated conditions may be of substantial help in preserving their functionally viable, habitat network.

Today, the management of semi-natural grasslands is supported by agricultural subsidies that compensate landowners for the production losses incurred compared to more profitable forms of land use (Isselstein et al. 2005). To ensure successful results, such management targets should be carefully selected as they require long-term commitment and the allocation of substantial resources (Myklestad and Sætersdal 2004). Availability of suitable spatial information to focus the management actions, however, is generally limited and many of the existing data sources do not necessarily support these aims. One of the primary reasons for this is the complexity of semi-natural grassland habitats – they are formed over a long time span by a certain combination of land cover, land use, and soil characteristics, and often occur as small patches within the surrounding landscape matrix. Consequently, the majority of ready-made maps or land cover / land use classifications will provide only weak indications of potential semi-natural grasslands as they are easily classified together with more robust entities, or amalgamated with larger neighbouring patches. At the other end of the spectrum are the fieldwork campaigns, which are able to efficiently distinguish valuable semi-natural habitats, but which can only cover limited areas due to their intensive and resource-driven approach.

The mapping and modelling methods presented in this thesis aim to find solutions for better detection of valuable semi-natural grassland areas and thus improve their science-based management. The results provide relatively accurate and timely data to map potential sites for semi-natural grasslands, which can be used to focus fieldwork efforts (Weiers et al. 2004). In particular, the use of historical materials improve the detection of temporal and cultural landscape dimensions, therefore supporting the identification of valuable semi-natural habitat characteristics (Cousins and Eriksson 2002; Helm et al. 2006; Reitalu et al. 2010). Their advantage is the simultaneous interpretation of the temporal continuum, which helps to indicate grassland patches characterised by continuous but low-intensity management. In addition, those fragments that no longer belong to core habitats but still exist in the landscape pattern, or have recently started to transfer into woodland areas, can be identified. This helps to plan fieldwork campaigns, which are always required in the detection of specific habitat characteristics.

## 3.3 Case study sites

The three case study sites are good examples of the diversity of landscapes in the south-western Finland, and provide a cross-section of the environmental characteristics and history of this region (Fig. 4; see also Fig. 2). The study area of papers I and II is located on the coast, with landscape characteristics ranging from small and rocky archipelago islets to relatively flat inland terrain with urban structures, agricultural fields, and forests. The city of Turku, and its surrounding regions, now has a population of approximately 300,000 inhabitants and consequently extensive areas are characterised by infrastructure and built-up surfaces. Previous natural or semi-natural grasslands do however persist as generally small, often transitional and partly transformed patches within the relatively sparse urban structures.

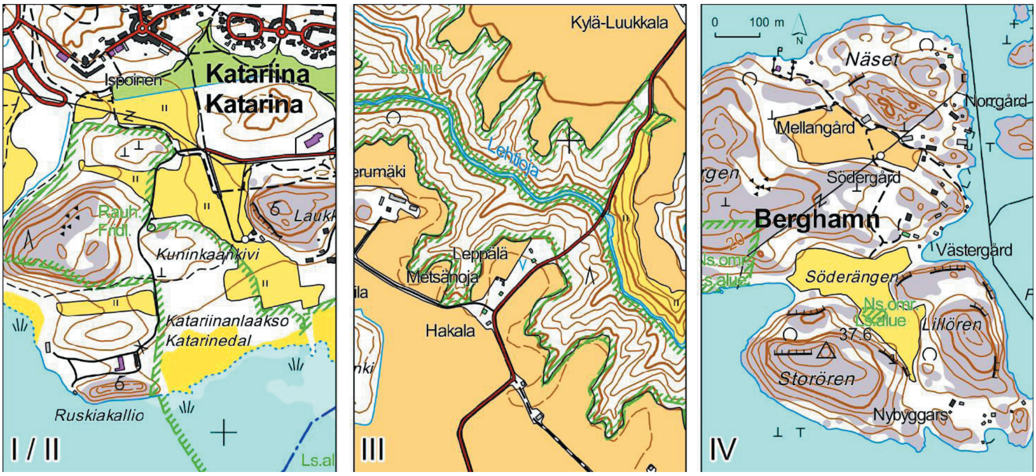

**Figure 4.** Case study sites as detailed samples: the left site is from Turku (papers I+II), the middle from Rekijoki (paper III), and the right from Berghamn (paper IV). All three maps are in the same scale and the elevation contours are drawn at 5 m intervals. The colour indicate agricultural fields (darker yellow), grasslands (lighter yellow and green), forests (white), water areas (blue) and bedrock outcrops (grey). National Land Survey of Finland, 2015.

Paper III represents a predominantly fertile agricultural area without urban structures. An exceptional landscape feature in the area is the Rekijoki river with its tributaries, which are characterised by long and relatively steep V-shaped valleys that contain the most significant semi-natural grassland areas with high conservation value (Vainio et al. 2001). The Rekijoki area is designated as a Natura 2000 site but despite conservation efforts and recent management activities, partially discontinued grazing has caused a decline in the number of vascular plants and many of the fragmented or partially overgrown grassland patches are threatened by the expansion of forest species (Luoto et al. 2003). Targeted management at suitable sites including renewed grazing regimes, however, have the potential to restore some of the deteriorated habitats relatively quickly (Kumpulainen and Sihvonen 2013).

Paper IV focuses on the three main islands of Berghamn village, which is part of the Archipelago National Park. The area is characterised by bare bedrock areas and windswept pine forests on rocky hills, but harbouring lush vegetation, broadleaved trees and frequent semi-natural grassland habitat patches in more sheltered places (Mussaari et al. 2012: 37). Abandonment of traditional grassland management techniques was relatively late in the area and has been succeeded by the gradual invasion by woody species. Restoration of some of the previous semi-natural grasslands, however, was already initiated in the late 1970s and still continues as a part of nature conservation activities (Kotiluoto 1998).

# 4. MATERIALS AND METHODS

## 4.1 Research design

This dissertation consists of four papers (I-IV), which evaluate the patterns, processes, and future potentialities related to hemiboreal semi-natural grasslands. With respect to the landscape dimensions described in Figure 1, most discernible variation is along the temporal axis, as illustrated in Figure 5.

