HERCULES

Sustainable futures for Europe's HERitage in CULtural landscapES: Tools for understanding, managing, and protecting landscape functions and values

GA no. 603447

D2.3 Dynamic models for analyzing long-term landscape change

Main authors:
Maurice de Kleijn, Frank Beijaard, Niels van Manen, Carole Crumley, Kim von Hackwitz, Jan Kolen and Daniel Löwenborg.

With contributions from
Eric Koomen, Henk Scholten, Philip Verhagen, Mark Groenhuijzen, Rowin van Lanen, Harm Jan Pierik and Marjolein Gouw-Bouman.

Reviewers:
Philip Verhagen
Hannes Palang

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Executive summary

Work Package 2.3 of the HERCULES project brings together a protocol for studying the long-term changes in cultural landscapes and spatial dynamic modelling frameworks and tools. Additionally it presents the possibilities of applying web GIS tools, which are available through HERCULES´s Knowledge Hub (WP7) to publish and share the research results with various actors having different disciplinary backgrounds.

The protocol defines an innovative methodological procedure for understanding the long-term development and transformation of cultural landscapes, drawing on recent insights from geography, landscape archaeology, (historical) ecology, anthropology and information science. The protocol subsequently deals with the following topics and issues:

- An *overview of the major concepts and approaches* in archaeological and historical landscape research in both North America and Europe and the major issues raised in landscape history over the past decades (Section 2.1). This also defines the necessity of developing an integrated approach to long-term changes in cultural landscapes (Section 2.2);
- A set of *premises* for understanding long-term changes in cultural landscapes (Section 2.3), as well as a number of *operational principles* for translating these premises to concrete starting points, procedures, methods and techniques in individual or comparative landscape projects (Section 2.4). These premises and operational principles are based on the methodological buildings blocks of the protocol: *historical ecology, landscape biography and complex systems theory*.

Based on the protocol two spatial dynamic modelling frameworks are presented and applied in two carefully selected case study areas (i.e. the Dutch Lower Rhine region and the Swedish Uppland region). The modelling frameworks present innovative methods that allow analyzing past spatial dynamics.

The presented modelling frameworks demonstrate the high potential of spatial dynamic modelling framework to better understand past landscape processes. However, it also shows that it is highly complicated to simulate these spatial dynamics. The main problems are the quality and detail of available data, and the uncertainties in assumptions made. Interpreting and using the modelling results must therefore be approached with care and requires additional research.

Additionally this deliverable shows the potential of HERCULES's Knowledge Hub. It shows how the results of one of the modelling frameworks can be interactively presented using advance web mapping technologies (i.e. story telling GIS tools). This does not only allow the research results to be published in a scientific transparent way, it also offers tooling to bridge the gap between academic spatial modelling experts, heritage landscape experts and non-scientific stakeholders.

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Abbreviations

AD	Anno Domini
ABM	Agent Based Modelling
APM	Archaeological Predictive Modelling
BC	Before Christ
BP	Before Present
CAS	Complex Adaptive Systems
D	Deliverable
DAL	The Dark Age of the Lowlands in an interdisciplinary light: people, landscape and climate in the Netherlands between AD 300 and 1000 - project
DEM	Digital Elevation Model
FOSS	Free and Open Source Software
FFL	Finding the limits of the Limes - project
GeoDMS	Geo Data and Model Software
GIS	Geographic Information System
HE	Historical Ecology
HERCULES	HERitage in CULtural landscapES
LB	Landscape Biography
LUS	Land Use Scanner
op	operational principle
PLUS	Past Land Use Scanner
SDI	Spatial Data Infrastructure
SoNaR	Social Natural Regions
UNESCO	United Nations Educational, Scientific and Cultural Organization
WebGIS	Web-based Geographic Information System
WP	Work Package

1. Introduction

This report describes the results for the development and implementation of "dynamic models for the analysis long-term landscape change using archaeology data and the landscape biography framework in the case study sites", which is the third deliverable (D2.3) of WP2 of the HERCULES project.

HERCULES strives for the empowerment of public and private actors to protect, manage, and plan for sustainable landscapes of significant cultural, historical, and archaeological value at local, national, and on Pan-European scales. By applying and developing innovative technologies and tools for assessing and mapping cultural landscapes, HERCULES will:

- Synthesize existing knowledge on the drivers, patterns, and outcomes of persistence and change in cultural landscapes;
- Close knowledge gaps regarding the dynamics and values of cultural landscapes;
- Generate tools for landscape observation and modelling in order to understand values of and threats to cultural landscapes in Europe;
- Develop a strong vision of pathways towards protecting heritage in cultural landscapes, especially for landscapes of high historical and archaeological value;
- Provide policy makers and practitioners with a cutting-edge Knowledge Hub to guide decision-making for the benefit of cultural landscapes with significant archaeological / historical components;

In achieving these goals, the HERCULES project responds to the European Landscape Convention's call for trans-disciplinary research and involves important actors with stakes in cultural landscapes across all project stages.

Within the HERCULES program, WP2 focuses on the study of long-term landscape change. The principal aim of WP2 is to enhance methodologies to collect data and to create knowledge about the long-term dimension of cultural landscape change. Its specific objectives are:

- To define an innovative methodological procedure for understanding the long-term development and transformation of cultural landscapes, drawing on recent insights from geography, landscape archaeology, (historical) ecology, anthropology and information science. The procedure will be informed by the definitions and the conceptual framework developed in WP1;
- To develop and test an infrastructural facility for retrieving and linking archaeological, historical and ecological data and geo-information to support the interdisciplinary study of landscape change;
- To develop models for analyzing long-term trends in landscape history in the case study sites;

The first two objectives have been discussed in deliverables D 2.1 and D 2.2. The present report is primary focused at the third objective i.e. the development and implementation of models for analyzing long-term trends in landscape history. However, since the outcomes of D 2.1 and D 2.2 form essential building blocks for the model development and interpreting the modelling results, this report can be characterized as an integrative final report for WP2. It combines and integrates the results of all various activities performed for WP2.

An overview of the reports structure is provided in figure 1. The report initiates (chapter 2) with an overview of WP2's first objective (D2.1). It presents the outcomes of the innovative methodological procedure for understanding long-term development and transformation of cultural landscapes. This procedure exists of premises for long term land use change which are translated into operational principles.

The protocol presented in the second chapter proposes to integrate the Landscape Biography (LB) and Historical Ecology (HE) as methods to realize a trans-temporal approach and foresees an important role for spatial dynamic modelling frameworks. These modelling frameworks are seen as methods to foster the understanding of long-term thinking.

The report will from that point be split in two parts with comparable chapters. Chapter 3 will be dedicated to the Past Land Use Scanner (PLUS) modelling framework. Chapter 4 to the Social Natural Regions (SoNaR) modelling framework.

Chapters 3.1 and 4.1 introduce the modelling frameworks which are from a theoretical perspective based on the premises derived from LB and HE. In chapters 3.2 and 4.2 of this report the modelling frameworks introduced are applied to two carefully selected case study areas. These are the Dutch Lower Rhine region, for which the Past Land Use Scanner modelling framework is applied and the Uppland region for which the SoNaR modelling framework is applied. Sections 3.2 and 4.2 discuss in detail how the modelling frameworks have been configured. In the following sections 3.3 and 4.3 the modelling results are presented. It systematically discusses the various simulations for different long term land-use change scenarios.

In the fifth chapter the two parallel parts come together. This chapter reflects on both modelling frameworks and results and present a state-of-the-art example on how the SDI (D2.2) and HERCULES's Knowledge Hub (WP7) are integrated by presenting the story telling WebGIS that has been developed for the Dutch case study as extended publication. The example demonstrates the potential of these instruments and stresses the importance of HERCULES's Knowledge Hub.

The final chapter of this report provides an overview and summary of all research outcomes for this deliverable. Furthermore, it provides a vision for future research on the role of spatial dynamic models to understand long term land use change and briefly reflects on its implications for geo-design and heritage landscapes.

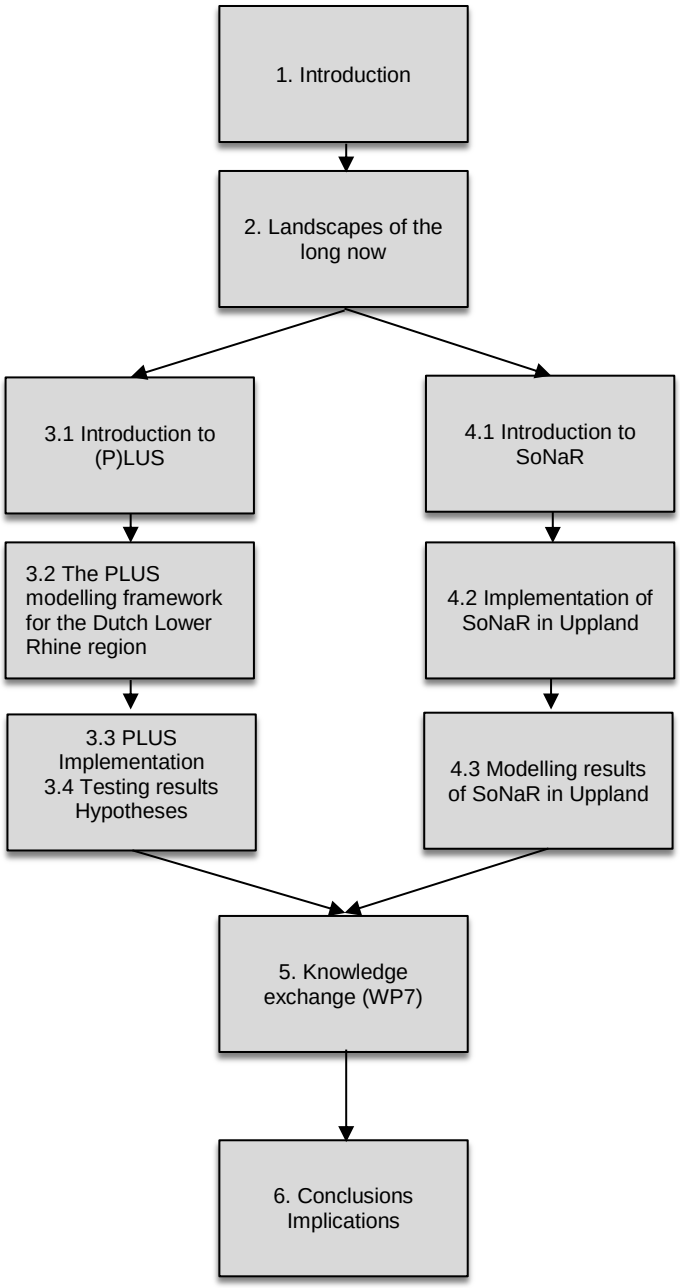

Fig. 1: Structure of report

2. Long-Term Landscape Change[1]

2.1 Rationale: the ongoing divide in landscape research

It is important to understand something of the history of landscape research before introducing the premises and operational principles of an integrated long-term approach. In recent decades the long-term study of landscapes has seen rapid international growth. While archaeological theory and practice has been at the forefront, the disciplines of geography, anthropology, history, ecology, and philosophy have also made important contributions. Our approach draws from both European and North American archaeological traditions, which together reflect the contributions of other key disciplines.

Beginning in the 1970s, European and North American landscape studies were often divided between more social science and humanities-oriented constructivist approaches (taking landscape as a social construct) and more natural science-based essentialist approaches (seeing landscape as an external natural phenomenon), which prevented landscape researchers from developing truly interdisciplinary perspectives. Particularly in Europe, the more essentialist approaches primarily aimed at objectified knowledge of landscape as an external phenomenon, either in terms of processes and systems or in terms of morphologies (field divisions, built structures, infrastructure, etc.). In the 1970s the old holistic landscape approaches of cultural geography (e.g. Sauer, 1925) and local history (e.g. Hoskins, 1955) had gradually given way to ever more advanced theories and models for spatial analysis and cross-cultural comparison that followed the quantitative and statistical paradigm that was developed within the 'new' human geography and the 'new' processual archaeology. The new approaches were, however, not only essentialist, but also markedly reductionist, treating humans as little more than anonymous particles and statistical factors.

By the end of the 1970s European reactions appeared, first within 'humanistic' geography and, from the early 1980s, within the 'new' cultural geography. The 'humanists' (Meinig, 1979) defended the message that landscape was 'in the eye of the beholder' and, hence, visions of landscape always showed the subjective fascinations, interests and ambitions of the perceiver. This last point was followed some years later in the new cultural geography developed by Cosgrove and Daniels, who were strongly inspired by the humanistic geography and iconographical approaches in history (Cosgrove and Daniels, 1988; Cosgrove, 1984). In the early 1990s, research in the Anglo-Saxon academic world seemed to have moved increasingly towards the study of landscapes as social and symbolic constructions. This perspective was also adopted by hermeneutic and interpretative ("post-processual") landscape archaeology, notably in the United Kingdom. On the other hand, large numbers of regional landscape studies, partly related to planning, still described and mapped landscapes in the traditional way of the 'local history approach" and landscape morphology. The gap between these different worlds of research seemed unbridgeable and kept growing, hence the frustrations about over-theorizing in geographical and archaeological landscape research (see Fleming, 2007 and Johnson, 2007 for an example of the controversy).

[1] For this chapter we have integrated parts from D2.1

In 2003 Cosgrove even went as far as stating that there are two distinctive discourses in landscape research – semiotic and ecological– that barely interact with each other (Cosgrove, 2003).

In the United States and Canada, response to processual archaeology was enthusiastic in some influential circles, but also generated strong resistance. This response took a variety of forms, including but not limited to gender archaeology (feminist, queer theory), political archaeology (issues of class and power), mortuary studies (the body), historical archaeology (combining physical remains and documents), the archaeology of agency (individual and group identity and decision making), and an explicitly cultural re-engagement with environment and ecology. Contract archaeologists, reflecting their own growing importance and diminished interest in theoretical battles, adopted a pragmatic approach to heritage management and historical/environmental conservation. One could argue that in North America, landscape archaeology drew on these lively initiatives and had become, in its own right, a response to processual archaeology by the end of the 1980s.

To conclude, there is a continuing divide between more essentialist and naturalistic approaches to landscape on the hand and more constructivist and 'culturalist' approaches on the other, both in postwar European and – to a lesser extent – North American research.

In sum, European landscape archaeology responded to processual archaeology by re-engaging humanistic geography, history and phenomenology; in North America landscape archaeology developed within a four-field (cultural/social anthropology, linguistic anthropology, physical anthropology, and anthropological archaeology) framework and was influenced by history and ecology.

2.2 Towards an integrated approach

In 1996, The Danish-American geographer Kenneth Olwig tried to synthesize the essentialist and constructivist traditions, based on a thorough investigation of the origins of the landscape concept, by re-introducing the 'substantive' nature of landscape (Olwig, 2002; Olwig, 1996). Although such a synthesis of paradigms, if possible at all (as many researchers oppose the idea of paradigms itself), is not an explicit goal of the integrated long-term approach to be developed in WP2, there is certainly a link between WP2 and Olwig's endeavor. WP2 too aims at developing an integrated approach to the study of landscapes, combining the long-term perspective of archaeology and history with recent insights from cultural ecology, anthropology and geography. To achieve this goal, elements of recent "landscape biography", "historical ecology" and "complex systems theory' will be used as theoretical building blocks. Landscape biography and historical ecology are among the prominent emerging approaches to the study of long- term landscape history, and are now being combined and integrated with a complex systems approach to human-land and human-nature interactions.

Landscape biography studies the long-term transformations in landscapes, preferably from prehistory to the present, viewing landscape at each point in time as a complex interplay between social and economic developments, culturally specific perceptions of the environment, the history of institutions and political formations, and ecological dynamics (Roymans *et al.*, 2009; Kolen *et al.*, 2015). As a historical research strategy, it expresses a strong sense of the multi-layered nature of landscapes. It acknowledges the non-linear and path-dependent character of cultural landscapes and the active role that landscapes play in the life histories and social memory of people (cf. Ingold, 2000). This means that landscapes are not only seen as the (interim) outcomes of drivers, but in themselves are considered drivers for social, economic and climate change as well. From a social perspective, prominent focus is given in landscape biographies to the identity constructions of communities and the role played here by landscape.

Historical ecology developed a practical framework of concepts and methods for studying the past and future of the relationship between people and their environment. The framework emerged within a holistic tradition in North American anthropology that was first developed by Franz Boas (1858-1942). With his students, Boas set about joining the study of cultural and physical anthropology, archaeology, and linguistics in departments across the United States and Canada. Drawing on this tradition, which unifies the study of the human species across time and space and in many dimensions, historical ecology is a practical framework of concepts and methods for the dialectical study of people and their environments (Balée, 1998; Balée and Erickson, 2006; Crumley, 1994, 2012; Hornborg and Crumley, 2007; Meyer and Crumley, 2011). While historical ecology may be applied to spatial and temporal frames at any resolution, it finds particularly rich sources of data at the "landscape" scale, where human activity and cognition interact with biophysical systems, and where archaeological, historical, ethnographic, environmental, and other records are plentiful. The term historical ecology draws attention to a definition of ecology that includes humans as a component of all ecosystems and to a definition of history that goes beyond the written record to encompass both the history of the Earth system and the social and physical past of our species. Historical ecology provides tools to construct an evidence-validated, open-ended narrative of the evolution and transformation of specific landscapes, based on records of human activity and changing environments at many scales. Historical ecology offers insights, models, and ideas for a sustainable future of contemporary landscapes based upon this comprehensive understanding of their past.