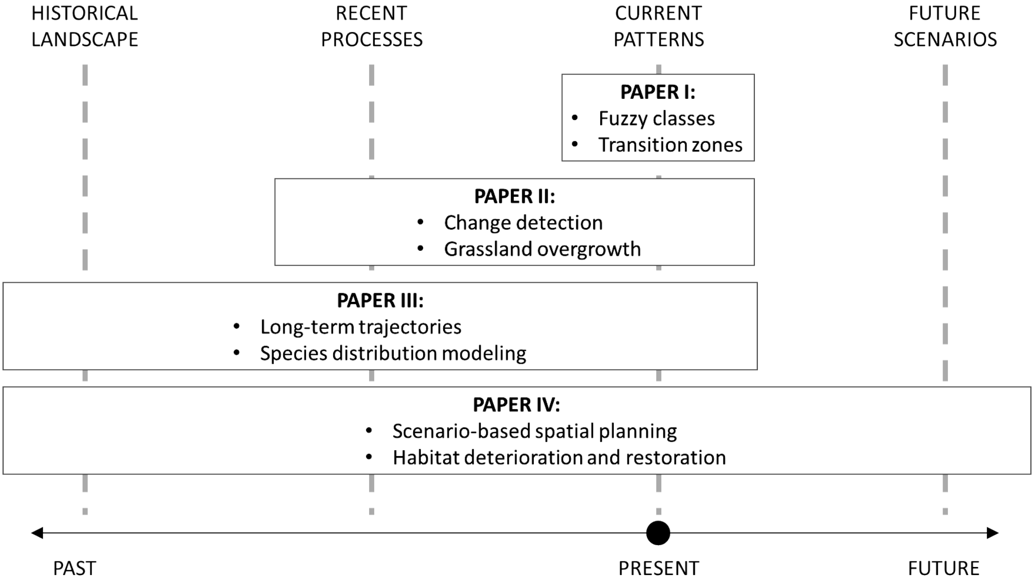

**Figure 5.** Characterisation of the study papers (I-IV) according to their principal characteristics.

**Paper I** develops new strategies to detect overlapping yet ecologically distinct landscape components, which in this case refer to the transition zones between grassland and woodland vegetation. These mixed components are typical for semi-natural grasslands but the problem in most contemporary maps is their tendency to generalise transitional vegetation elements into a few robust classes. This provides the user with a clear 2D categorical representation of the landscape, but considerably reduces the ability to interpret patterns of landscape structure in a detailed way. In this paper, contemporary data sources used to predict the fractional values of the modelled vegetation components i.e. represented as a fuzzy set. Furthermore, the characteristics and importance of such an approach to distinguish fractional land cover components is discussed, and combining them with existing map materials is exemplified. These results may further be refined to pinpoint detailed biotope and habitat properties from the landscape, and they can provide important information for detecting gradual landscape changes.

**Paper II** focuses on the detection of recent processes, providing essential information on how the pattern structure described in paper I has potentially emerged, and whether it is currently under a major vegetational shift. The development of a new method is described in the paper to detect vegetation succession in abandoned grassland areas, where this process occurs naturally after management has ceased, and may have slow but drastic consequences for the biodiversity values of semi-natural grasslands (Eriksson et al. 2002; Pykälä et al. 2005). It shares the same study area with paper I and utilises some of its results, but focuses more on recent development than transient landscape state. The principal source of data are laser-generated lidar acquisitions i.e. observations of (x, y, z) reflection points collected from an aeroplane, combined with multitemporal satellite and aerial images. The results indicate that while low-density lidar data itself is highly capable of detecting vegetation structures, such information content is generally not sufficient to indicate processes that occurred previously. However, complementing lidar with other data improves the detection of overgrown grasslands, and assists their separation from unchanged land cover types.

**Paper III** extends the detection of processes over a longer span compared to paper II, indicating that in addition to observing the present landscape state and its recent shifts, proper understanding of semi-natural ecological values requires knowledge of a considerably longer trajectory. It concentrates on species distribution modelling to find the principal environmental determinants for Fumewort (*Corydalis solida*) occurrence. Fumewort can be regarded as an indicator species of valuable semi-natural grasslands in the study area and, therefore, can assist in locating these ecologically significant but fragmented habitats. This paper uses a variety of geospatial data sets from the 1870s to the present. The results support the high significance of historical factors, especially the extents of previous grasslands, which cannot be interpreted based only on the present situation. However, the selection of model variables must be done carefully, on order to result in an outcome that respects both the core as well as the marginal habitat patches.

**Paper IV** synthesises the messages of the previous papers and combines detailed information on the present landscape state with habitat changes that occurred previously, in order to support practical actions. These can be regarded as the key determinants for science-based spatial planning of semi-natural grasslands, which in paper IV are used to identify overgrown grasslands sites for potential restoration. The approach in paper IV is mainly based on the interpretation of aerial images, which simulates a more practical and strongly expert-based analysis, but which initially is founded on the principles discussed in papers I-III. Furthermore, paper IV emphasises the importance of targeted management rather than strict protection of semi-natural habitats when attempting to ensure their long-term existence.

## 4.2 Data sources

A range of geospatial data sources were combined for pre-processing, classification, and modelling or validation purposes. The data types included seven distinct categories based on their information type, contents, and production strategy: categorical maps, aerial images, satellite images, digital elevation models (DEM), light detection and ranging acquisitions (lidar), national forest inventory data (NFI) and field data (Table 1). In addition, the modelled results from paper I were used as an important input dataset in paper II.

**Table 1.** Data sources used in the four papers.

| | Categorical maps | Aerial images | Satellite images | DEM | Lidar | NFI | Field data |
|---|---|---|---|---|---|---|---|
| **PAPER I** | X | X | X | X | | | |
| **PAPER II** | | X | X | | X | X | |
| **PAPER III** | X | | X | X | | | X |
| **PAPER IV** | X | X | | | | | X |

The following software products and digital tools were used: ArcGIS (versions 10.1 and 10.2; in all the papers), Erdas Imagine (versions 2013 and 2014; in all the papers), R statistical software (versions 2.15, 3.0 and 3.1, in papers I, II and III), Python programming language (version 2.7; in papers I, II and III), Idrisi (version Selva; in paper I), GRASS GIS (version 6.4; in paper III), MaxEnt (version 3.3; in paper III) and FragStats (version 4.1; in paper IV).

### *4.2.1 Categorical maps*

Categorical maps used in the dissertation were relatively heterogeneous materials. The oldest of these data sources were topographic maps from the 1870s, hand-drawn by Russian military surveyors at a nominal scale of 1:21,000; they systematically describe landscape elements with relatively high amount of detail (paper III). They were produced to cover the majority of southern Finland, and as a contemporary novelty, they also include elevation contours instead of the previous shading-based visualisations (Mönkkönen 2006: 16). Further historical data sources included a hand-drawn general parcelling map of Berghamn hamlet from the year 1890, prepared to divide the previous common land into private plots (paper IV). General parcelling (*isojako* in Finnish) started in the mid-1700s and was based on the fair distribution of resources, mainly related to agricultural and forestry use, and for that purpose maps needed to be highly accurate and also include a detailed description of the land fertility (Mönkkönen 2006: 57-59; Päivänen 2010). In addition to these historical maps, relatively old basic maps from the 1960s were utilised in paper III. Their appearance and information content were quite similar to present day maps, thus allowing a more straightforward interpretation compared to the maps from the late 1800s. The older maps, however, indicated important information regarding the previous land cover and land use characteristics, such as the extent of non-cultivated grasslands or the development of the villages prior to later landscape modifications.

Digital categorical maps, used in the dissertation papers for either pre-processing or modelling purposes, included features extracted from the presently available topographic database (papers I, III and IV), CORINE Land Cover classification (paper I) and SLICES land use classification (paper III). The topographic database (*maastotietokanta* in Finnish) was acquired from the National Land Survey of Finland with an accuracy corresponding to a nominal scale of 1:5000 at best (Anon. 2015). SLICES and CORINE classifications were raster data sets indicating land cover / land use characteristics, the former being a national product at 10 m pixel size and the latter a Pan-European classification with 25 m pixels.

### *4.2.2 Aerial and satellite images*

Aerial and satellite images were used in all the papers, either alone or to provide earth observation data at both finer and coarser resolutions. Aerial images produced a detailed interpretation of the landscape, and were also applied as stereo pairs in paper IV. Compared to relatively recent satellite materials, aerial images extended the study range from 1939 to 2013, thus covering the span when farming activities experienced drastic changes in the study area. Earlier images contained only greyscale information and their pre-processing was more tedious due to film deformations, lower spatial accuracy or missing parameters. Newer images were available in colours and some even as readily orthocorrected frames where distortions were minimised. Some of the aerial images included a near-infrared band which specifically assists in distinguishing between the different types of vegetation (Ihse 2007). The aerial images proved invaluable in many of the attached papers but due to slow and expensive production process, their availability was generally relatively limited. Most of the images used in this dissertation were produced by the National Land Survey of Finland for general, topographically oriented mapping purposes. Further, this meant that the majority of them were early spring images, i.e. showing the terrain as accurately as possible without leaves on the trees, but they are not designed for vegetation mapping. However, with the lack of resources prohibiting the arrangement of any new and more optimal acquisition campaigns, they offered the only available material that it was possible to obtain. Furthermore, some analyses such as the visual image interpretations in paper IV were highly tedious and thus restricted the total area of analysed landscape components.

Satellite images provided synoptic coverage, and were used to detect larger landscape continuums at lower resolution compared to aerial images. They contained a range of wavelength-specific bands and a regular acquisition schedule, which assisted in the extraction of vegetation patterns at suitable dates. In this dissertation, satellite images included optical frames that had been acquired by Landsat or RapidEye satellite systems. Landsat images were particularly useful due to the extensive repository that is usable at no cost via the internet (Loveland and Dwyer 2012). Landsat frames were used in papers I and II, acquired by TM and ETM+ sensors, both of which having six bands at 30 m pixel ground resolution (excluding thermal and panchromatic bands) and a fixed 16-day revisit cycle. RapidEye materials were used in articles I, II and III, respectively. Compared to Landsat, RapidEye has a finer resolution (6.5 m; resampled to 5m) but fewer bands (5), although it has a specific red edge band that supports vegetation analyses (Tyc et al. 2005). However, RapidEye has a much shorter total temporal range compared to Landsat (since 2009) and acquiring the data is costly, thus the use of RapidEye images was limited to applications requiring repetitive acquisitions or large coverages (Gärtner et al. 2016; Kussul et al. 2012).

### 4.2.3 Digital elevation models

DEM materials, produced by the National Land Survey of Finland in raster format, were applied for masking (i.e. removing unwanted landscape components) and modelling purposes in papers I and III. They were used in the two resolutions that were suitable for the respective purposes: 2 m (paper I) and 10 m per pixel (paper III). The 2 m DEM was the most accurate publicly available elevation model in Finland and produced based on lidar acquisitions, while 10 m DEM has a considerably wider coverage.

### 4.2.4 Lidar and national forest inventory data

Lidar acquisitions and national forest inventory data (NFI) were utilised only in paper II. Lidar instruments measure the roundtrip time for a pulse of laser energy to travel between the sensor and a target, which further provides a distance from the instrument to the object (Dubayah and Drake 2000). In particular, the abilities of lidar to describe complex vegetation structures with frequent gaps and produce detailed observations based on multiple returns were highly useful in paper II (Bradbury et al. 2005; Gaveau and Hill 2003; Suárez et al. 2005). NFI data concerning various forest-related attributes, in turn, had only a minor role in the estimation of the Landsat-derived vegetation trend, but it should be recognised as a data set of its own. NFI was acquired without cost from the Natural Resources Institute (formerly the Finnish Forest Research Institute). NFI data could have been used more widely in the other papers as well, but being a modelled result with consequent potential errors, it was not found to be highly suitable to train or validate other models.

### 4.2.5 Field data

Field data were used in papers III and IV. In the third paper, field-derived observations of Fumewort (*Corydalis solida*) were applied for the purpose of species distribution modelling. This data was collected by Kumpulainen et al. (2013) in 2012-13 by observing Fumewort occurrences during the springtime flowering period. The observations were recorded mainly in 50 m x 50 m squares, and divided into three categories: abundant Fumewort coverage, single plants observed, and no plants observed. Part of the data was collected using 100 m x 100 m squares, but due to their substantially different spatial extents they were not used in the paper III. In addition to the third paper, field data was also important in paper IV, although in a more qualitative manner. More specifically, paper IV required collection of field information by repetitive visits and GPS-based observations (incl. photographs) which guided the trajectory classification process and helped to validate their interpretation for management purposes. These field visits were essential to understand the present landscape, interpret its weak historical signals, and gain knowledge for trajectory classification, which otherwise might have been performed using erroneous assumptions.

## 4.3 Methods

A three-stage method was employed. Firstly, data were pre-processed. Secondly, classification and modelling methods were used to combine data sources to provide structured interpretations of the surrounding landscape. Thirdly, post-modelling analyses and landscape applications were undertaken. Each of these steps will be discussed in turn.