Complex systems are self-organizing and exhibit what are known as "emergent properties", which cannot be deduced from the individual natural or cultural components of the system. Agent-based perspectives on complex systems (cf. McGlade and Van der Leeuw, 2013; Bentley and Maschner, 2003) combine the principles of complex systems theory with the concept of interacting agents. Agent-based modelling (ABM) allows to study whether developments inevitably lead in a certain direction (path dependence), and whether different scenarios will produce similar outcomes (equifinality). By this, it is very suitable for exploring long-term developments in cultural landscapes, allowing testing different hypotheses of the development of the cultural heritage embedded in these landscapes. As ABM also leads to insights on how micro-scale processes give rise to macro-scale phenomena, it is of great interest to landscape archaeology, where we can usually only observe the macro-scale results of micro-scale actions in the past. Several archaeological studies have used ABM for this purpose (Kohler *et al.*, 2007; Wilkinson *et al.*, 2007; Kohler and Varien, 2012; Wurzer *et al.*, 2015).

Together, these frameworks encompass the range of variation that is currently found in international landscape studies. While the frameworks largely overlap, landscape biographic approaches focus on the regional scale of analysis and are more explicitly phenomenological and aimed at heritage studies, while historical ecological approaches are multi-scalar and are more comprehensive and explicitly empirical. Both frameworks embrace the stakeholders, planners, and managers of landscapes. For the first time, WP2 aims at integrating the so far separate concepts of landscape biographies and historical ecology with a complex systems-based perspective on cultural landscapes. With spatial dynamic models specifically designed for the needs of interdisciplinary study of landscape change, HERCULES intends to provide landscape researchers with new tools to understand long-term developments in cultural landscapes by more effectively linking archaeological, historical, ecological and social data.

2.3 Understanding long-term changes in cultural landscapes: premises

By integrating landscape biography, historical ecology and complex systems theory, WP2 wishes to realize a trans-temporal approach to landscape, treating epochs, periods, and other temporal divisions as ripe for research and not firewalls that protect temporal divisions and chronological schemes. Such a trans-temporal approach has several advantages. Particularly important for planning and heritage, the coupled human/environment system can be analyzed with regard to effective management strategies under specific (local, regional) cultural and environmental conditions and the results used to formulate future scenarios.

Thus a major issue is how to practically envision future landscapes. Many archaeologists, geographers, architects and heritage managers are employed to plan and manage entire towns or regions, taking into account the complexity of changing environments. In addition to the trans-temporal approach, WP2 wishes to contribute to overall approaches for HERCULES by including future management aspects and by enhancing the role of long-term thinking and analysis in geodesign, urban planning, landscape design, and stakeholder involvement.

Moreover, traditional historic landscape assessments are poorly matched with the needs of planners, policy makers and public interest groups. Such knowledge communities actively contribute to the further development of landscapes and regions, including their heritage (Fairclough and Grau Møller, 2008; Janssen *et al.*, 2014; Kolen *et al.*, 2015). We wish to introduce these important knowledge communities to new possibilities for understanding complex interactive processes over the long term by clarifying the powerful roles of narrative, social memory, and practical experience (from the past and the present) in collaboration and design.

In order to tackle these challenges, an integrated and multidisciplinary approach to long-term changes in cultural landscapes should start from the following 15 premises (ps), or at least from a combination of a significant number thereof:

- **[ps1] The Earth system and human societies are, together, the most complex system we know.** Complex systems (also called complex adaptive systems, abbreviated CAS) are densely connected networks with several features that set them apart from simpler systems such as internal combustion engines. The behavior of some elements in CAS cannot be predicted (termed non-linearity), but they emerge in the course of time.
- **[ps2] A complex systems approach offers a useful focus for the study of biophysical systems that include humans** which, now that the Anthropocene has arrived, are everywhere on Earth. The goal of 'long-term studies' is to combine knowledge of past human societies with knowledge of past biophysical conditions and use their analysis to model sustainable future possibilities for heritage management.
- **[ps3] Much of what we know about such systems cannot be based on extrapolation from present conditions.** Yet these CAS are remarkably historical: initial conditions of the system are a strong predictor of later states. Past decisions shape and constrain subsequent ones and small differences are disproportionately the cause of later circumstances. This is called *path dependence*. Thus physical infrastructure, social practices, and other conditions can impede necessary system-wide change.
- **[ps4] Diversity plays a critical role in ensuring resilience to systemic shocks**, not just of living organisms but also of thought and practice and how, together, these have shaped landscapes over time.

- **[ps5] A region's linked human and environmental history contains information about how it responds to extremes**. For example, knowledge of past climate extremes allows managers to anticipate changes in the region (e.g., ground water levels, the impact on particular species, or clever innovations people found in the past).
- **[ps6] Knowledge of past management strategies can help avoid earlier mistakes or, in the case of good results to a particular strategy, offer viable alternatives to a similar contemporary challenge.** These 'old-and-new' solutions stimulate 'tinkering' to arrive at hybrid innovations and stimulate sustainable current development. They have many advantages: use of low-cost, low-impact, locally available materials, a local and motivated work force, and a source of local pride which strengthens community.
- **[ps7] Knowing a system's history can be seen as using completed experiments undertaken in the laboratory of the past.** All (pre)historic techniques are not sustainable, but it is true that their persistence is, at least in part, witness to their utility.
- **[ps8] Landscape change is affected by forces at all spatial scales, from local to global.**
- **[ps9] Landscapes have their own temporalities and rhythms**, in relation to but distinctive from individual and community life cycles. The past is also always present in the landscape of 'today'. All landscapes incorporate "the powerful fact that life must be lived amidst that which was made before" (Meinig, 1979: 44).
- **[ps10] The holistic form of -historical ecology (Crumley, 2015) that we employ is theoretically and methodically strong**, embracing the contribution of many different knowledge communities and types of data, working with diverse stakeholders, and to project future scenarios for regions.
- **[ps11] An explicit research question of landscape biography is to investigate the power of existing landscapes on people and their spatial practices, as well as the dynamic way in which people have dealt with their environment through time.**
- **[ps12] Landscape biography highlights the importance of social memory and the means to construct "a chronicle of life and dwelling"** (Ingold, 2000: 189). To engage today with past landscapes we must be able to tell stories that re-connect heritage visitors to the thoughts and emotions of previous inhabitants. Additionally, landscape biography can make people aware of similarities and differences (otherness) in the perceptions, emotions and thoughts of people, both in the past and in the present. In this way, heritage landscapes can be promoted as tools of tolerance, openness and pluralism.
- **[ps13] Historical ecology and landscape biography both study long-term transformations in landscapes** from prehistory to the present, viewing landscape as a dynamic and complex interplay between social and economic developments, culturally specific perceptions of the environment, the history of institutions and political formations, and ecological dynamics (Crumley, 1994, 2015; Kolen *et al.*, 2015; Meyer and Crumley, 2011; Roymans *et al.*, 2009). It is important to realize that the disciplines contributing to this exercise, like landscape archaeology, historical geography, historical anthropology and palaeo-ecology, explore quite different datasets (see 7.2 below) covering different time-intervals and aspects of landscape

change. These datasets and the methods used to analyze and interpret them must be related and integrated in systematic ways in order to synthesize long-term changes.

- **[ps14] Together, historical ecology and landscape biography can link social memories to the long term, connecting the micro-histories of places to broad-scale developments, and integrating experience and process.**

  One of the routes to this end is by the study of how, in different mnemonic, religious and social systems, memories, values and ideas concretely interact with the material world (e.g. Küchler, 2002).

- **[ps15] Thus landscape biography and historical ecology view landscapes as palimpsests that are transformed continuously, both through conscious interaction by people with the material past in the environment and through less conscious forms of agency.** This illustrates that landscapes cannot simply be seen as the outcomes of drivers, but that landscapes themselves are also drivers of social, political and economic change.

Taking the above set of premises as its methodological starting point, this protocol will not produce a single paradigm but rather offers a toolbox of concepts and competencies (cf. De Kleijn *et al.*, 2014; Kolen *et al.*, 2015; Meyer and Crumley, 2011; Crumley, 2015). At the same time, the premises can be chosen as explicit theoretical guidelines for research projects that tackle long-term changes in cultural landscapes.

2.4 Operational principles

A set of 10 operational principles (OP) (in addition to the conceptual tools outlined above) guide our research design (Meyer and Crumley, 2011:122). These principles include:

- [OP1] A commitment to begin with a research design constructed by all collaborating scholars and evaluated/supported by relevant stakeholders who jointly decide central questions, elucidate desired outcomes, and plan the data gathering, data merging, and interpretive phases of the project;
- [OP2] A commitment to work with both quantitative and qualitative empirical data (see also 6.1);
- [OP3] A commitment to integrate both academic and non-academic knowledge (see 7) in a fashion, which privileges neither and attempts to translate each to the other;
- [OP4] A commitment to employ data collected using ‘best practice’ protocols for each relevant discipline when available;
- [OP5] A willingness to keep independent from one another these various lines of evidence until such time as discipline-based data gathering is considered sufficient, but also to keep researchers themselves in constant dialogue;
- [OP6] A willingness to see conclusions about the history of a region constantly modified or reversed by new, evidence-based interpretation;
- [OP7] A recognition that changes in knowledge about a region tend to have material (and thus historical) effects in the region;
- [OP8] A recognition that evidential gaps (both spatial and temporal) raise questions about the appropriate extent of extrapolation, leading to questions of scale and reliability;

- [OP9] A recognition that designers' decisions about temporal and spatial parameters must be tied both to desired outcomes and to available information about historical and on-going processes of change; and
- [OP10] A recognition that 'baselines' are very important but have the potential to introduce errors into later interpretations.

3. The Past Land Use Scanner modelling framework

Maurice de Kleijn and Frank Beijaard

The protocol presented in the previous chapter proposes to apply spatial dynamic modelling frameworks which combine long-term perspective of archaeology and history with insights from cultural ecology, anthropology and geography. Applying spatial dynamic modelling frameworks are believed to realize a trans-temporal approach and foster the understanding of long-term landscape change.

As stated in the theoretical frameworks presented above, past landscapes must be approached as complex interplays between natural and cultural processes with varying temporal rhythms. The natural conditions of the physical landscape are influenced by human activities and *vice versa* the human activities are influenced by natural and ecological processes. In recent years, various studies have applied modelling frameworks to simulate past land use, in which both the physical dynamics and human activities are combined (e.g. Van Dinter et al., 2014; Dijkstra, 2011; Goodchild and Witcher, 2010; Whitley *et al.*, 2010; Danielisová *et al.*, 2015). These studies have produced detailed calculations on the required resources (i.e. food, fuel and construction material) and confronted these to the physical landscape and ecological circumstances of the area. However, these landscape studies have a) not taken into consideration recent spatial theory and allocation models and b) work with strong (and often oversimplified) generalizations on a regional level. Although existing theoretical frameworks, such as Von Thünen and Christaller's Central place theories (Clarke, 1977), have been applied in many archaeological landscape studies, only a few studies have applied these allocation models on a regional scale taking into account the political dimensions of land use, e.g. competition for land use between various settlements (in particular Verhagen *et al.*, 1999; Robb and Van Hove, 2003; Kohler *et al.*, 2007; Whitley *et al.*, 2010; De Cet *et al.*, 2015). Integrating these aspects offers opportunities for testing hypotheses for reconstructing past land use, allowing to improve the understanding of past landscape dynamics. Additionally, by applying more spatially explicit allocation modelling techniques, path dependencies over longer time periods steered by cultural and natural ecological processes can be researched in more detail. This is especially true for de- and reforestation processes which are assumed to have shaped the landscape significantly and often irreversibly changed it. Applying spatially explicit dynamic modelling techniques which allocate land use on a regional level would therefore fit the theoretical frameworks of both HE and LB. The main problem, however, is the limited availability of modelling tools which are able to compute these complex models. GIS is currently not very well suited for running complex dynamical models, whereas ABM and systems dynamics modelling are still limited in their capacities to deal with large and complex spatial datasets.

3.1 Introduction to Past Land Use Scanner modelling framework

In this chapter the aim is to address the challenges for applying spatial dynamic modelling techniques by applying the Past Land Use Scanner (PLUS) modelling framework. The goal is two-fold: first, to show how the PLUS can be utilized as a tool to spatially explicitly allocate land use by combining demographical data and the physical and ecological characteristics of

the landscape. Second, to use the PLUS results for identifying long-term land use processes. It must be stressed, however, that the PLUS should not be seen as a tool for reconstructing past land use. It is foremost a framework in which existing hypotheses can be confronted with the spatial limitations of their research area. Moreover, the transparency and easy adjustability of data that is provided by the PLUS allows for dealing with multiple scenarios to establish the bandwidth of hypothetical land use systems.

It should therefore be seen as a heuristic tool with a specific role in the research process of developing and testing scientific theory (cf. Verhagen and Whitley, 2012).

The PLUS modelling framework is based on the Land Use Scanner (LUS), which has its origins in the spatial economics and environmental studies domain for modelling land use change in the near future. The LUS is based on the understanding that land use is influenced by socio-economic development (Hilferink and Rietveld, 1999; Koomen, Hilferink and Borsboom-van Beurden, 2011; Dekkers *et al.*, 2012). In that context, the LUS has been used in a large number of national and international policy-related research projects (see Koomen *et al.*, 2011; Dekkers *et al.*, 2012). The basic principle of the LUS is that it simulates land use patterns based on estimated regional demands for various land use types combined with local assessments of suitable locations for these uses (figure 2). The regional demands within the LUS are based on a combination between economic and demographic scenarios. The local suitability for certain land use types are based on the present land use, policy maps, distance relations and thematic information varying from safety (e.g. floods, earthquakes and other risks) to accessibility (e.g. distance to ports and train stations). To what degree the local suitability of a specific land use is influenced by these factors is based on expert judgement. To balance the demand for land for different types of use with the supply of suitable locations, a logit-type approach is applied that simulates the competition for land.

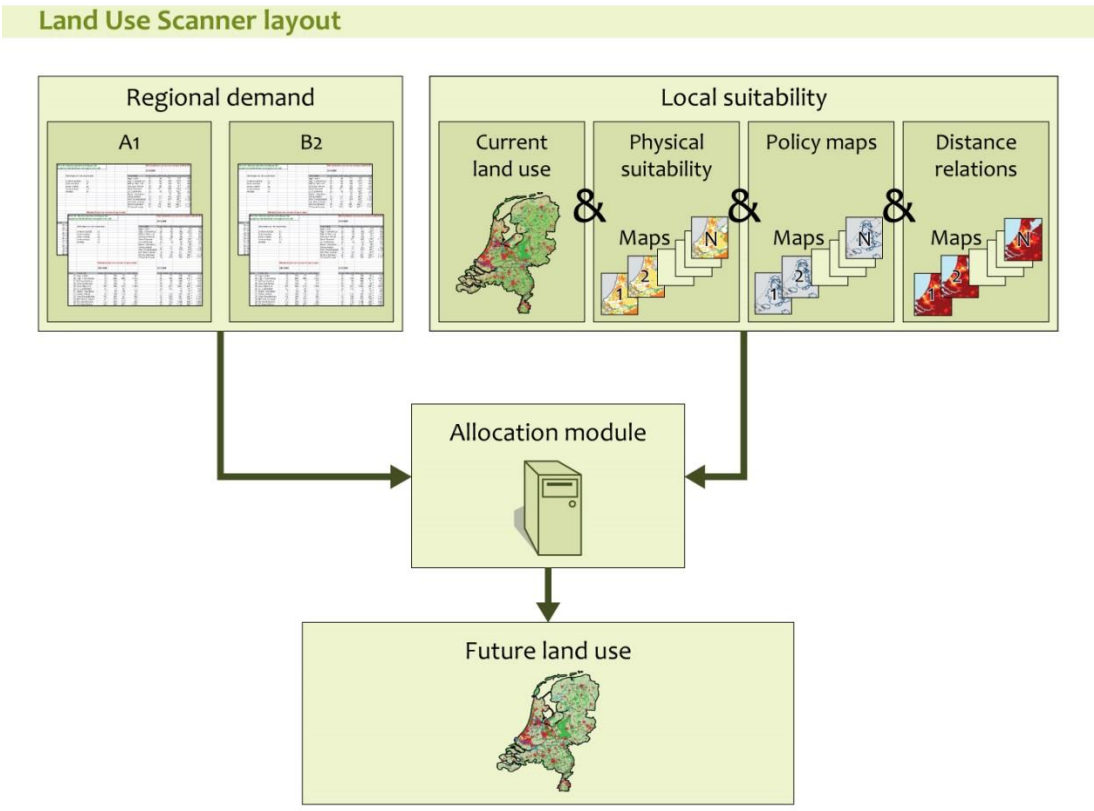

Fig. 2: Schematic overview of the LUS modelling framework (adopted from Koomen et al., 2011)

Adjusting the LUS modelling framework for simulating past land use allows for integrating and combining knowledge on the physical characteristics of the landscape with socio-economic forces. The regional demand for past land use is derived from demographical studies, whereas the local suitability is based on the start situation (archaeological spatial data), the physical suitability of the landscape for individual land use types, distance relationships and policy (e.g. political and military decisions derived from historical sources and other studies).