### *4.3.1 Data pre-processing*

The pre-processing procedures included georectification, atmospheric correction and image interpretation procedures, manual digitisation, extraction of various image-based variables, and calculation of the transformations needed in later phases.

Georectification places the data sources into a coordinate system to allow overlay and comparison, and considerable care is needed here as poorly performed rectification may lead to misleading results in change detection studies (Brown et al. 2007; Singh 1989). Georectification procedures were applied in all the attached papers with two variations: photogrammetric block triangulation was used for raw aerial images (Paper IV), and a simpler rectification based on polynomial functions for scanned maps and satellite images (all papers). Both of these methods are principally based on the user-defined control points, indicating the corresponding locations in the non-rectified and reference materials. Block triangulation requires a longer processing chain, an applicable photogrammetric software product, and setting the tie points between the overlapping image frames. However, it is the only applicable method to process raw aerial images, characterised by central projection with significant relief displacement distortions, into distortion-free orthophotos. In addition, block triangulation also produces an accurate digital elevation model and allows user to view the overlapping image areas in stereo, thus being of substantial help in Paper IV. In general, georectification was performed carefully and the used control points were re-initialised to gain an acceptable result. The satellite images in Papers I and III were also subject to atmospheric correction, which removes distortions which arise due to aerosols, thin clouds and cloud shadows (Liang et al. 2001). Atmospheric correction is not always necessary, especially in the case of using a single image frame to produce an image classification; however, for change detection purposes, as well as when calculating band ratios, atmospheric correction is essential (Song et al. 2001). Two different methods were employed to perform the correction: COST in Paper I (Chavez 1996) and 6S in Paper III (Vermote et al. 1997). Satellite images were also used in Paper II, but they were obtained as readily corrected, LEDAPS-processed versions (Masek et al. 2006).

Pre-processing procedures also included visual interpretation and classification of single aerial image layers (Paper IV), digitisation of the scanned and rectified maps (Papers III and IV), and square- or raster-based extraction of geospatial variables to be used in the models (Papers I, II and III). In addition to variables related to a single attribute or its direct applications (such as DEM-based slope and solar radiation in Paper III), further variables were calculated using a normalised difference vegetation index (NDVI; Papers I and II), a principal components analysis (PCA; Papers I and III) and grey level co-occurrence matrices (GLCM; Paper II). NDVI belongs to a wide group of satellite-derived vegetation indices, which are calculated based on red and near-infrared bands and have a well-established relationship with vegetation productivity and photosynthetic activity (Pettorelli et al. 2005). In contrast, PCA and GLCM do not have any single specified purpose for their use, and their outputs are calculated based on larger entities than only a single pixel. PCA aims principally at removing or reducing redundancy in multispectral images and helps to filter out noise, thus being highly beneficial for modelling purposes (Avena et al. 1999; Muñoz and Felicísimo 2004). GLCM, in turn, focuses on pixel neighbourhood co-occurrence statistics instead of their initial values, and aims at quantifying their textural characteristics (Haralick 1979; Haralick et al. 1973; Wood et al. 2012). GLCM values have little significance as independent measures, but they can assist in the interpretation of fine-resolution images when connected to other variables. Various pre-processing procedures were also implemented using open source R statistical software and the Python programming language to speed data processing and to provide an automatised trail of methods.

### *4.3.2 Classification and modelling*

Classification and modelling were used to connect the extracted environmental data for the underlying landscape properties. In this dissertation, the term classification refers primarily to Paper IV where a trajectory-derived delineation of landscape units was constructed by expert-based rules. In contrary, Papers I-III rely primarily on modelling approaches that were initialised, improved and validated during the process with little manual work. These models included k-Nearest Neighbours (k-NN; paper I), Random Forest (RF; paper II) and Maximum Entropy (MaxEnt; paper III), all of which can be regarded as belonging to machine learning methods. In general, machine learning is based on user-supplied instances (training data) that are used to train the learning system (computer) in the form of a scalar reinforcement signal; this signal constitutes a measure of how well the system operates and can be further used to make predictions about future instances (Kotsiantis 2007).

The modelling methods of papers I-III were aimed at providing information on landscape dynamism but from slightly different perspectives. Paper I focuses on present pattern-wise land cover heterogeneity that arises partly from previous trajectories, while Paper II concentrates on efficient observations related to recent and ongoing grassland overgrowth. Paper III pinpoints how long-term knowledge of the landscape history can help to understand the distribution characteristics of the present species. All these three papers, however, were targeted at describing shifts from grassland to woodland vegetation, either spatially or temporally, and emphasising the decline of potential semi-natural grasslands.

The k-NN method, used in Paper I, is based on determining the class or continuous value of an unknown instance by the *k* most similar observations (Cover and Hart 1967). The k-NN method has been found to perform well in forest-related studies in Northern Europe (Reese et al. 2003; Tomppo et al. 2008), and in this context it was used to determine the fractions of grassland/woodland land cover types at a subpixel level, which were then further applied to complement existing classifications. RF modelling, applied in Paper II, is an ensemble modelling technique that relies on the common outcome of numerous classification trees which are built using data subsets (Breiman 2001). RF approaches have gained popularity in the geospatial context due to their good classification performance related to land cover classes (Pal 2005; Rodriguez-Galiano et al. 2012), and were applied in Paper II to construct different comparative models for distinguishing overgrown grasslands from unchanged locations. The maximum entropy approach in Paper III in turn is a relatively new and intuitively more complicated method, but which has been found to be highly efficient in species distribution modelling and therefore widely used at present (Halvorsen 2013; Phillips et al. 2006). The basic idea of a MaxEnt model is to minimise the entropy between two probability densities in covariate space, one of which has been measured from the field observations and the other from underlying landscape characteristics, in order to indicate the likelihood of species occuring in unknown locations (Elith et al. 2011). Similar to Paper II, comparative models were created with different sets of environmental variables – one based on contemporary information, one on historical data sources, and one combining these two – to discover the importance of features related to landscape history for Fumewort distribution.