The LUS thus offers a tool that can build a bridge between two aspects of archaeology that are notoriously difficult to connect; individual settlement sites and a broader landscape scale. It connects the physical ecology with the landscape's usability by its inhabitants.

Another advantage of the PLUS is the ability to use the allocation results of one period as the starting point for a subsequent period. The ability to join different periods together allows for the study of long term developments and path dependencies within the scenarios. Reflecting on the challenges that previously existed with modelling past land use, the PLUS modelling framework is able to overcome these because:

- it combine knowledge of past human societies and past biophysical conditions (ps2);
- it uncovers how initial conditions of the system are a strong predictor of later states (path dependencies) (ps3);
- it analyzes landscapes in terms of various temporalities and rhythms (including the long-term)
- it adopts a long-term heritage perspective: the modelling framework takes into account that the past has always been present in the landscape ("the past in the past" Roymans et al. 2009) and has been reused continuously through time (ps 9, ps15);

3.1.2 Operationalizing the PLUS

The PLUS is a grid based modelling framework of which the cell size can be determined by the user (most configurations use 100x100 meter cells). The original LUS distinguishes two approaches: discrete and continuous. The discrete LUS module calculates the land-use for every cell and provides only one value as outcome per cell, the continuous LUS module calculates the relative probability for every land-use type for every cell, thus generating multiple values for one cell. For the PLUS, the continuous approach is more appropriate, since it allows to deal with more uncertainties, something which is obviously the case for past land-use reconstructions.

We will not go deeper into the theoretical and mathematical background of the PLUS, since this can easily be found in above mentioned studies. The allocation formula, however, is provided as it forms the backbone of the model. The continuous PLUS module is based on the following formula:

$$M_{cj} = a_j \times b_c \times e^{Scj}$$

where:

M_{cj} is the amount of land in cell c expected to be used for land-use type j;

a_j is the demand balancing factor that ensures that the total amount of allocated land for land-use type j equals the specific claim;

b_c is the supply balancing factor that ensures that the total amount of allocated land in cell c does not exceed the amount of land that is available for that particular cell;

e^{Scj} is the suitability of cell c for land-use type j based on its physical properties and neighborhood relations of which the importance of the suitability value can be set by adjusting a scaling parameter.

(Adopted from Koomen *et al.*, 2011, a more extensive description of the mathematical aspects of the model has been published by Hilferink and Rietveld, 1999)

3.1.3 Modelling software

The PLUS has been performed on the modelling software Geo Data and Model Software (GeoDMS). This modelling software is developed by Object Vision BV (http://www.objectvision.nl/) using the programming languages Delphi and C++ and is available as Free and Open Source Software (FOSS). The software is thus reusable by others and because the code is available, others can also participate in its continuing development. One of the main advantages of using the GeoDMS software is that it is relatively fast in performing calculations on large datasets. Another advantage is that its openness, meaning that other researchers can easily recreate scenarios studied by others or adapt existing setups with new (updated) datasets. An extensive description of the used software can be found here: http://www.objectvision.nl/geodms.

Beside the modelling software a number of scripts were written using Python 2.7 (https://www.python.org/download/releases/2.7/) to optimize the time it takes to run all different scenarios. These scripts will be published on GitHub to allow other researchers to recreate the scenarios presented in this deliverable.

3.2 The Dutch Lower Rhine region

3.2.1 Introduction to the case study landscape[2]

The first case study landscape selected is the Lower Rhine region between the modern-day municipalities of Katwijk and Utrecht-Vechten (Bunnik) (Figure 3). The reason for selecting this area is two-fold. First, the region underwent significant political and socio-economic changes during the first millennium AD, making it a good case for studying long-term changes and path dependencies. Second, the area has a relative high density of archaeological sites and historical landscape features, and a large and rich database of archaeological and palaeo-environmental data is available, allowing for setting up more robust models and testing of the outcomes.

Parts of the Dutch river landscape were already occupied during the Mesolithic and Neolithic. Initially, land use was limited to the higher levees alongside rivers or old river dunes from the Upper Pleistocene and Early Holocene. By the Middle and Late Bronze Age, significant parts of the levees were transformed into true rural landscapes, with scattered (and wandering) farmsteads with associated burial mounds, gardens, field systems and roads. This rural landscape was part of a mosaic environment consisting of woodlands, wetlands and more open cultivated areas.

[2] Case study description (party adopted from D2.2)

In the Roman Period, the study region formed the Northwestern part of the Roman frontier on the continent. By then, land use had intensified considerably, creating a more open landscape with an increased human impact on the water system. The process of increased control over water systems is most profound in the construction of at least two canals during the first centuries AD: Corbulo canal and the Mare canal (Vos, 2007; De Kort and Raczynski-Henk, 2008; cf. Dijkstra 2011, 58 note 185). Although discussion exists on whether the canals were extensions of existing waterways or completely designed (Cohen *et al.*, 2009), their existence does suggest an attempt was made to control and adjust the natural waterways to human needs. Apart from these new, artificial waterways, human impact on the natural water system, e.g. the dynamics of its courses and sedimentary environments, increased considerably during the Roman period as well.

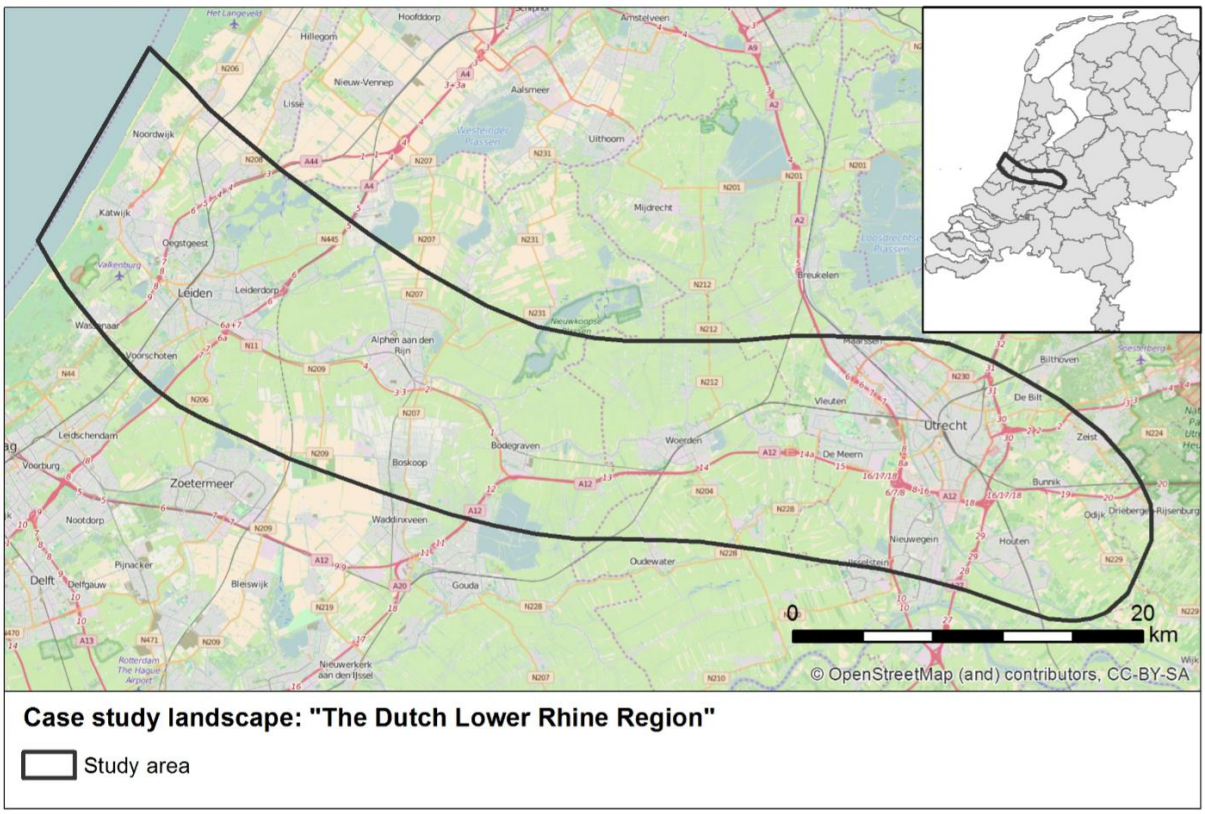

Fig. 3: The Lower Rhine region case study landscape (© OpenStreetMap-authors)

Around AD 1000, the inhabitants of the river villages in the study region began to construct embankments along major rivers like the Rhine and Meuse. Along with the villages themselves, fields and gardens occupied the highest parts of the banks, while the slopes down to the floodplains behind the banks were used as communal meadows and pastureland. In the period from AD 800 to 1250, towns in the Lower Rhine delta area expanded significantly and there was a growing demand for agricultural products. To satisfy this demand, the agricultural land area had to be extended to the low-lying peat areas and river basins. But before these areas could be drained and reclaimed, embankments had to be built along the river courses and any obstructing ones had to be dammed. Several centuries later, the remaining open spaces between the village embankments were closed off and long, uninterrupted dikes were built. This process was completed in most parts of the Dutch delta by about AD 1300. Inside the dikes, where in winter especially the river water was sometimes dammed up to a significant extent, river forelands were created.

For HERCULES D 2.3 we focus our modelling scenarios on the first millennium AD. By integrating knowledge based on archaeological and historical insights with palaeogeographic reconstructions of the landscape for five subsequent time slices (i.e. AD 40, 70, 140, 500 and 800) in the PLUS, we aim to simulate long-term landscape changes for the first millennium AD. We deliberately choose to focus on this period and these specific time slices, since these are assumed to have been crucial in transforming the landscape, but not all processes involved are understood yet. Another reason for selecting these time slices it that they have been studied in detail by others, resulting in valuable and necessary data on the demand for land use. As an introduction to every time slice the following paragraphs will briefly summarize the main changes prior the specific time slices.

AD 40

By the second half of the first century BC the Romans extended their political influence to the Rhine-Meuse river area. The formal Roman military occupation of the area, however, began several decades later with the construction of a large legionary base near Nijmegen during the Augustan military campaigns in c. 19-16 BC (Polak and Kooistra, 2013). In the following three decades, the Roman army established several fortifications (*castella*) on strategic locations in the Rhine-Meuse river area. In the Lower Rhine region the first military fort, *Fectio*, was built near present-day Vechten (Zandstra and Polak, 2012). After AD 16-17, further military expansion into Germany came to a halt and no new building activities were undertaken by the Roman army until AD 40.

Before the Roman occupation, the rural population of the Lower Rhine delta is assumed to have been for the most part self-sustainable, producing little surplus. The arrival of the Roman garrison at *Fectio* had a big impact on the cultural landscape of the eastern part of the Lower Rhine region. First, the garrisoned legionary soldiers had to be partially fed with the surplus generated by the local population. This meant that farmers had to increase their arable production. The size of their cattle herds had to increase as well in order to meet the military demand for meat. Second, the construction and maintenance of the *castellum* required a lot of timber and firewood. This demand for wood had a big impact on the existing woodlands of the surrounding area of the military fortification.

AD 70

Between AD 40 and 70 the Romans started to consolidate their grip on the Lower Rhine region by constructing more frontier forts and watchtowers alongside the river. Constructing and maintaining such a military project required a new type of infrastructure that was unknown to these lands and which had a significant impact on the landscape. Not only did the need for large quantities of timber and firewood increase, also a limitless supply of food was required to sustain the newly constructed frontier.

The impact of the arrival of the Romans on land use for this period was analyzed in detail by Kooistra *et al.*, (2013) and Van Dinter *et al.*, (2014) in a diptych of articles. The main question addressed in their study is whether the local population of the Lower Rhine region was able to supply the Roman army stationed at the frontier forts. In their analysis they combined archaeological, palaeo-ecological and geomorphological data in order to calculate the need for food (in kCal) and wood (in m^3) to create a sustainable frontier. These demands were translated into a demand for space (in ha) of different land use types which would produce the various demands. The calculated demands were divided over three distinct geomorphological regions (western coastal region, central peat area and the eastern river area) in the western Lower Rhine region (figure 2). The thoroughness and level of detail provided by the study of Kooistra *et al.*, (2013) and Van Dinter *et al.*, (2014) is a perfect starting point for modelling the land use in the PLUS modelling framework. We have adopted their above-mentioned three regions and used these as input for our

modelling activities. By analyzing their work and integrating the findings and calculations in the PLUS we have been able to generate spatial explicit scenarios in which allocation is driven by physical suitability and distance relationships.

AD 140

As the third time slice we selected AD 140, which marks the end of the middle Roman period. In AD 69-70 the local population of the Rhine-Meuse delta revolted against the Roman occupation. The Batavian Revolt, as it is called, resulted in the destruction of all Roman military fortifications in the region. When the uprising was subdued in AD 70, the Roman army quickly restored the original wooden forts along the Rhine delta, and the Romans integrated the region more firmly in their administrative and economic system. It is assumed that this led to changes in taxation and land distribution. By c. AD 100 the original Roman occupation force of AD 70, stationed in Nijmegen, was considerable reduced in size. As far as the auxiliary forces are concerned, there is little evidence that indicates a severe reduction of the occupation size in the Lower Rhine region. Furthermore, archaeological studies show that no forts seem to have been evacuated during this period (Polak, 2009).

The period AD 70-140 also saw an increase population size in both the rural areas and *vici* (small villages associated with the military forts) of the Lower Rhine region. Overall, this population growth must have put pressure on the food production capacity of the local landscape and rural population. The food demand was even further strained because of a new administrative division of the landscape. It has been suggested that after AD 70 the Rhine became a more fixed border. For this reason, the available lands north of the river were supposedly no longer used for the production of food surplus for the Roman garrisons (Van Dinter *et al.*, 2014, 23-24). The combination of population growth and political limitations raises the question if the local rural population was still able to feed the Roman military and civilian settlements.

AD 500

The fourth time slice is AD 500 and was chosen because of the various political, demographic and socio-economic changes that occurred in the fourth and fifth century. How these changes affected the land use of the local rural population of the Lower Rhine region is the main question for this case study.

The fifth century in Northern Europe is commonly known as a period of political instability, characterized by social transformations, large-scale migrations and an overall decline of the population size (Van Lanen *et al.*, 2015; Gerrets, 2010; Cheyette, 2008). The withdrawal of Roman troops and the collapse of their provincial government created a power vacuum which was eventually filled by various Germanic tribes, predominantly Frankish immigrants (Van Enckevort and Thijssen , 2002).

The withdrawal of the Roman armies did not only have political consequences for inhabitants of the Lower Rhine region. First, the withdrawal of the Roman garrisons brought an end to the military demand for locally produced food. The rural population no longer needed to generate large quantities of surplus. The archaeological evidence shows that with the abandonment of the military forts along the Rhine their associated settlements (*vici*) were no longer occupied either. This reduced the demand for food surplus even further (Van Es, 1981; Kemmers, 2008). Secondly, the infrastructure built by the Romans eventually collapsed. For example, the extensive road network which connected all the various fortifications and urban areas was no longer maintained by the local Roman garrisons.

Archaeological research suggests that repairs to roads seem to have stopped somewhere in the third century AD and had all but disappeared by the end of the fifth century (Dijkstra, 2011: 52). Environmental changes did occur during this time period, most prominently the rising sea level coupled to increased flooding (Dijkstra, 2011). It has been suggested however that this increasing 'wetness' of the land did not significantly alter land use in the Lower Rhine region (Dijkstra, 2011: 47, 57-58). Most of the human activity in this area was already confined to the highest levees and an increase in water levels did not change the situation much. As a result, a majority of the Late Roman settlements in the region saw a continuation into the Early Medieval period (Dijkstra, 2011: 57-58).

AD 800

The fifth and last time slice is AD 800 and was chosen because of the demographic and economic growth that occurred in the Lower Rhine region in the sixth and seventh century. During this period the delta regained the transport-geographical importance that was lost previously and AD 800 is regarded as the peak of this development (Van Es and Verwers, 2010).

The frontier character of the Lower Rhine Delta persisted into the eight century. In these days, all settlements along the Rhine were part of a vast, international trade network, with several cities evolving into the principal ports of the Carolingian empire, such as Dorestad. During the eighth century, regal power within the Frankish empire changed hands from the Merovingians to the Carolingian family, named after the most famous member: Charlemagne. Part of the economic revival that took place in the delta was because of the stability that was brought by the Carolingian empire.

3.2.2 Relationship to other research projects

For simulating the land use for the time slices AD 40, AD 70, AD 140, AD 500 and AD 800 most of the data is obtained from two detailed studies. The work by Van Dinter *et al.* (2014) and Kooistra *et al.* (2013) has been used to estimate the demand and partly the suitability of land use for the Roman period. The work of Dijkstra (2011) has been used as input for the demand and suitability of AD 500 and AD 800. Beside these published works we have worked with members of the "Finding the limits of the Limes" – project (FFL) and "The Dark Age of the Lowlands in an interdisciplinary light: people, landscape and climate in the Netherlands between AD 300 and 1000" – project (DAL).

Finding the Limits of the Limes – principal investigator: Dr. Philip Verhagen,

"The project aims to apply spatial dynamical modelling to reconstruct and understand the development of the cultural landscape in the Dutch part of the limes zone during the Early and Middle Roman period (15 BC – 270 AD). It will focus on modelling economic and spatial relations between the Roman army and the local population, in particular the interaction between agriculture, animal husbandry and wood management, and the related development of settlement patterns and transport networks in the area.

The ambition is to develop quantified spatio-temporal palaeo-economic scenarios of agrarian production in a complex context. The study area and period offer two challenges in this respect. Firstly, the Roman Empire developed macro-economic policies concerning taxation and land ownership that strongly influenced the local agrarian economy. Furthermore, the Dutch part of the limes zone is located in the Rhine-Meuse delta, a dynamic fluvial environment in which the Romans developed a sophisticated water management infrastructure. An integral analysis of the socio-economic system in that area therefore has to consider all the local, regional and supra-regional factors involved in economic development. The interaction of environmental, economic and

socio-cultural factors must also be examined. The Dutch limes zone is one of the archaeologically best researched areas in the world (Willems, 1986; Kooistra, 1996; Roymans, 2004; Groot *et al.*, 2009; Vos, 2009; Heeren, 2009). Consequently, a rich set of archaeological and palaeo-environmental data has been collected over the past decades. It is therefore an ideal laboratory area to construct new models of the development of the cultural landscape." (https://limeslimits.wordpress.com/full-project-proposal/)

The Dark Age of the Lowlands in an interdisciplinary light: people, landscape and climate in the Netherlands between AD 300 and 1000 – principal investigator Prof. Esther Jansma.

"This research programme focuses on a period of severe pan-European economic and demographic change: the Late Roman Period (AD 300-500) and Early Middle Ages (AD 500-1000). Physical-geographical and bio-geological data point at marked climatic variability and changing landscapes during this time interval. In geomorphologically sensitive regions such as river deltas and coastal areas these changes must have had a noticeable impact on the location and lay-out of urban centres and rural settlements, land use and subsistence strategies, and connections of population centres to their economical "hinterland". Recent developments in digital infrastructure in the Humanities and Geosciences in the Netherlands for the first time enable us to study these phenomena from an interregional and interdisciplinary perspective." (Jansma *et al.*, 2013).

Both projects focus at reconstructing past dynamics and processes on a regional scale by connecting the physical ecological landscape with human actors. Working together with these research teams allows us to:

- integrate knowledge on the suitability of various land use types for different physical ecological conditions of the landscape (see paragraph 3.3.2.).
- access the most up to date information on the physical characteristics (i.e. updated palaeogeographical reconstructions) of the past landscape.
- access up to date reinterpreted and structured archaeological datasets.
- constantly and critically appraise and position our research in the ongoing discourse of integrating the physical ecological landscape and human actors (archaeology).

Additionally, this collaboration offers clear opportunities for future academic research such as:

- A comparison on spatial dynamic modelling methods. This accounts especially for the ABM and network analysis activities that are performed in the context of the FFL project (e.g. Groenhuijzen *et al.*, 2015).
- Appling the PLUS modelling framework to other case study areas and test for hypotheses that are formulated in an ongoing research projects. This especially accounts for the DAL project in which the more inland eastern part of the Rhine Meuse delta between Utrecht and Millingen aan de Rijn is studied.
- Validating the results of the PLUS by confronting it with vegetation studies. This account especially for the research performed by Gouw-Bouman.

3.2.3 The case study landscape from a heritage perspective

From a heritage landscape perspective the chosen periods for the case study area are also believed to be highly relevant. First, modelling land use during the Roman period will provide us with new insights into the cultural landscape alongside the borders of the Roman Empire. The results of the case study can be used in several ways:

1. For improving our understanding of the region's landscape development, with specific attention for long-term human impact on the environment, including its water system;
2. For better assessing the heritage potential of the present-day cultural landscape in the area;
3. For supporting the region's nomination of the Roman *limes* landscape for UNESCO's World Heritage list;
4. For better defining the starting points and reference models for nature conservation and rewilding in the area, especially now rewilding programs have become rapidly popular in Dutch wetland areas such as the Rhine-Meuse delta;
5. In this way contributing to the integral assessment of Landscape System Services for the case study region.

3.3 PLUS implementation

As stated above the PLUS framework offers a tool to test hypotheses by confronting them with the spatial limitations of their case-study area. For the selected time slices we have decided to focus specifically on the demand which has been reconstructed by previous studies and to see if these reconstructions hold up by confronting them with the limitations of space. By simulating the spatial distribution of land use and taking into account distance relationships and competition for land use between sites, we aim to test the feasibility of reconstructed land uses. In addition, we will define different scenarios in which we will study the path dependency of land uses.

The first hypothesis considers the production of food for the Roman soldiers between AD 40 and AD 140. Van Dinter *et al.*, (2014) hypothesize that 50% percent of the cereals required to sustain the Roman soldiers and vici inhabitants was produced locally. They conclude that both the landscape and the workforce have posed no limit. In the present study we apply the PLUS in order to understand if the land system and the local population could actually produce this figure and to test the upper limits of the land use system.

The second hypothesis considers the woodland for AD 500 and AD 800. Dijkstra (2011) hypothesizes that a medium sized settlement requires 2 ha of woodland per year. This figure differs significantly to the figures presented by Van Dinter *et al.* (2014) for settlements from the Roman period (i.e. 10.7 ha of woodland are required every 40 year). By applying the PLUS we can simulate the implications of both scenarios by making them spatially explicit, thus evaluating their feasibilities.

The following paragraphs can be divided in three parts. First, a section (3.3.1) is dedicated to identify the various land use types distinguished for these periods. The second section discusses the suitability of these land use types looking at distance relationships, physical conditions and introducing various wood regeneration scenarios. This section is followed by an extensive discussion and analysis on the two hypotheses presented above.

3.3.1 Land use types for the first millennium AD

To test the hypotheses considering the demand, the first step is to determine the land use types which can be distinguished. Based on the available data and after consulting experts from the research projects mentioned above, we have distinguished six land use types, which are considered to be valid for all time slices researched in this project (i.e. AD 40, AD 70, AD 140, AD 500 and AD 800):

- **Arable farming:** This land use type produces cereals for food production.
- **Pasture:** Pasture is used as grazing land for cattle to produce food (i.e. meat and dairy products).
- **Meadow:** Meadows are used to harvest hay as food for cattle during winter.
- **Woodland:** Woodland is used for timber and fuel. Within woodland a division between primary and secondary woodland has been included. Primary woodlands are considered to be fully natural which have grown without any human interventions.

  Secondary are considered to be woods which appears at abandoned areas where in previous periods the land has deforested. Primary and secondary forests differ in terms of their potential for human exploitation.[3]
- **Residential and military**; Residential and military represent areas where settlements and military constructions have been presented.

Besides these endogenous land uses we have distinguished water, and for AD 70 and AD 140 we have included the military *limes* road. Finally, the model contains a category "unused land" as a residual category for land that has not been used, as the PLUS modelling framework needs to allocate a type of land use for every cell.

Technically, the PLUS can handle a more diverse list of land use types (e.g. types of trees, type of agriculture etc.). However, not all time slices have the same level of detail in their data, so implying that this level of detail could be acquired using the PLUS would give a false impression and over-exaggerate the reliability of the model. We therefore decided to keep these more generic categories. Considering the geographical scale at which the model can be used, we determined that the modelling framework is foremost useful at the regional level (Koomen *et al.*, 2011) with a cell size of 100 x 100 m. Again, from a technical point of view it would be possible to use the modelling framework to study a higher resolution; however since the data availability and the purpose for which the underlying algorithms have been developed we decided to focus at the regional level.

Considering the temporal scale, the PLUS framework follows the timescale that is used for the LUS. For studies in which the LUS is applied the temporal scale applied varies between 30 - 100 years. Although in theory the PLUS could handle larger time spans, we have limited relating periods to each other to these time ranges. For AD 500 and AD 800 we have therefore not included the output from the previous period as input start situation. However, if we would have had more detailed information for the periods in between, it would have been possible to integrate this and simulate causality chains. In the current study we have only been able to do that for AD 40 – 140.

3.3.2 Suitability for land use

The suitability for the various land use types is assumed to be a combination of the physical conditions of the landscape, distance relationships between various settlements and the land use of the prior period.

[3] It should be noted that woodland can also be used as a grazing ground for pigs and cattle. However, in the current model cattle is used as the prime source for meat and pig herding is therefore ignored. Also, cattle can use woodland as grazing grounds but overall prefer open meadows. To keep the exploratory model simple, we are therefore not using woodland as a landscape for husbandry.

The physical suitability

To define the physical suitability for the land use types arable farming, meadow and pasture, we have thoroughly analyzed the palaeogeography of the study area and, have given a score for every land-use type on a 0 to 5 scale, where 0 is completely unsuitable and 5 is highly suitable. This scoring method is the result of a combination of literature study and a meeting with experts in the field of palaeogeography and palaeo-vegetation (the panel existed of Gouw-Bouwman, Pierik and Van Lanen, see Appendix A for the scores and literature references). Since during the period studied no major changes in land cultivation techniques occurred, the scores for the physical suitability apply to the whole first millennium AD.

Even more, since the palaeogeography of our study area did not change, the physical suitability of the landscape is the same for every time slice (based on expert judgment by Gouw-Bouwman, Pierik and Van Lanen). This relative stability of the landscape allowed us to consult a wide variety of studies in our assessment of the physical suitability of the palaeogeographical landscape.

The palaeogeographical reconstruction used in this study is an updated version by Groenhuijzen *et al.*, (2015) of the palaeogeographical reconstructions developed and updated by Cohen *et al.*, (2012); and Van Dinter *et al.*, (2014) (figure 4).

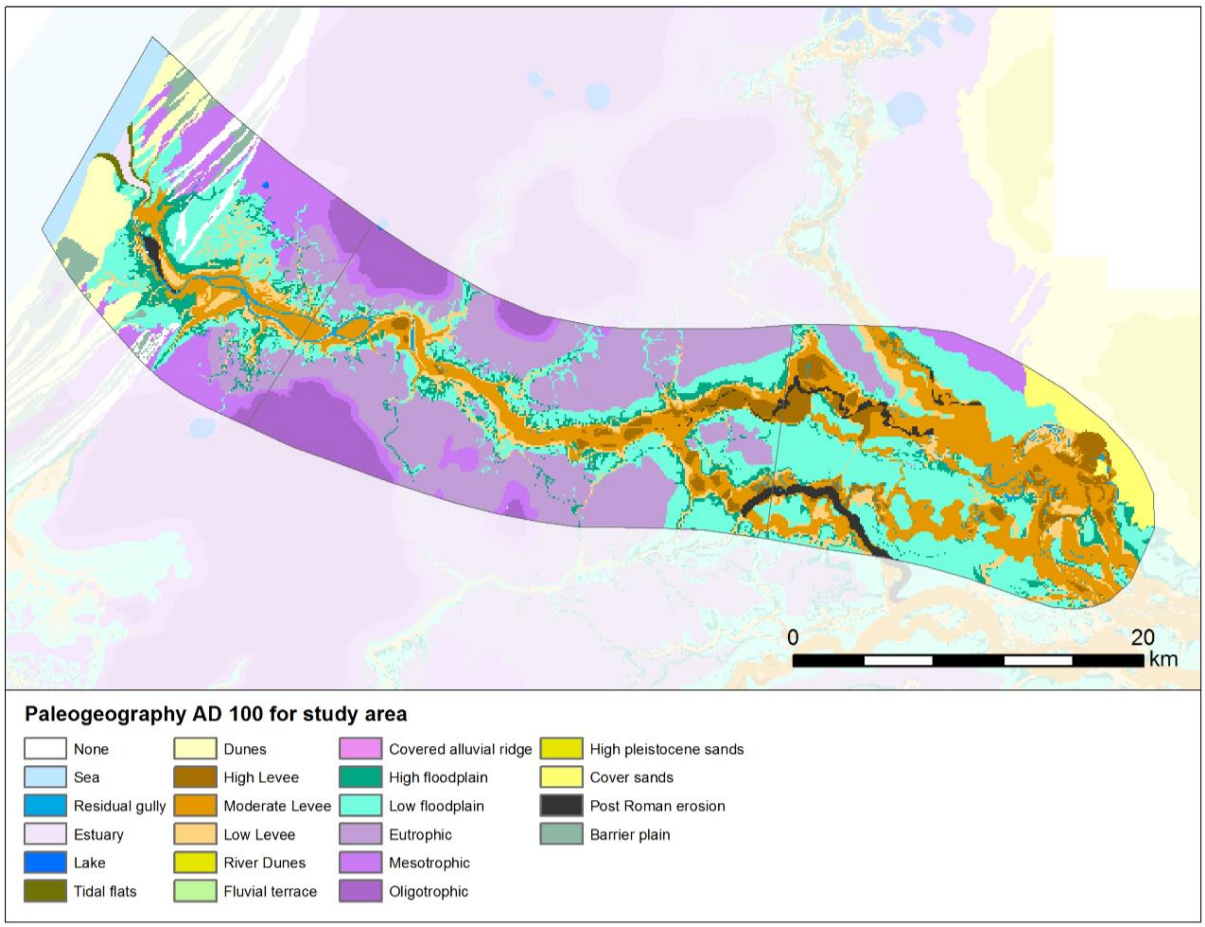

Fig. 4: Palaeogeographical reconstruction for AD 100
(based on Groenhuijzen et al., 2015; Cohen et al., 2012; and Van Dinter et al., 2014)

The physical suitability layers for agriculture and pasture/meadow (both are considered to have a similar score for their physical suitability) are presented in figures 5 and 6. The underlying reasoning, including references, is included as appendix A.

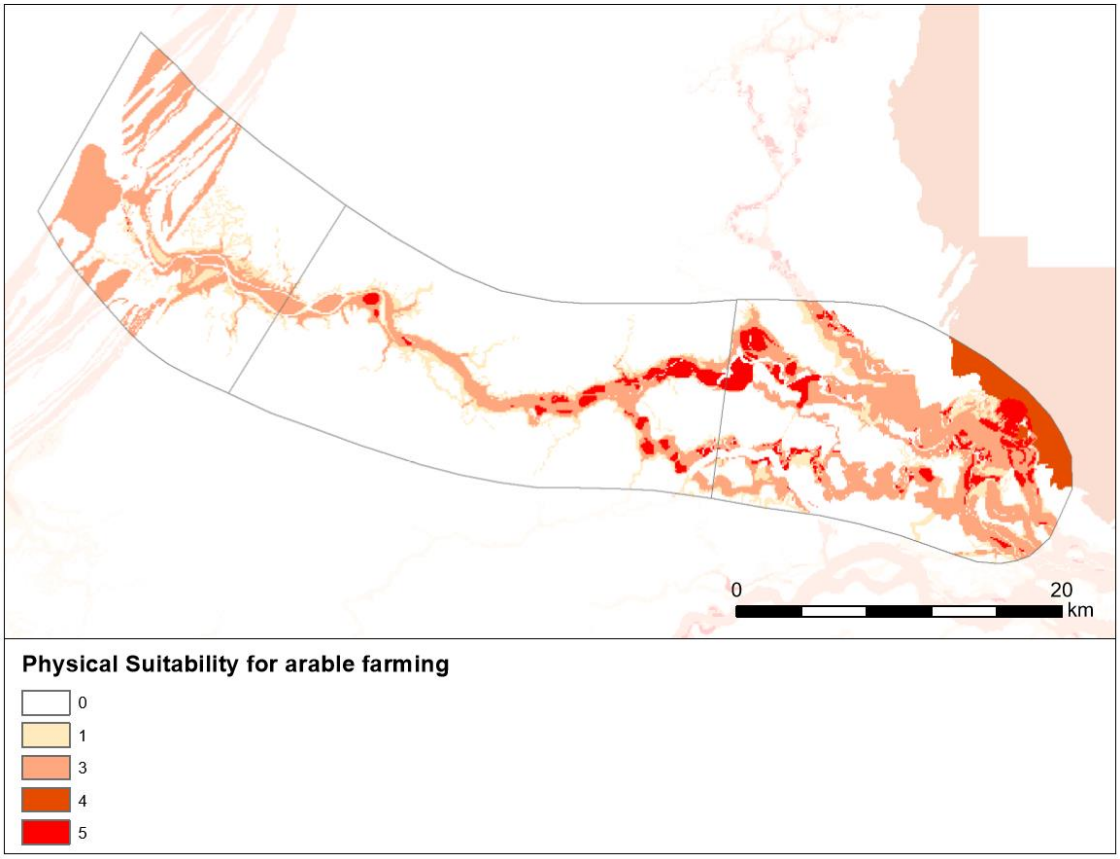

Fig. 5: Physical suitability for arable farming based on expert judgement Gouw-Bouman, Pierik and Van Lanen