The classification approaches used in Paper IV can be seen as an application of landscape change trajectory analysis, emphasising the identification of ways by which landscape has been transformed over time (Käyhkö and Skånes 2006, 2008). The analysis was conducted in a retrospective way, reconstructing the past by regressing from the relatively well-known present (Skånes and Bunce 1997), i.e. classifying first the newest aerial image layer and continuing stepwise to older materials. Basically, the idea of the analysis is simple – creating a classification for each of the used layers, overlaying them, and making a new classification based on the different class combinations. Gaining a successful result, however, requires certain conditions to be fulfilled. Firstly, the classifications of single layers must match each other to enable the detection of permanency versus changes. Secondly, as $m$ layers with $n$ classes will each lead to $n^m$ potential combinations, efficient generalisation is usually needed with respect to the emphasised phenomena. Thirdly, as trajectories are always only based on snapshots of the prevailing conditions at single moments, good knowledge of the local conditions and their potential changes is essential. In Paper IV, change trajectories were applied to indicate potentially valuable semi-natural grasslands and their recent overgrowth, which can help in prioritising restoration actions if conditions have not deteriorated or shifted too drastically (Bestelmeyer et al. 2009; Milberg 1995; Öckinger et al. 2006).

### *4.3.3 Post-modelling analyses and landscape applications*

Post-modelling analyses and applications were essential to interpret, evaluate, and discuss the outputs. These analyses included comparison of different models and the used variables (Papers II and III), evaluation of modelling results using independent validation data (Papers I and III), use of landscape indicators (papers I and IV) and construction of result-based scenarios (Paper IV).

Comparison of distinct models and variables was used as an important post-modelling step in Papers II and III, but with slightly different aims. In Paper III the purpose was to ascertain the disparities between the variable groups of different temporal characteristics (contemporary vs. past landscape), while in Paper II the comparison was primarily targeted at the importance of single data sets. Both, however, were intended to provide information on how to interpret contemporary landscape features resulting from long-term dynamic processes, which may not be fully supported by contemporary landscape patterns. Furthermore, the independent validation data used in Papers I and III provided unbiased measures to evaluate the errors of the deciduous fractions and Fumewort distribution model. In Paper II, using an RF algorithm, an unbiased error estimate is provided by the model; thus, further validation was not needed.

Restoration scenarios, constructed in Paper IV based on the trajectory classes, were intended to provide a simplified presentation of potential restoration sites and their effects on the landscape structure. They reflect the expected semi-natural grassland qualities which were determined by grouping together suitable trajectory classes, primarily based on habitat permanence and land productivity measures. To evaluate the scenario characteristics in Paper IV as well as quantify transitional land cover components at various thresholds in Paper I, various landscape indicators were also applied. Landscape indicators (alternatively indices or metrics) generally measure the size, shape, and spatial juxtaposition of certain land cover or use types with a wide range of applications in landscape research (Dale and Kline 2013; Uuemaa et al. 2013). Such indicators can offer a powerful tool to measure landscape structures but their interpretation must be performed with sufficient care (Li and Wu 2004), and results should be understood as a threshold-specific outcome. In Papers I and IV, the selected indicators aimed at being relatively simple, intuitively understandable, and relevant for the studied phenomena. In addition, related to the threshold selection, the arbitrary nature of determining land cover or land use classes was tested and discussed in Paper I by comparing the existing CORINE-derived class entities with the modelled land cover fractions.

# 5. RESULTS AND DISCUSSION

## 5.1 Geospatial data needs semantic, conceptual, and contextual interpretation

Geospatial data are able to provide accurate, contextually smart, and flexible realisations of the surrounding landscape, which can be applied to indicate various natural and anthropogenic entities. However, this requires that the semantic and conceptual properties of the data are well known, and properly acknowledged. Semantic issues are specifically important when dealing with secondary data, which have nowadays become increasingly available along with the improved supply of earth observation data (Ahlqvist 2005; Comber et al. 2005). As geospatial information is often based on human perception and social agreements, and may be identified differently across information communities (Kuhn 2005), this means that the characteristics of the data can vary significantly. This is particularly important when dealing with data integration between semantically heterogeneous data sources (Worboys 1998), or with long time series where the actual changes need to be separated from semantic confusion (Eriksson and Skånes 2010). Detailed analyses and suggested strategies concerning how to deal with this are further discussed by Ahlqvist (2004; 2005; 2008), and simplistic but workable ways to match a temporally extensive sequence of observations are presented in Papers III and IV.

When applying geospatial data to indicate ecological values, a fundamental mismatch between the conceptual levels must be acknowledged. While geospatial data sources principally provide information on signal reflectance, land cover/use tendencies, and relatively generalised biotope characteristics, ecological values are normally related to habitat types and species occurrences on finer, more heterogeneous and dynamic landscape levels. This leads to the notion that the extracted elements of geospatial data and targeted ecological values seldom have a one-to-one relationship at a transient moment of time, which must be recognized in the analyses. In reality, rather than focusing on the detection of species or habitats strictly *per se*, a geospatial approach should be generally seen primarily as a way to detect potentialities and qualities that are known to support the existence of certain ecologically valuable landscape components. These guidelines have been applied in the papers in this dissertation, with emphasis either the potential created by current patterns (I), or the interplay between the contemporary landscape and its past drivers (II-IV).

Reliable recognition of the potential ecological values depends fundamentally on the way we interpret and operate the geospatial data. Raw data such as satellite and aerial images are only the initial phase of the production process where data is turned into knowledge using human vision, domain expertise, and various computational tools (MacEachren and Kraak 2001). Consequently, the results gained using geospatial data are intrinsically subjective and usually products of a long decision chain. In a study by Powell et al. (2004), this subjectivity was traced to being the result of various reasons, including human errors due to misinterpretation or recording mistakes, but often also reflected disagreements between different observers about land cover types or their dominance percentages. More importantly, these differences were noticed to appear regardless of explicit criteria for feature identification, thus reflecting the inborn vagueness of human interpretation when defining landscape entities. The importance of such personal opinions is discussed, particularly in Paper IV, where fine-resolution visual interpretation has been utilised. Visual-based classification relies primarily on the interpreter's skills and often lacks a well-defined standardisation scheme (Morgan et al. 2010). However, on the other hand it allows for detection of relatively minute details and gaining a more holistic perception of the landscape (Käyhkö and Skånes 2006) that may have considerable importance for specialised applications. Visual-based classification was necessary in Paper IV as the targeted partially overgrown grasslands are a complex land cover class, and was mainly based on orthophotos but partly assisted by the realised historical trajectories as well as field-based knowledge. Careful expert-based planning, however, was used to ensure the validity and applicability of the results by tailoring them to the given case study area.

## 5.2 Classifications represent landscape variation selectively

Classified land cover / use data sets are one of the most common inputs when assessing ecological values in the landscape, but their proper use requires great care. Classes are basically a framework for organizing geospatial observations where intrinsically imperfect spatial data, arising from imprecision and vagueness of geographical information as well as high complexity of landscape features (Duckham et al. 2001; Kuhn 2005; Wu and Marceau 2002), is divided into Boolean-based categories that normally cover the whole area of interest. In addition, classifications only reflect a selected variation of landscape dimensions, which basically determines how heterogeneity and patterns are detected (Wu 2013), and have a profound effect on how we interpret our surrounding environment. Nevertheless, classifications have an important role in the dissertation papers – as source data, to indicate the results, or both. Indeed, classifications are beneficial and needed for various purposes, but an important precondition is to recognise several limitations related to their use.

First and foremost, the principal characteristics of class delineations always depend on the primary purpose and scale of the classification, which must be recognised in the intended applications. Fundamentally, this may affect all the aspects, including the geometric accuracy, as was observed in Paper IV where fertile areas of the historical map were found to be drawn with much higher quality compared to low-productive hinterlands. Normally, however, uncertainties and internal variations are hidden behind the apparently well-defined class entities for which the accuracy, unfortunately, is often inadequately quantified or poorly documented (Foody 2001). This leaves the end user having to make the decision whether the material is suitable to be used or not. One of the most important accuracy-related factors is the determination of the minimum mapping unit, i.e. the smallest single unit that is classified. This phenomenon is exemplified and discussed in Paper I concerning the CORINE data, which is constructed through efficient generalisation procedures, and thus having significant fractions of other neglected land cover components within the homogeneously classified patches. This is an expected characteristic of CORINE classification rather than an error or unintentional defect but may lead to detrimental consequences if it is not properly addressed in the analysis. In the hemiboreal zone, where ecologically the most valuable habitats are scattered and small in size (Einarsson and Milberg 1999; Siitonen et al. 2011), using only CORINE classes would impair our abilities to distinguish the desired landscape components with sufficient accuracy, and would not be a recommended way to proceed.

Furthermore, thresholds used for classes, as discussed particularly in Paper I, affect the detection of transitional and fragmented landscape components. Basically, different class types are easy to distinguish at their extremes but become less readily separable near to the dividing values between the categories, finally reaching an arbitrary level which defines a border line between two potentially very different classes (Gopal and Woodcock 1994). Sometimes, however, certain very small and easily generalisable entities such as grassland patches inside the woodland vegetation can provide significant resources for various species (Nilsson et al. 2001). This point of view also challenges the dichotomous and simplified landscape division into *habitats* and *non-habitats*, often also called a *matrix*, which fails to properly recognise actual environmental gradients or metapopulation structures (Prevedello and Vieira 2010; Ricketts 2001). In addition, as emphasised in Paper I, calculation of class-based landscape indicator values should be understood as highly threshold-affected outcomes. They may be beneficial in describing a single landscape, or when employed to compare similarly processed landscape components such as different islands in Paper IV, but should be used with caution when applied to different landscape settings (Lechner et al. 2009). To keep landscape indicators as useful as they can be, simple and easily interpretable metrics should be favoured instead of more complicated ones (Šímová and Gdulová 2012). This has also been an important guideline when selecting appropriate indices for Papers I and IV.

A step forward in the classification problem is to use fuzzy approaches to recognise multiple and overlapping components as demonstrated in Paper I, given that patterns with mutually exclusive classes are not generally found in nature (Rocchini and Ricotta 2007). Basically, fuzzy approaches omit the final step of classification in which the posterior probabilities of membership are truncated into one class per pixel or feature (Atkinson and Lewis 2000). Applying fuzziness instead of exclusive classes will not remove all the problems related to classified units, such as a need to define class entities, but it helps to delineate landscape elements in a way that corresponds better to their physical and biological realities; it also indicates the vagueness and transitional character of natural boundaries (Hansen et al. 1988; Strayer et al. 2003). Most importantly, observations related to overlapping components and consequent recognition of land cover fractions can narrow down the gap between the aims and targets of detecting landscape elements with reasonable accuracy, and better point out various key habitats that often are transitional mixtures of several land cover types.

Fractions can also be used to complement other classes as presented in Paper I, thus acting as supplemental data for more robust classes. This approach has the advantage of capturing larger entities, such as land use classes, together with finer detections related to vegetation fractions, therefore improving the landscape perception and mutually contributing to a better understanding of habitat patterns and structures.

## 5.3 Simple and well-performing models assist in holistic landscape approaches

Models are valuable tools in landscape analysis since they assist interpretation of various landscape elements at different scales, and combine data sources together in a structured way. Predictive and semi-automatic models were essential tools in this dissertation, and used as primary methods in Papers I, II and III to indicate relationships between landscape features and their surrounding environment. Comparison of several models has been helpful in determining the most significant variables and their importance for observing both landscape patterns and processes (Papers II and III). Specific differences between the modelling methods are not specifically discussed in this context, and such conclusions would nevertheless be predominantly case-specific. However, certain general outcomes related to the use of models can be drawn based on the studies, as well as resulting from several attempts related to model development and testing phases without particular documentation in the papers.

While the importance of choosing an appropriate modelling method is often emphasised, their success in ecological applications is dependent on a solid understanding of the theoretical background and consequent selection of relevant predictor variables (Austin 2002). In the worst case, ecological drivers, causalities and relationships between the landscape dimensions are not properly recognised or addressed, which can lead to biased results and explanation of landscape characteristics using local case-specific interactions. If such models are further used for prediction and extrapolation in time or space, their results will be highly prone to inaccuracies and errors (Elith and Leathwick 2009; Miller et al. 2004). This is well exemplified in Paper III where different models – either including or excluding factors related to temporal variability – are concluded to result in significant differences in their performance when extrapolated to validation areas. In addition, obscure transformations of the model variables (e.g. logarithmic, trigonometric, or even combination of these) for the sake of statistical reasons should be avoided if possible, as they finally set the initial data into a state that cannot anymore be interpreted as real phenomena outside of the modelling approach (Guthery 2008). Some relatively complex transformation such as principal components analysis has been used in the dissertation papers, but with the main purpose of data simplification rather than detailed explanation of the results based on the transformed predictors.