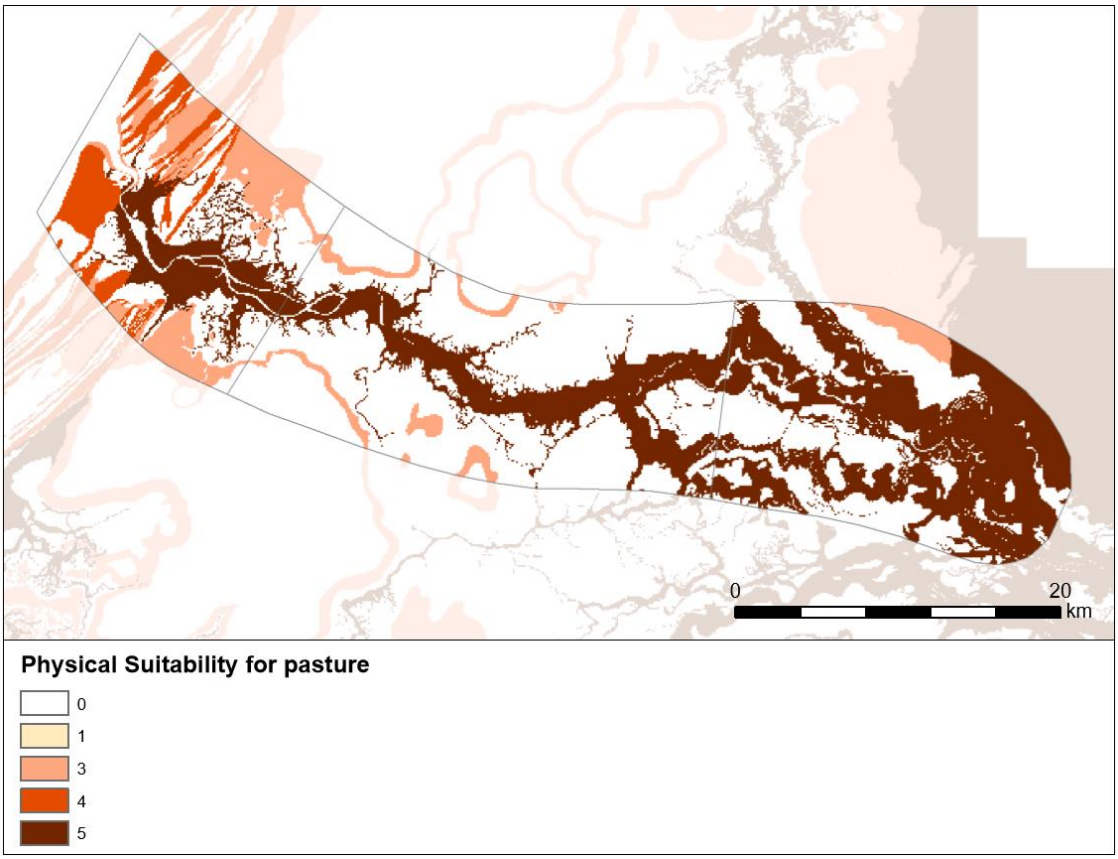

Fig. 6: Physical suitability for pasture and meadow based on expert judgement Gouw-Bouman, Pierik and Van Lanen (see appendix A)

Distance relationships

As for the distance relationships between land use types and archaeologically known settlement we have applied basic cost-distance principles derived from Von Thünen's theory and archaeological Site Catchment Theories (Higgs and Vita-Finzi, 1972). Based on these theories, we have formulated various distance relationships between settlements and land use types and between land use types themselves. We have decided to express distance in walking time rather than in meters. To do so we have used the work presented by Groenhuijzen and Verhagen (2015). They have calculated the speed a normal person could travel on foot without a significant load through specific palaeogeographical units (based on Soule and Goldman (1972), see Groenhuijzen and Verhagen, 2015). By translating these values into the time it would cost to travel 100 meter through a specific palaeogeographical unit, we have generated a cost raster which we have used to perform cost-distance analyses to settlements and other relevant elements in the landscape (table 1).

Table 1: Time for a normal person without any load to travel 100 meters through each specific palaeogeographical unit. (based on Groenhuijzen and Verhagen, 2015)

Palaeogeographical unit	Time (s) to travel 100 meter
Sea	320
Residual gully	88
Estuary	320
Lake	320
Tidal flats	78
New Dunes	78
Old Dunes	78
High Levee	75
Moderate Levee	75
Low Levee	75
River Dunes	100
Fluvial terrace	75
Covered alluvial ridge	100
High floodplain	88
Low floodplain	96
Eutrophic	96
Mesotrophic	96
Oligotrophic	96
High pleistocene sands	88
Cover sands	78
Post Roman erosion	100
Barrier plain	96
Military Road or Limes Road	71

Arable farming

Arable farming is considered to be the most labor intensive land use type from the period selected for our case-study landscape. People would have visited these lands on a daily basis. This land use type is therefore considered to have taken place nearest to a settlement. Based on site catchment theories, we have therefore limited the distance from a settlement to these lands to a maximum of 1 hour walking. Within this 1 hour walking time, we have included the rule that areas near to the settlement are more attractive than areas further away, using a linear distance decay function.

Pasture

Like arable farming, pasture is also considered to have taken place near to settlements. The main distinction, however, is that the distance to pasture is not limited to 1 hour, but 2 hours walking distance. Furthermore, we have configured arable farming to weigh heavier than pasture, giving arable farming precedence above pasture.

Meadow

For meadow we configured the same conditions as for pasture. However, assuming that the land use meadow was only periodically used to obtain hay, this land use type has been weighted slightly lighter than pasture, making cells nearer to settlements more attractive for pasture compared to meadow (Dijkstra, 2011). This, however can be questioned since the transport of hay from the meadow to the settlement probably needs carts or pack animals, suggesting that it might be easier to have the meadow closer to the settlement. This is something we might take into consideration in a follow up study.

Woodland

Woodland works differently compared to the other land use types. Whereas arable land, pasture and meadow are land use types which increase in size with an increasing number of people and higher number of settlements, woodland decreases. Although woodland is assumed to regenerate every 10 to 15 years into useful wood for fuel and timber (Van Dinter *et al.*, 2014), the demand for wood is mostly higher than the regeneration rate. For the deforestation of the study area we have formulated the following rules. For AD 40, AD 70 and AD 140 we have configured an area of 500 meter around military sites which would have been deforested first. We have configured this rule based on the statement of Van Dinter *et al.* (2014: 44) that woodland around military sites for safety reasons is not likely to have been allowed to regenerate. We have applied the same principle for the *limes* road for the periods AD 70 and AD 140, with a deforested zone of 300 meters on both sides of the road. On the one hand we have configured it as such for the safety reasons mentioned, on the other hand we assume that wood was also used to construct and maintain the road itself. Besides the deforested zones related to the military structures and *limes* road, we have configured the area within 1 hour walking time from settlements to be more likely to be deforested first and to be replaced by other land uses types (i.e. arable farming, pasture and meadow).

Starting situation:

The starting situation allows taking into account that land use allocation for a simulation of a certain period is influenced by the location of land use of the previous period. Normally, when using the LUS to model future land use development, current land use is used. However, when modelling past land use this is obviously more problematic.

Since we do not have any information on land use prior to AD 40, we have left the starting situation for the land use types arable farming, pasture and meadow empty. For residential and military we have used the known sites of AD 40. Water has been included as exterior. As stated above, woodland decreases with increasing population, which makes it problematic to start it as an empty layer. Instead, we have generated a hypothetical starting situation of woodland for AD 40 by translating the yield production per palaeogeographical unit proposed by Van Dinter *et al.* (2014: table 6, p16) into percentages of useful wood per cell. In our simulations we thus start with a landscape with relatively dense woodland. In reality, it is likely to have been somewhat less dense because of the presence of earlier settlement in the area. Vegetation studies based on archaeobotanical data and more detailed settlement data for the preceding period would be required to provide a more accurate view of the starting situation for woodland in AD 40.

To model woodland in the subsequent time slices after AD 40, i.e. AD 70 and AD 140 we have formulated three possible scenarios (figure 7).

- **No regeneration of wood;** The first scenario is that once woodland has been deforested, no regeneration of woodland will take place. This means that the modelling output for AD 40 will be used as input – starting situation – for AD 70 and subsequently the output for AD 70 will be reused for AD 140.
- **Regeneration of wood not within time slice;** The second scenario is that deforested areas will not be reused within the selected period for simulating the time slice. This means that areas where woodland has been deforested and where these have not been reused for other land use types will regenerate secondary wood. These areas of secondary wood will then be added to the simulation outcome and will be used as input for simulating the subsequent time slice.
- **Optimal regeneration and reuse of wood;** For the third scenario, all regenerated wood will be reused immediately and will be allowed to regrow again. For this scenario, the model is first run to simulate the decrease of wood and allocate the areas where secondary woodland might grow. Next, all secondary woodland will be multiplied by the number of time periods in which it can regrow (e.g. between AD 40 and AD 70 are 2 cycles in which the wood can regenerate i.e. AD 50 and AD60). This figure will then be combined with the demand for wood as timber fuel. To allow taking this into account, the demand for woodland will be lowered, a figure that is used to rerun the model and simulate the allocation for woodland.

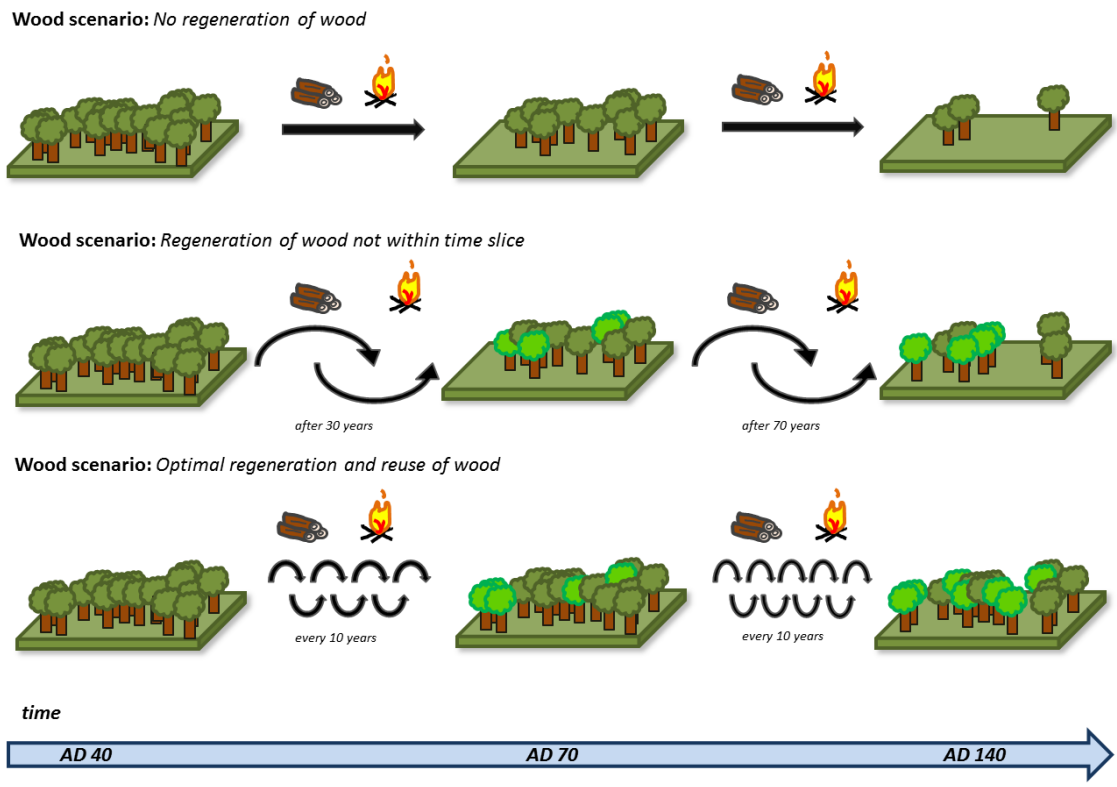

Fig. 7: Schematic representation of various scenarios for wood regeneration applied

These scenarios for woodland allow us to work with uncertainties, knowing that the truth must have been somewhere in between these scenarios. Approaching the simulation of land use in this way allows us to include temporal causalities, which allows for the testing of path dependencies.

Since the time gap between AD 140 and AD 500 is considered to be too large for applying the different wood regeneration scenarios, we have decided not to take these into account for the later periods. Instead, we have used the original input woodland starting situation for AD 40, assuming that most woodland would have been regenerated between AD 140 and AD 500.

Balancing the suitability factors:

An important aspect for the suitability as component of the PLUS modelling framework is the balancing of the various factors. Basically the various suitability factors per land use type are summed up resulting in a value which represents the attractiveness of a cell for that land use type. These resulting suitability maps per land use time are combined with the demand which then allocates the land use based on the algorithm presented in paragraph 3.1. The land use will basically be allocated to the cells having the highest value for attractiveness:

Residential	= [Start_situation] + [Physical_suitability] + [Distance_relation_X] + …
Agriculture	= [Start_situation] + [Physical_suitability] + [Distance_relation_X] + …
Grassland	= [Start_situation] + [Physical_suitability] + [Distance_relation_X] + …
Hay-land	= [Start_situation] + [Physical_suitability] + [Distance_relation_X] + …
Woodland	= [Start_situation] + [Physical_suitability] + [Distance_relation_X] + …
Unused land	= [Start_situation] + [Physical_suitability] + [Distance_relation_X] + …

The extent to which these various components have influenced the land use has been studied by various researchers (Verhagen *et al.*, 1999; Robb and Van Hove, 2003; Kohler *et al.*, 2007; Whitley, *et al.*, 2010; De Cet *et al.*, 2015). Although these studies show interesting leads, it is obvious that more research to balancing these components is required. For the PLUS we have balanced the various factors on expert judgement. It would be interesting to follow leads for applying statistical methods for balancing these factors. For the current study we have balanced the various components as presented in appendix B. The numbers used in this table are between 0-80, this is a technical requirement for the PLUS.

3.4 Testing hypotheses for the demand of land use

3.4.1 Hypothesis 1: local production for Roman army

To test the hypothesis formulated by Van Dinter *et al.* (2014) that the local population of the Lower Rhine delta could supply the Roman army, the first step is to calculate various scenarios for the demand for land use. The demands have been calculated for the 3 claim regions distinguished by Van Dinter *et al.* (2014) (figure 8). For AD 140 we have split these claim regions in a northern and southern part, following the hypothesis that the Roman army and *vici* only obtained their resources south of the border. Calculating the demand for the various land use types is performed in two steps. First, we calculated the demand for food and wood per local settlement under the assumption of self-subsistence. Second, we calculated the demand for food and wood for the populations of the Roman military structures and *vici*. This second demand would be the surplus, of which 50% needs to be produced by local settlements according to Van Dinter *et al.* (2014). Since this assumption will have a huge impact on the demand, we have tested the maximum production of the local settlements by translating the demand into hectares and by applying the PLUS. For the settlements in the study area we have used an updated archaeological dataset which has been produced in the context of the FLL project. For this project all known archaeological datasets for the area have been thoroughly analyzed and combined, producing a more reliable dataset (Verhagen, 2015).

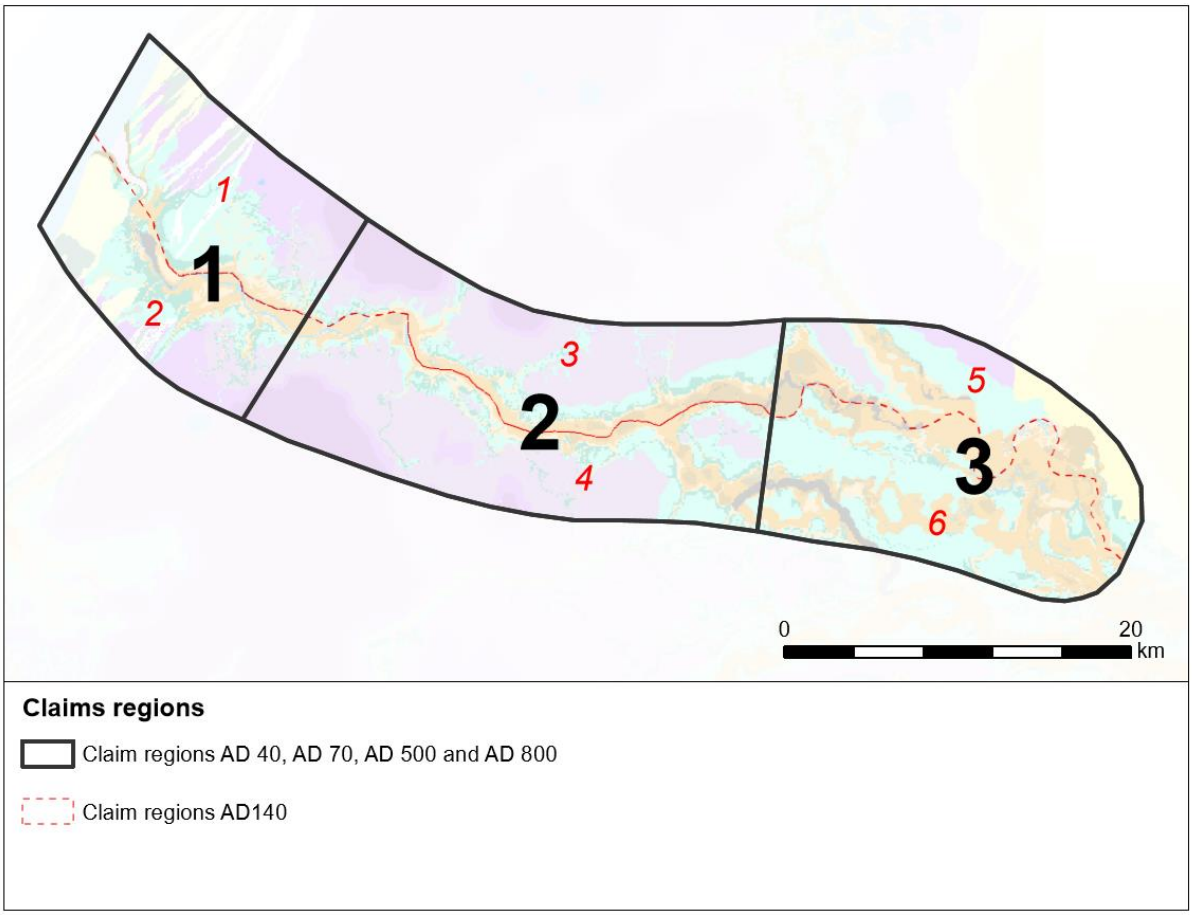

Fig. 8: Claim regions in the study landscape

Self-subsistent farming

For self-subsistent farming of the local settlements, Van Dinter *et al.*, (2014) provide a series of assumptions thought to be valid for AD 40, AD 70 and AD 140, to calculate the required amount of land use for food and wood production in hectares per settlement. These calculations are summarized in table 2.

Table 2: Overview of the assumptions to calculate the demand for land use for rural settlements AD 40, AD 70 and AD 140 based on Van Dinter et al. (2014)

Demand for food (general)
settlements were on average inhabited by 10 people
an adult person would on average need 2,200 kCal per day
67.5% of the food is acquired from arable farming (i.e. cereals)
22.5% of the food is acquired from animal meat
10% of the food is derived from other plant-based or animal products, which are on such a small scale that they don't need extra land. These have therefore been left out of the calculations.

Arable farming (cereals)
one kg of cereals produces 3,100 kCal
one ha produces 1,000 kg per year of which 800 kg can be consumed. The other 200 kg are needed for the next sowing season.
half of the required kCal per year will be produced as surplus to survive bad years
after a year of arable farming, the land will be fallow
Calculation for the demand of arable farming per rural settlement
(67.5 % (percentage of diet) x 2,200 kCal (daily need per person) x 10 (number of persons per settlement) x 365 (number of days per year)) / (800 kg (yearly weight of cereals) x 3,100 kCal (amount of kCal per kilo cereals)) x 1.5 (surplus production) x 2 (to take fallow lands into account) = **6.6 ha of arable farming needed per settlement**

Pasture and Meadow (for meat)
every settlement had a herd of approximately 50 animals (cows) which could produce 3,800,000 kCal of meat per year (which they did not have to use)
every heard needs 16 ha as pasture lands and 10.1 ha meadows.
in periods that lands for arable farming are fallow, these are used as pasture
Calculation for the demand of pasture per rural settlement
(22.5 % (percentage of diet) x 2,200 kCal (daily need per person) x 10 (number of persons per settlement) x 365 (number of days per year)) = 1,806,750 kCal
1,806,750 kCal (required production from a herd) / 3,800,000 kCal (maximum production meat of a herd of 50 animals) = 47% of the meat had been used
16 (ha needed for pasture for a herd of 50 cows) - 3.3 (fallow land) = **12.7 ha pasture needed per settlement**
10.1 ha meadow needed per settlement

Woodland (for timber and fuel)
Every settlement had on average 1.5 farm
An average farm had a surface of 82 m^2
Every farmstead required 0.21 m^3 of wood per m^2 meter of farm for construction
Every 10 years the all wood in farm was replaced
The total amount of firewood for every settlement is 944.1 m^3 per 40 years (between AD 1 and AD 70)*
The total amount of firewood for every settlement is 2386.9 m^3 per 70 years (between AD 70 and AD 140)**
Every ha of woodland produces on average 100 m^3 meter of wood (no distinction between fuel and construction wood is made)
Calculation for the demand of woodland per rural settlement
((1.5(number of farms) x 82 m^2 (average surface of a farm) x 0.21 m^3 (required m^3 of construction wood per m^2 of farm) x 5 (initial costs + 4 decades for replacements AD 1 - AD 40)) + 944.1 m^3 (firewood needed per 40 years)))/ 100 (the number of m^3 every ha produces on average) = **10.7 ha of wood required per settlement over 40 years**
((1.5(number of farms) x 82 m^2 (average surface of a farm) x 0.21 m^3 (required m^3 of construction wood per m^2 of farm) x 4 (initial costs + 3 decades for replacements AD 40 - AD 70)) + 708.1 m^3 (firewood needed per 30 years)))/ 100 (the number of m^3 every ha produces on average) = **8.1 ha of wood required per settlement over 30 years**
((1.5(number of farms) x 82 m^2 (average surface of a farm) x 0.21 m^3 (required m^3 of construction wood per m^2 of farm) x 8 (initial costs + 7 decades for replacements AD 40 - AD 70)) + 2,386.9 m^3 (firewood needed per 70 years)))/ 100 (the number of m^3 every ha produces on average) = **25.9 ha of wood required per settlement over 70 years**

*this figure was not very clear from the article from Van Dinter *et al.* (2014). We used the figure for firewood for the rural settlements given on page 48 for the Early Roman period (i.e. 114,236 m^3) and divided it by the number of rural settlements for this period (i.e. 121)

** like the Early Roman period the figure for the Middle Roman period was not very clear in Van Dinter *et al.* (2014). We used the figure for firewood given on page 48 (i.e. 467,833 m^2) and divided it by the number of settlements (i.e. 196).

Translating these demands to the various claim regions for the different periods results in the overview provided in table 3.

Table 3: Overview of the demand for land use for rural settlements Early and Middle Roman period

	AD 40			AD 70			AD 140					
Number of rural settlements	19	0	70	39	9	115	22	26	2	14	14	118
Claim region	west (1)	central (2)	east (3)	west (1)	central (2)	east (3)	west north *(1)*	west south *(2)*	central north *(3)*	central south *(4)*	west north *(5)*	east south *(6)*
Land use type												
Arable land (ha)	125.4	0	462.0	257.4	59.4	759.0	145.2	171.6	13.2	92.4	92.4	778.8
Pasture (ha)	241.3	0	889.0	495.3	114.3	1460.5	279.4	330.2	25.4	177.8	177.8	1498.6
Meadow (ha)	191.9	0	707.0	393.9	90.9	1161.5	222.2	262.6	20.2	141.4	141.4	1191.8
Woodland (ha)	-203.3	0	-749	-315.9	-72.9	-931.5	-569.8	-673.4	-51.8	-362.6	-362.6	-3056

Demand for land as result of arrival Roman army

For the demand to construct, maintain and inhabit the structures that arise with the arrival of the Roman Army Van Dinter *et al.* (2014) made various assumptions which are summarized in table 5.

Table 4: Overview of the assumptions to calculate the demand for land use for military structures AD 40, AD 70 and AD 140 based on Van Dinter et al. (2014)

Demand for land use
Normal forts accommodated 350 soldiers, larger forts 700
an average soldier needs 3,000 kCal per day, a *vicus* inhabitant 2,200
A soldier´s diet had the same ratio as a normal person: i.e. 67.5% cereals, 22.5% meat and 10% other resources that do not need significant land
A normal vicus would have had approximately 350 inhabitants a large vicus 700
50% of the cereal was obtained locally, the rest was imported
After AD 70 resources for the Roman army were obtained only south of the border

Woodland (for timber and fuel)
For every fort an estimated need for construction wood per period (AD 40, AD 70 and AD 140) has been provided in table A4, p. 41 from Van Dinter *et al.* (2014) and included as table 6.
Every watchtower required 7,4 m^3 of timber
Every vicus contained approximately 60 houses resulting in a need of 2,052 m^3 construction wood
Every fort had 2 granaries which requires approximately 47 m^3 of timber each
Every fort had a 2 wharfs or quays which requires approximately 231 m^3 of timber each
All timber in every construction needs to be replaced every 10 years.
Infrastructure, especially the *limes* road, required 5,108 m^3 of wood
A fort or vicus need 1,533 m^3 of wood as fuel per year. A large fort or *vicus* needs approximately twice that amount (i.e. 3,066 m^3) per year.

For calculating the demand of arable land that is needed to sustain the Roman military in AD 40 the following calculation is applied per claim region:

((a (Number of normal forts) x 350 (number of soldiers) + b (Number of large forts) x 700 (number of soldiers)) x 3,000 (kCal per day needed for a soldier) x 365 (days in a year) x 0.675 (% of diet existing of cereal)) + ((c (Number of normal *vici*) x 350 (number of inhabitants) + d (Number of large *vici*) x 700 (number of inhabitants)) x 2,200 (kCal per day needed for a normal person) x 365 (days in a year) x 0.675 (% of diet existing of cereal)) /

(3,100 (kCal per kg) x 800 kg (the useful amount of kilos that 1 ha produces) x 2 (to include fallow lands) = the number of ha of additional arable land required.

For calculating the demand of meat the first step is to calculate the amount of kCal required:

((a (Number of normal forts) x 350 (number of soldiers) + b (Number of large forts) x 700 (number of soldiers)) x 3,000 (kCal per day needed for a soldier) x 365 (days in a year) x 22.5 (% of diet existing of meat)) + ((b (Number of normal vici) x 350 (number of inhabitants) + d (Number of large *vici*) x 700 (number of inhabitants)) x 2,200 (kCal per day needed for a normal person) x 365 (days in a year) x 22.5 (% of diet existing of meat)) = the total kCal of meat required for the Roman army and *vici* inhabitants.

Since every rural settlement is assumed to have had a herd of approximately 50 animals which has the potential of producing 3,800,000 kCal of meat per year of which only 1,806,750 kCal is used, every settlement could at least deliver 1,993,250 kCal without needing additional pasture and meadows. By multiplying this figure with the number of rural settlements and subtract this from the total amount of meat required for the Roman army and *vici* one can calculate the additional kCal still needed, thus calculating how many additional herds are required and what the impact would be on the land use.

Combining these calculations result in table 5.

Table 5: Demand for arable farming based with varying percentages of locally produced cereal

	AD 40				**AD 70**				**AD 140**						
Claim region	west (1)	central (2)	east (3)	**total**	west (1)	central (2)	east (3)	**total**	west north *(1)*	west south *(2)*	central north *(3)*	central south *(4)*	west north *(5)*	east south *(6)*	**total**
Number of rural settlements / Percentage of local cereal	19	0	70	**89**	39	9	115	**163**	22	26	2	14	14	118	**196.0**
0%	124.6	0.0	459.0	**583.6**	255.7	59.0	754.0	**1068.8**	144.2	170.5	13.1	91.8	91.8	773.7	**1285.1**
10%	124.6	0.0	531.3	**655.9**	318.3	142.5	888.9	**1349.7**	144.2	279.0	13.1	236.4	91.8	918.3	**1682.9**
20%	124.6	0.0	603.6	**728.2**	380.9	225.9	1023.8	**1630.6**	144.2	387.4	13.1	381.1	91.8	1063.0	**2080.7**
30%	124.6	0.0	675.9	**800.5**	443.5	309.4	1158.8	**1911.6**	144.2	495.9	13.1	525.7	91.8	1207.6	**2478.5**
40%	124.6	0.0	748.3	**872.8**	506.1	392.8	1293.7	**2192.5**	144.2	604.4	13.1	670.4	91.8	1352.3	**2876.2**
50%	124.6	0.0	820.6	**945.2**	568.6	476.3	1428.6	**2473.5**	144.2	712.9	13.1	815.0	91.8	1496.9	**3274.0**
60%	124.6	0.0	892.9	**1017.5**	631.2	559.7	1563.5	**2754.4**	144.2	821.4	13.1	959.7	91.8	1641.6	**3671.8**
70%	124.6	0.0	965.2	**1089.8**	693.8	643.2	1698.4	**3035.4**	144.2	929.9	13.1	1104.3	91.8	1786.2	**4069.6**
80%	124.6	0.0	1037.6	**1162.1**	756.4	726.6	1833.3	**3316.3**	144.2	1038.4	13.1	1249.0	91.8	1930.9	**4467.3**
90%	124.6	0.0	1109.9	**1234.5**	819.0	810.1	1968.2	**3597.3**	144.2	1146.8	13.1	1393.6	91.8	2075.5	**4865.1**
100%	124.6	0.0	1182.2	**1306.8**	881.6	893.5	2103.1	**3878.2**	144.2	1255.3	13.1	1538.3	91.8	2220.2	**5262.9**

For the demand for wood and food with the arrival of the Roman army, Van Dinter *et al.* (2014) have looked at the military forts and known watchtowers, *vici*, quays, wharfs and granaries (table 6 and table 7).

Table 6: overview of Roman forts and estimated amount of wood per period (after Van Dinter et al., 2014)

Name	Latin	Construction timber (m^3)			Region
		AD 40	AD 70	AD 140	
Katwijk*	Lugdunum Batavorum		2229	2488	west (1)
Valkenburg	Praetorium Agrippinea		2802	2949	west (1)
Roomburg	Matilo		1910	2488	west (1)
Alphen	Albaniana		1751	2163	central (2)
Bodegraven			2020	2488	central (2)
Zwammerdam*	Nigrum Pullum		2229	2232	central (2)
Woerden	Laurium		2020	2020	central (2)
De Meern, Utrecht			1910	2488	east (3)
Domplein, Utrecht 1,2	Trajectum		2618	2618	east (3)
Vechten**	Fectio	7599	7599	7599	east (3)
Total claim region 1		0	6941	7925	
Total claim region 2		0	8020	8903	
Total claim region 3		7599	12127	12705	

* unknown size, average size known forts taken

** extra large

Table 7: overview of Roman structures besides forts per period (after Van Dinter et al., 2014)

	AD 40			AD 70			AD 140					
Claim region	west (1)	central (2)	east (3)	west (1)	central (2)	east (3)	west north *(1)*	west south *(2)*	central north *(3)*	central south *(4)*	west north *(5)*	east south *(6)*
Vicus	0	0	0	0	0	0	0	3	0	4	0	2
Large *vicus*	0	0	1	0	0	1	0	0	0	0	0	1
Watchtower	0	0	0	8	15	11	0	8	0	15	0	11
Granary	0	0	4	6	8	10	0	6	0	8	0	8
Wharf / quay	0	0	4	6	8	10	0	6	0	8	0	8

Combining the results in the demand for wood leads to the totals presented in table 8.

Table 8: Total Demand for wood (ha) for the various time slices

Claim region	West (1)	Central(2)	East (3)
AD 40	-203.9	0.0	-3844.9
AD 70	-2186.1	-2383.0	-5222.4
AD140	-5843.7	-6374.7	-7252.7

Results

Although many of the assumptions presented in the previous paragraph can be debated, the work of Van Dinter *et al.* (2014) offers a solid starting point for further research. An important element in their assumptions is that 50% of the cereals were produced locally, and that the other half would have been imported. This assumption is discussed rather succinctly, but it is assumed to have had a significant impact on the land use pattern. Table 11 provides an overview of the required arable land for different percentages.

A difference between 50% locally produced and 100% locally produced would result in a difference of 361.6 ha of arable land for AD 40, 1404.7 ha for AD 70 and 1988.9 for AD 140. As half of the arable land is annually fallow and used for pasture, this percentage will also influence the amount of pasture required.

Using these figures as input to the PLUS modelling framework provides a hypothetical spatial distribution of the land use. This in itself is already valuable for landscape archaeologists to understand the implications of their assumptions and to sharpen their ideas for reconstructing the past dynamics.