The modelling approaches used in Papers I-III can all be classified as machine learning methods, which have often been found to outperform many traditional modelling approaches. Machine learning, however, should be principally seen as a framework to automate certain modelling processes and not to replace initial human intuition or the fundamental need to understand landscape processes (Olden et al. 2008). Moreover, the ability to build larger and more complicated models does not necessarily help in providing better perception of the environment. Instead, it may lead to highly complex and overfitted models that perform well only when checked against the training data, but are characterised by poor prediction ability. Such an overfitting tendency can further be exaggerated if model training locations are selected from small regions and are too close to each other, thus being strongly affected by spatial autocorrelation as well as failing to recognise the whole range of targeted environmental conditions (Anderson et al. 2003). These issues and potential pitfalls have been addressed carefully in the dissertation papers by purposely reducing excess model complexity (Paper III), setting a minimum distance between the training locations (I), using systematic sampling over the total study area to include all the necessary environmental variability in the model (III), and ensuring that the sampling covers the whole range of observed variation (I). Moreover, the need of external validation data is emphasized in papers I and III, which cannot be generally replaced by model-generated accuracy estimates due to their too optimistic values. The only exception to this is the RF model, used in Paper II, where error estimates can be regarded as being unbiased and therefore removing the urgent need for a separate test set (Breiman 2001).

While models can be highly efficient in connecting ecological observations with underlying environmental conditions, many issues must be understood in the variable selection. Depending on the modelling strategy, collinearity i.e. non-independence of predictor variables can be a serious problem by inflating the variance and potentially leading to an incorrect identification of relevant predictors (Dormann et al. 2013). The solution to this problem is presented in Paper III by removing all the strongly correlated variables, but this strategy can only be applied to continuous variables. In addition, as indicated in the results in the paper, statistically calculated correlation cannot properly measure all forms of interdependence. This can be recognised when comparing different models: certain variables that appear to be significant in one context have only minor importance when additional predictors are added. Such a result has been interpreted to be due to surrogate-like relationships, which only become apparent when adding better variables, i.e. having stronger connections to the initial ecological drivers. This pinpoints the importance of not only knowing how to build models, but also properly understanding the factors that affect ecological phenomena both in space and time.

Regardless of the recent advance in developing better models and increasing their computational power, our environment remains inherently diverse, characterised by complex interactions and their partially random realisations. In reality, this means that an important part of ecological variation will persist in being unexplained by our models, no matter what method we use or how well we expect to understand the initial determinants. Moreover, the specific habitat requirements for many species are poorly understood and consequently there is often a lack of good quality data for modelling purposes (Swetnam et al. 1998). However, selecting a representative but not too large or redundant set of variables, choosing a modelling method that does not aim at highly stringent fitting of the data, and ensuring that the value range of the predictors covers most of the targeted variation can help to make models as good as they can be. They may not be applicable for extensive extrapolations – regarding environmental conditions, modelling area, or especially in terms of temporal dimension – but often that is not even the target. Furthermore, modelling results should be seen as indicating potentialities rather than telling the "truth"; this is emphasised in several contexts in this dissertation. When these preconditions and considerations are fully acknowledged in the modelling process, the results can help to indicate realistic dependencies between the landscape dimensions, and assist in gaining a more holistic interpretation of its distinct features.

## 5.4 Linkages between the spatial and temporal dimensions are essential

The results of this dissertation show that information regarding past landscape phases and changes provide essential knowledge to understand contemporary landscape characteristics. This perspective should be regarded as an important standpoint for detecting ecological values that are often based on cumulative qualities of the past, as agreed in previous studies concerning agrarian landscapes (Lindborg and Eriksson 2004; Lunt and Spooner 2005; Reitalu et al. 2010). Often, regrettably, the importance of the temporal dimension is neglected or even omitted when interpreting ecological values through contemporary spatial patterns. This may be derived from the high complexity of how these patterns have been shaped, and challenges to link previous processes with their present state (Tscharntke et al. 2012), leading potentially to attempts to explain the present landscape configuration without stressing the past. In addition, distorted memories, belief in undisturbed ecosystems or lack of relevant data can support the idea of long-term landscape stability (Christensen 1989; Marcucci 2000; Swetnam et al. 1999), thus diminishing the expected need to focus on the past phases. However, knowledge and understanding of previous change is essential to understand properly the organisation of present landscape components. It is a fact that historical signals are often weak, materials used for their interpretation may be deficient, and translations of their messages into contemporarily understood features can be problematic. However, this should not be used as an excuse to neglect their importance.

In the geospatial context, the present landscape can be accurately and easily interpreted based on various data sets. Focusing on previous landscape phases and changes occurring in the past is not always straightforward, but it will have certain essential benefits. Firstly, acknowledging previous dynamics may be the only way to distinguish conditions that are relatively similar at present but result from different processes, which may have important consequences for their current ecological values. This is one of the principal issues discussed in Paper II, which concludes that knowledge of previous trajectories provides an important context in which to understand contemporary vegetation patterns. Secondly, knowing earlier land cover or land use characteristics can assist in finding better and more realistic linkages between the present features and their initial causes along the temporal landscape dimension. This phenomenon is stressed in Paper III where, for example, present-based results suggest that the presence of Fumewort (*Corydalis solida*) is affected by the distance to watercourses, but adding historical data into the analysis indicates their proximity rather to be a surrogate for previous management regimes and overgrowth conditions. Thirdly, knowing *when* certain landscape changes have occurred improves the understanding of present spatial characteristics and assists in estimating how radically conditions have been altered. The importance of this is discussed in Paper IV, where the date concerning the cessation of grassland management is used as an indicator of restoration potential. In this context it is expected that semi-natural grasslands, which have been too long overgrown, have more than likely lost their previous characteristics due to the disappearance of viable seed bank (Auffret and Cousins 2011; Milberg 1995), or deteriorated soil conditions (Janišová et al. 2007).

Successful linking of spatial patterns with temporal variation does not necessarily require highly complicated methods. In Paper II, this is demonstrated using a relatively short series of Landsat-derived NDVI values and the Mann-Kendall test, to assess whether a set of temporally ordered variables indicate a monotonic trend, which in this case is vegetation succession (de Jong et al. 2011; Martínez and Gilabert 2009). Change trajectory analysis, used in Papers III and IV, is a more subjective method and requires in-depth knowledge of the specific conditions, but, however, can provide important information regarding long-term landscape permanency and detection of certain key changes. In general, trajectory classification is based on sequential snapshots that often need to be generalised to be commensurate, and the resulting combinations have to be grouped based on characteristics which are expected to either improve or impair the focused qualities. However, as indicated in the papers, trajectory classes are important due to the combined description of an extended continuum, even if representing subjective decisions and, therefore, providing valuable information that any single layer along the landscape history is not capable of depicting.