For the present study, we have run scenarios using the inputs given in tables 5 and 8. Furthermore, we have, for every scenario, run three additional types of scenarios taking into account the 3 possibilities for woodland regeneration described in section 3.3.2. In total, we thus have run 99 scenarios. The results of a selection of these are shown in figures 9, 10 and 11. The Knowledge Hub, which will be discussed in chapter 5, will contain all results. Figures 9, 10 and 11 show the predominant land use type. Each cell can also have a percentage of other land use types. By confronting these outcomes to the palaeogeography we can identify trends in land use per palaeogeographical unit, taking into account competition for land use as well. We thus go one step further than most landscape researchers have been able to do previously. As woodland has been configured as an less attractive land use type in relationship to arable land, pasture and meadow, the results for arable farming, pasture and meadow for all three woodland regeneration scenarios are the same. We have therefore selected the ‘no regeneration’ scenario to analyze the results from the perspective of the hypothesis of local cereal surplus production.

To confront the modelling outcomes with the palaeogeography, we performed spatial summary statistics producing tables that show the areas of palaeogeographical units that have been used to allocate the various land use types (Appendix C). To analyze trends in the different claim regions and for the different time slices, graphs have been produced for the land use types arable farming, pasture and meadow (Appendix C). In these graphs, the areas used for the various palaeogeographical units are shown combined with the percentage of locally produced cereal for the Roman military and *vici*.

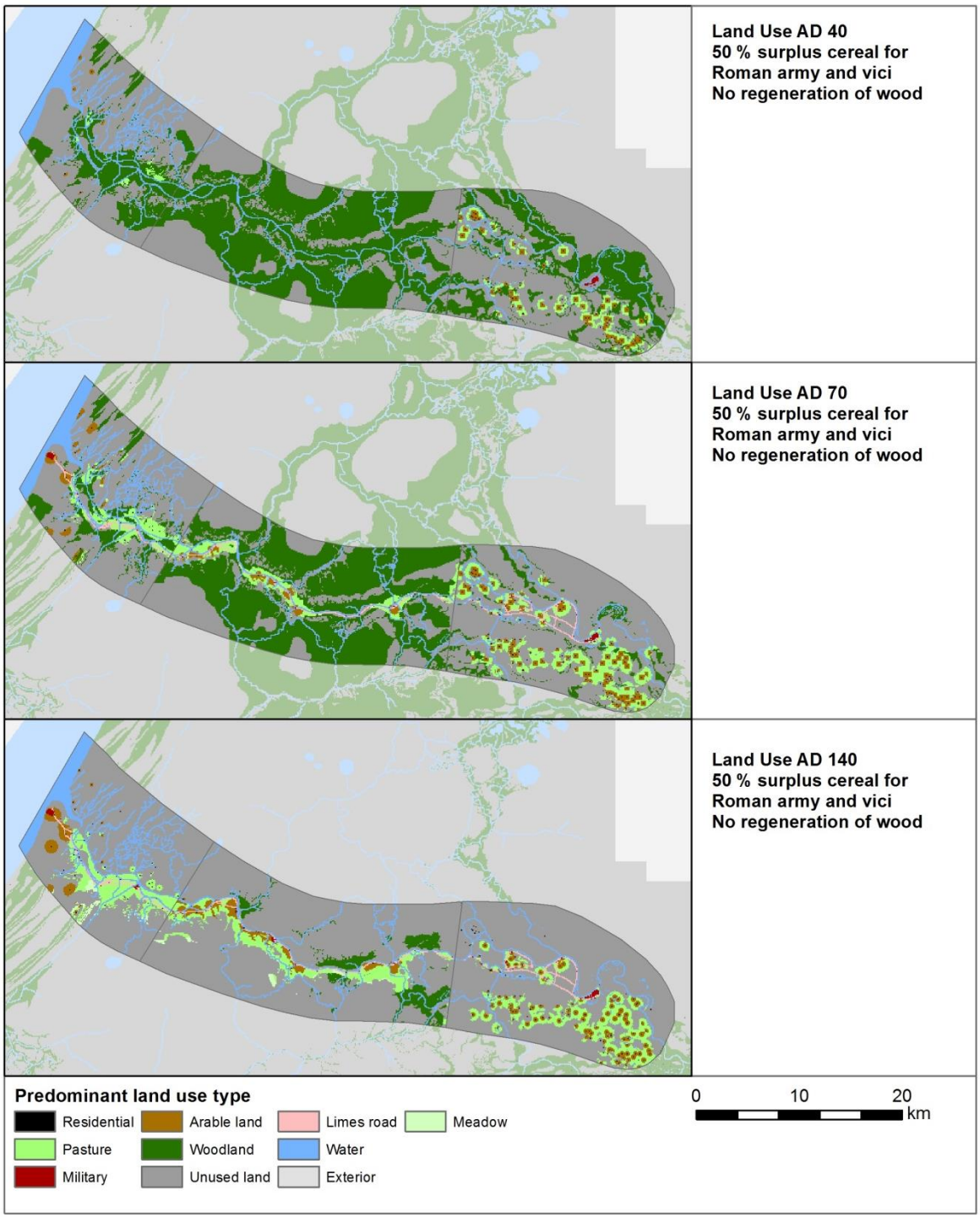

Fig. 9: Predominant land use per period with 50% local surplus production and no regeneration of wood

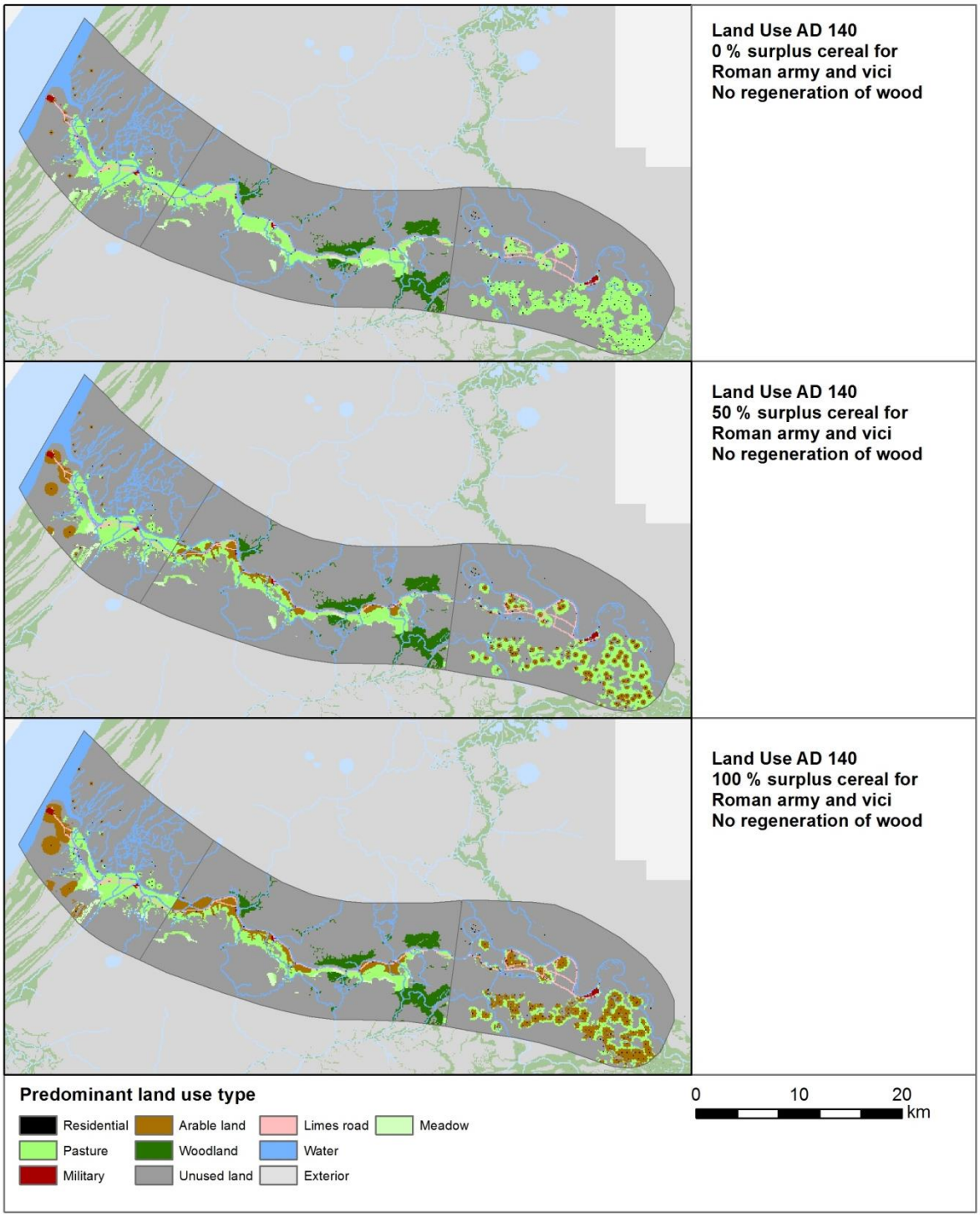

Fig. 10: Predominant land use for AD140 0%, 50% and 100% local surplus production and no regeneration of wood

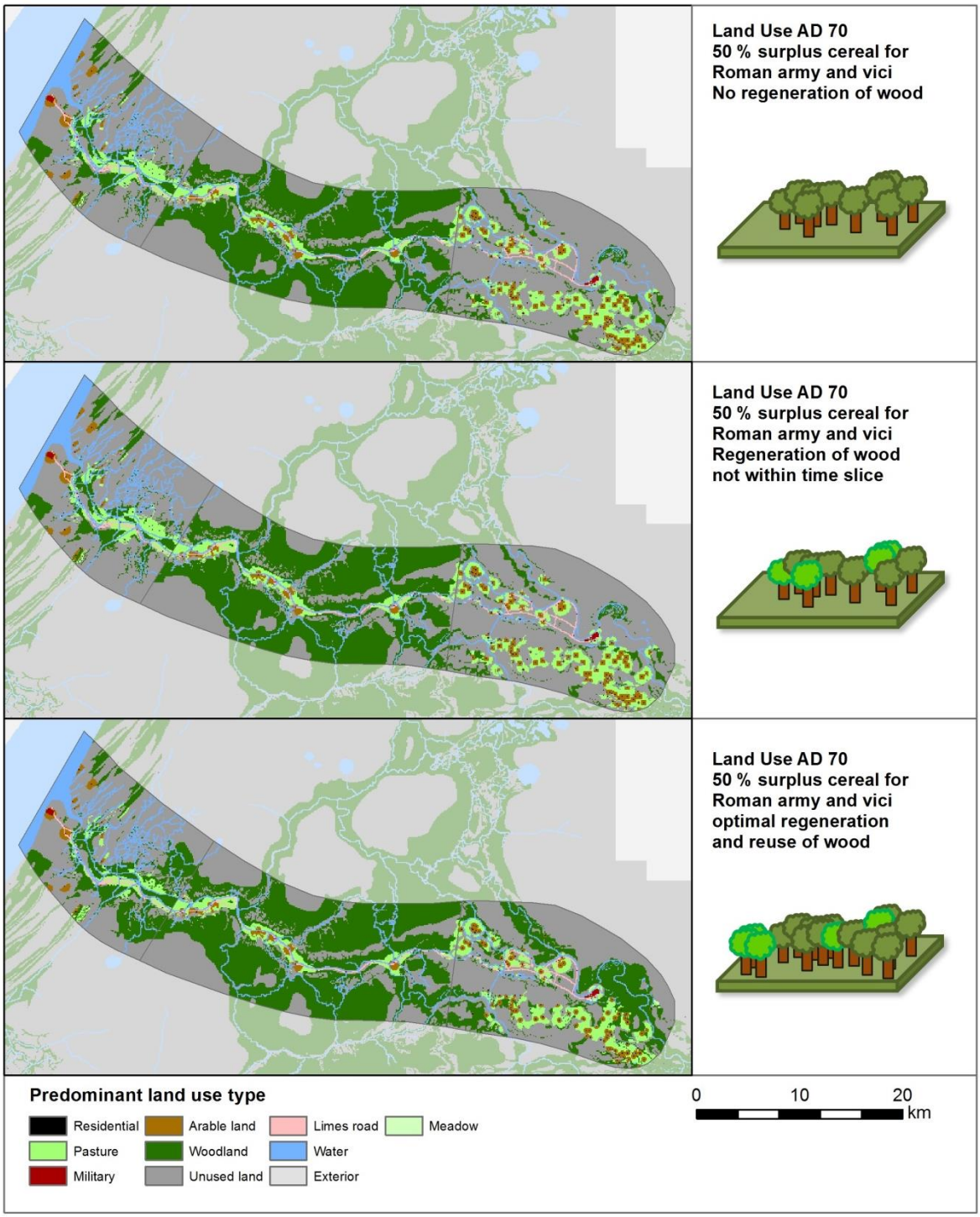

Fig. 11: Predominant land use for AD 70 with 50% local surplus production and three woodland scenarios

Analyzing the PLUS results have led to the following observations:

Arable land:

Arable land is by far most commonly placed on the moderate levees, followed by the high and low levees. It shows an overall increase from AD 40 to AD 140, and also, unsurprisingly, increases with higher surplus production demands.

In AD 40 arable land is most prominent on the moderate levees (and all levees in general). This increases further with an increase in surplus production.

In AD 70, the allocation of arable land is different in the western coastal region compared to the central and eastern region. Instead of a showing a strong presence on the levees, arable land is most prominently placed on the dunes. This can be explained by the fact that the coastal region contains more dune areas than levees. To cope with the pressure of population increase between AD 40 and 70, the simulation indicates that the local farmers must start have started cultivating the dune areas. In both the central and eastern region, arable land is still commonly found on the levees, and most prominently on the moderate levees.

In AD 140, arable land is even more prominently allocated on dunes in the western coastal region. In the central peat region, the levees are again the most common geographical units on which arable land is placed. It is interesting to note that at around 90% surplus production the amount of arable land on the levees stops increasing. Instead, the land use is allocated more in eutrophic peat areas. Although this is not a realistic scenario, the result shows that a near 100% surplus production is limited by the availability of space suitable for arable land. In the western river region, the majority of arable land is allocated on levees, most prominently on the moderate levees. This is because of the higher availability of levees in this area.

Pasture:

Pasture is most commonly found on the levees and floodplains and shows a decrease in hectares when the percentage of surplus production increases. This decrease is explained by the increase of fallow land which can be used as pasture. This increase of fallow land is the result from an increasing demand for arable land and the use of a two-field rotation system.

In AD 40, pasture is predominantly placed on moderate levees followed by high and lower levees.

In AD 70, pasture in the western coastal region is again for the most part found on the moderate levees. Because of the limited space on the levees, the higher floodplains are also used for pasture. In the central peat region, pasture is also mostly allocated on moderate levees. This presence decreases with an increase in surplus production. Surprisingly, high floodplains are increasingly used as pasture with an increase in surplus production. At around 30% surplus production, pasture is more commonly found on floodplains than on the lower levees. This is due to a very strong decrease in allocation of pasture on low levees. The gradual shift of pasture from low levees to the floodplains can be explained by the above-mentioned increase in arable land on the levees because of population growth. Such a strong competition for free space on the levees does not seem to exist in the eastern river region. Here, pasture is found most commonly on the moderate levees, followed by the high and low levees.

In AD 140 pasture is still most commonly found on moderate levees in the western coastal region. However, high floodplains now account for a much higher percentage than before. This shows that the available space on the levees is under increasing pressure by the demand for arable land. In the central peat region, the shift of pasture from the levees to the floodplains, which was noted in the previous time slice, continues. With an increase in surplus production, the allocation of pasture on levees decreases so drastically that both low and high floodplains become the most common geographical units on which pasture is allocated. Again, this shift from the levees to the floodplains can be explained by the increasing demand for arable land which can only be cultivated on the higher levees. In the

eastern river region, there is still no shortage of space on the levees as the majority of pasture is still allocated on moderate levees, followed by low and high levees.

Meadow:

Meadow is the most constant land use type in all three periods (AD 40, 70 and 140) and on all different levels of surplus production (0 to 100 %).

In AD 40, meadow is strongly present on moderate levees, followed by high and low levees respectively. This indicates that there was enough space available on the levees to accommodate all land use types.

In AD 70 a slight change occurs in the central peat area. As opposed to the western coastal region and the east river region, in the central peat region the land use type is allocated more prominently on the low floodplains. Furthermore, the presence of meadow on the floodplains increases with the increase of surplus production, while at the same time it is decreasing on the moderate levees. An explanation for this change is the increase of arable land on moderate levees (and all levees in general). This increase in arable land on the levees pushes the use of meadows to the lower-lying areas of the floodplains.

In AD 140 another shift occurs, this time in the western coastal region. Meadow is now no longer most prominently allocated on moderate levees, but instead on the higher floodplains. The allocation also shifts with the increase in surplus production. At 10% surplus production, both high floodplains, moderate levees and mesotrophic peat areas are the most used geographical units on which meadow appears. With the increase in surplus we see a steady increase in the allocation on the higher floodplains and levees, while the presence of meadow on mesotrophic peat and lower floodplains decreases.