When focusing on semi-natural grasslands, the most important single determinant in the past landscape seems to be the extent of the previous habitat network and its remaining fragments. Historical maps used in Papers III and IV indicate clearly that in the late 1800s, grasslands in the study areas were still connected in large, continuous networks and their present remnants are only small and scattered fractions of what used to be. These historical traces do, however, have significant effects for the presently observed landscape characteristics, as emphasised in Paper III and agreed on by several earlier studies (Lindborg and Eriksson 2004; Reitalu et al. 2010). This pinpoints the importance of knowing the past to understand present landscape patterns, and to indicate where the search of potentially valuable landscape components should be focused. If previous landscape phases are not known, thus representing a missing link between the spatial and temporal dimensions, research and management resources may be concentrated on areas that are not likely to contain or produce the targeted qualities.

## 5.5 Effective management requires science-based and spatially explicit decisions

The European Union recently announced that the target for halting biodiversity loss by 2010 had been missed (European Commission 2010), and we need accurate but simultaneously flexible science-based planning tools to prevent a similar reports having to be published in the future. What is problematic in this context, however, is that biodiversity loss is often an unintended side action of other decisions, and its consequences may emerge spatially or temporally far away from the initial damage (Rands et al. 2010). Management of semi-natural grasslands, for instance, was once part of daily routines, supported by the economy, and ensured livelihood of the agricultural communities, but this is not the case anymore. Currently, it is easier for farmers to intensify their agricultural production thereby reducing production costs but simultaneously creating monofunctional landscapes (Jongman 2002). In the long term, this has caused a drastic decline and fragmentation of semi-natural grasslands as well as the deterioration of their habitat quality. Furthermore, as the initial basis of managing semi-natural grasslands has disappeared, drivers supporting their existence have changed from economic reasoning to other factors such as maintaining their ecological and aesthetical values. In practice, however, these altered reasons are generally seen as consuming rather than providing resources, and management activities are concentrated only on relatively small areas. This calls for a careful targeting of management to the most beneficial locations.

One example of such a process supporting the restoration and management of partially overgrown semi-natural grasslands is presented in Paper IV. Its results can be simplified into three conclusions, which in this context refer to grassland management, but can be generalised to various other purposes where ecological values are emerging from the interplay of spatial, temporal, and cultural factors in the landscape. First, evaluation of present habitat quality must be based on a structured and systematic approach, where geospatial data can be of substantial help. In terms of semi-natural grasslands, it is essential to recognize previous temporal dynamics and change trajectories as they can provide detailed information on the present state and indicate potential restoration sites. Second, to make these quality considerations to be usable for actual spatial planning, there is a need for additional measures, realistic plans and simplified visualizations connected to them. In paper IV, this has been accomplished by building up scenarios and measuring their effects on the landscape configuration with respect to the assessed habitat quality and consequent needs for management or restoration actions. Third, these steps as well as further decisions regarding management targets will require extensive fieldwork efforts in order to be realistic, efficient, and well justified. These considerations pinpoint the need of science-based approaches for management planning, while simultaneously recognising the supportive rather than decisive role of geospatial data in the process.

As discussed above, smart use of geospatial data and field observations can help in deciding further management or restoration targets but nevertheless, at best, we are capable of producing only educated guesses instead of optimal solutions. This stems from deficiencies in the data and its interpretation, and also from other factors that cannot be known in advance. For example, the viability and potential of seed banks to support grassland restoration has highly controversial estimates, and similar tendencies can be expected to apply to various other conditions as well. External factors such as the fertilisation effects of airborne nitrogen (Bobbink et al. 1998; Stevens et al. 2010) may also have unknown consequences that can affect semi-natural grasslands, as well as purely anthropogenic factors such as land ownership; thus, potentially posing legal restrictions for planned activities. Furthermore, after a certain time of transformation, habitat conditions can eventually turn into a new, virtually irreversible state (Bestelmeyer et al. 2009; Briske et al. 2005), but the timing of this changeover is largely unpredictable and case-sensitive. Regardless of these considerations, however, it is important that management planning does not remain only at the level of conceptual models but is also implemented into practice via well-evaluated practices to support actual management efforts (Sutherland et al. 2015). Achieved knowledge and any consequent decisions may not be perfect, but will nonetheless be highly beneficial and can ensure the use of a holistic landscape concept in spatial planning. Furthermore, the use of geospatial data will help to observe larger landscape elements thus assisting in focusing the fieldwork on the most suitable places. As a result, management resources can be targeted according to our best scientific understanding and field expertise, supporting the long-term preservation of ecological values that otherwise might be lost forever.

# 6. CONCLUSIONS

- Contextually smart use of geospatial data helps to distinguish and delineate ecologically important landscape components. However, instead of detecting specific ecologically relevant features, most data sources rather indicate quality potential which needs to be interpreted through case-sensitive applications and often combined with other information sources. In this process, fundamental understandings of the semantic and conceptual characteristics of the data as well as detailed knowledge of the study area are essential.

- Land cover / land use classifications are efficient in disseminating generalised landscape information, but inherently subjective and often lacking transparency in their production process. This is highly problematic for the detection of semi-natural grasslands, which consist predominantly of fragmented and transitional patches among the more expressive landscape features. To enhance the realistic perception of contemporary landscape patterns, fuzzy approaches should be emphasised due to their ability to describe overlapping and mixed components.

- When building models using geospatial data, simplicity should be preferred. For semi-natural grasslands, a limited number of ecologically relevant drivers, which reflect variation in the three landscape dimensions, will result in effective models. Further, these models are not limited to describing specific characteristics of the training data, but also extrapolate well.

- Understanding the temporal landscape dimension needs particular attention in landscape studies. Neglecting it may cause erroneous interpretations of pattern-related determinants, and lead to attempts to explaining current landscape features through irrelevant surrogates. Interpretations related to temporal dimension do not necessarily need to be complicated, because even relatively simple measures may indicate important variation related to previous processes.

- Protection of biodiversity consists of single actions, such as restoring a patch of degraded semi-natural grassland. These actions, however, must be based on both careful qualitative and quantitative assessments, and their effects need be reflected in future scenarios to ensure the efficient use of limited resources. The role of geospatial data in this sense should be seen as material that supports decisions and provides measures over wider landscape structures, but will not replace fieldwork efforts.

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