In the central peat area low floodplains are again the most common geographical unit on which meadow is placed. The presence on levees has decreased even further in favor of eutrophic and mesotrophic peat areas. This can be explained by an even further increase in competition of free land on the levees. Since arable lands and pasture are not suitable land uses on wetlands, meadow is forced into the peat areas.

The results show interesting leads to be confronted with ecological and vegetation expertise. It raises questions that can be compared to archaeological evidence and aids in formulating future research agendas. However, looking at the assumptions used and proposed here it can be concluded that the landscape itself does not seem to pose a limitation on the production of additional cereal and dairy products with the arrival of the Roman army and the rise of various *vici*. The remaining question, however, is whether the local population had a labor force large enough to produce such numbers. For each settlement, Van Dinter *et al.* (2014) state that the available workforce could exploit 12.8 ha of land. Taking into account fallow lands, this would equal an arable land use of 25.2 ha per settlement. Confronting this number to the demand for AD 70 and AD140, the hypothesis that 50% of the cereals were locally produced can already be rejected. The calculations show that the local rural settlements could for these time slices produce a maximum surplus of 30 to 40% (see table 9). It therefore seems that the local labor force was the limiting factor for producing a surplus of cereals, assuming that no hired labor was used (e.g. the *vicus* inhabitants).

Table 9: Demand for arable farming based with varying percentages of locally produced cereals. All red cells could not been produced by the claim region itself due to the limited available labor force

	AD 40				**AD 70**				**AD 140**						
Claim region	west (1)	central (2)	east (3)	**total**	west (1)	central (2)	east (3)	**total**	west north *(1)*	west south *(2)*	central north *(3)*	central south *(4)*	west north *(5)*	east south *(6)*	**total**
Number of rural settlements	19	0	70	**89**	39	9	115	**163**	22	26	2	14	14	118	**196.0**
Maximum capacity of arable land for settlements (ha)	243.2	0	896	**1139.2**	499.2	115.2	1472	**2086.4**	281.6	332.8	25.6	179.2	179	1510.4	**2508.8**
Percentage of local cereal															
0%	124.6	0.0	459.0	**583.6**	255.7	59.0	754.0	**1068.8**	144.2	170.5	13.1	91.8	91.8	773.7	**1285.1**
10%	124.6	0.0	531.3	**655.9**	318.3	142.5	888.9	**1349.7**	144.2	279.0	13.1	236.4	91.8	918.3	**1682.9**
20%	124.6	0.0	603.6	**728.2**	380.9	225.9	1023.8	**1630.6**	144.2	387.4	13.1	381.1	91.8	1063.0	**2080.7**
30%	124.6	0.0	675.9	**800.5**	443.5	309.4	1158.8	**1911.6**	144.2	495.9	13.1	525.7	91.8	1207.6	**2478.5**
40%	124.6	0.0	748.3	**872.8**	506.1	392.8	1293.7	**2192.5**	144.2	604.4	13.1	670.4	91.8	1352.3	**2876.2**
50%	124.6	0.0	820.6	**945.2**	568.6	476.3	1428.6	**2473.5**	144.2	712.9	13.1	815.0	91.8	1496.9	**3274.0**
60%	124.6	0.0	892.9	**1017.5**	631.2	559.7	1563.5	**2754.4**	144.2	821.4	13.1	959.7	91.8	1641.6	**3671.8**
70%	124.6	0.0	965.2	**1089.8**	693.8	643.2	1698.4	**3035.4**	144.2	929.9	13.1	1104.3	91.8	1786.2	**4069.6**
80%	124.6	0.0	1037.6	**1162.1**	756.4	726.6	1833.3	**3316.3**	144.2	1038.4	13.1	1249.0	91.8	1930.9	**4467.3**
90%	124.6	0.0	1109.9	**1234.5**	819.0	810.1	1968.2	**3597.3**	144.2	1146.8	13.1	1393.6	91.8	2075.5	**4865.1**
100%	124.6	0.0	1182.2	**1306.8**	881.6	893.5	2103.1	**3878.2**	144.2	1255.3	13.1	1538.3	91.8	2220.2	**5262.9**

3.4.2 Hypothesis 2: woodland in AD 500 and AD 800

The second hypothesis researched in this report considers simulating the woodland for AD 500 and AD 800. In order to do so, we have used the calculations presented by Dijkstra (2011) to reconstruct the demand for land use for both periods. For the data on the settlements we have used an updated version of the dataset produced for Van Lanen *et al.* (2015).

Demand for land use

Like Van Dinter *et al.* (2014), Dijkstra (2011) calculated the demand for food based on the amount of kCal required for an average person of a household. For this, he made a distinction between various household sizes (i.e. Small, Medium, Large and Extra Large), resulting in various demands. Since it is impossible to provide the exact size of the various settlements due to the quality of the data, we have adopted the calculations for medium-sized settlements and have used these as input for our PLUS model.

Contrary to Van Dinter *et al.* (2014), Dijkstra published a table containing the number of hectares required per settlement per land use type explicitly. There is therefore no need to extensively describe all the steps that have been taken, since these have all been described in Dijkstra (2011). The underlying assumptions, however, can be debated.

Table 10: Demand for land use of medium-sized rural settlements inhabited by 6 persons for AD 500 and AD 800 (after Dijkstra, 2011: 501-507)

Land use type	**Demand for land use (ha)**
Arable farming	
Arable two-coarse rotation (ha)	2.4
Fallow (ha)	2.4
Total Arable farming	**4.8**
Pasture	
Pasture for bovines & horses (ha)	10.5
Pasture for sheep & goats (ha)	15
Total Pasture	**25.5**
Meadow	
Meadow for bovines & horses (ha)	4.3
Woodland	
Woodland for timber & firewood (ha)	2 (per year)

The calculations provided by Dijkstra for the demands for land use of an average rural settlement are stated to be valid for both AD 500 and AD 800. Between AD 500 and AD 800 no significant technological innovations have taken place that have changed the yield per ha for the various land use types.

For calculating the demand for woodland, Dijkstra provides a figure of 2 ha per year per settlement. However, he does not provide extensive details on the sources for this figure. We have therefore decided to confront this figure to the calculation method applied by Van Dinter *et al.* (2014) for Roman rural settlement to in order to simulate the woodland for these periods.

As presented in table 2, Van Dinter *et al.* (2014) calculate that a rural settlement in the Roman period would require 8.1 ha of woodland per 30 years. Following Dijkstra, this would however be 30 x 2 = 60 ha. Since the two figures vary significantly, we have decided to compare the results taking into account 2 different scenarios for the regeneration of wood. Per time slice we have therefore run a total of four different scenarios simulating the land use for a period of 30 years.

Scenario 1: Required wood is based on Dijkstra, and once the woodland has been deforested it will not grow back.

Scenario 2: Required wood is based on Dijkstra, and once the woodland has been deforested it will grow back after 10 years and is fully reused.

Scenario 3: Required wood is based on Van Dinter *et al.* (2014), and once woodland has been deforested it will not grow back.

Scenario 4: Required wood is based on Van Dinter *et al.* (2014), and once the woodland has been deforested it will grow back after 10 years and is fully reused.

As the time between the two time slices is considered to be too large, we have not used the second wood scenario proposed in paragraph 3.3.2.

Applying the calculations for the various scenarios results in a demand for land use as given in table 11.

Table 11: Estimated demand for woodland for a 30-year period

Claim region	West (1)	Central(2)	East(3)
AD 500			
Wood (ha) method Dijkstra	-3,420	-1,200	-5,640
Wood (ha) method Van Dinter	-597	-209	-1,289
AD 800			
Wood (ha) method Dijkstra	-2,685	-1,770	-3,390
Wood (ha) method Van Dinter	-1,875	-1,236	-2,671

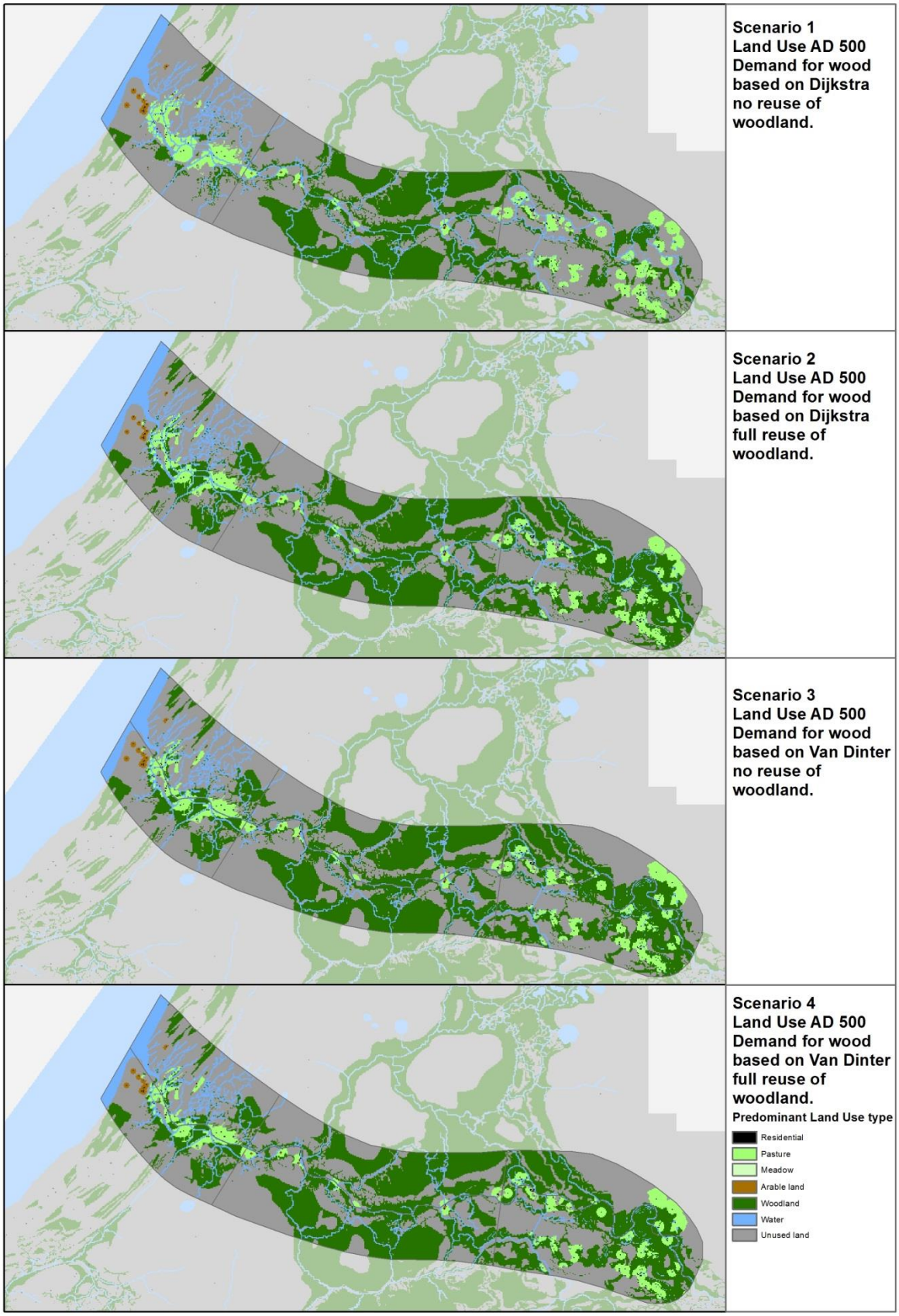

Fig. 12: PLUS modelling results AD 500

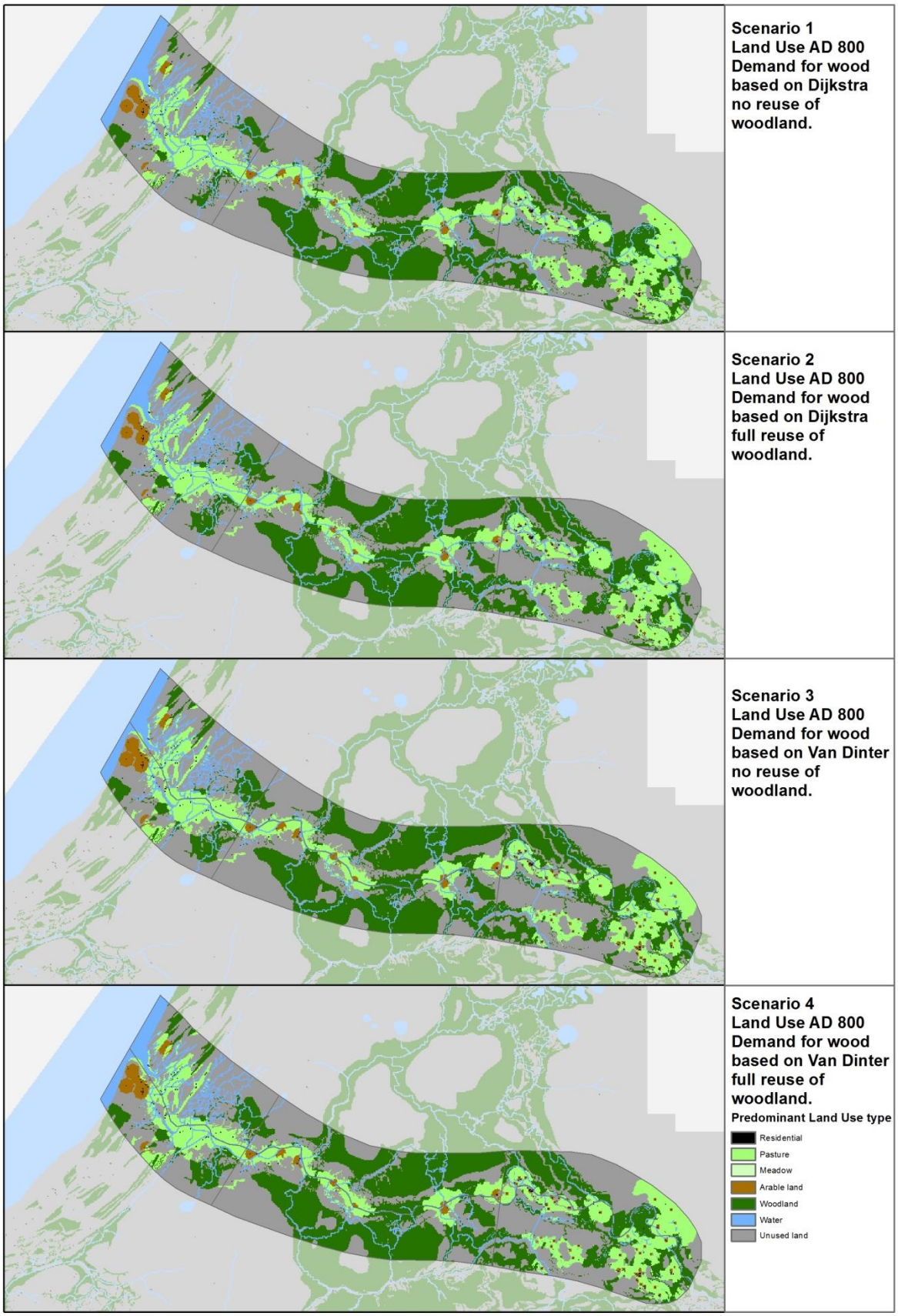

Fig. 13: PLUS modelling results AD 800

Results

Looking at the results of both AD 500 and AD 800, the effect of woodland regeneration is most prominent in scenarios 1 and 2, which both use the calculations based on Dijkstra. For scenarios 3 and 4, the effect of woodland regeneration is minimal (figures 12 and 13). Another observation which can be made is that the reduction of woodland in the central peat area is minimal. This can be explained by the high settlement density in the western coastal region and eastern river region compared to the central peat area.

These observations were already hypothesized beforehand, but by using the PLUS we can show that this hypothesis still holds up when incorporating the spatial dimension. . The next step would be to confront these modelling results to the hypotheses which are formulated in other research programs such as the DAL project introduced in section 3.2.

3.5 PLUS modelling framework: opportunities and limitations

As demonstrated in the previous paragraphs, the PLUS modelling framework can be a valuable tool for simulating past land use and aid in understanding past spatial dynamics. The PLUS combines ecology and physical characteristics of the landscape with human actors and interactions. It thus combines HE and LB theories in a spatial dynamic modelling framework. The results from the PLUS modelling for the Dutch Rhine region show the potential of such an approach, however demonstrate the complexity for application. Summarizing the various limitations can be done as follows:

- The demand for land use is based on various assumptions based on demographical studies. The formulas and figures used contain a lot of uncertainties.
- We have not taken into account the fact that people kept horses as well. For future calculations we will have to take their impact on the land use into account as well.
- The starting situation for the distribution of woodland in AD 40 is currently problematic, since it assumes that every suitable palaeogeographical unit was filled with wood. This assumption is believed to overestimate the woodland area and is therefore highly debatable. A more detailed reconstruction of the woodland in AD 40 based on archaeobotanical research would be necessary to address this issue.
- The demand for land use has been linked to claim regions and not to individual settlements. This means that settlements that, for instance, are located on a location that is very suitable for arable farming might get more arable farming land use types than the local population can cultivate, and that settlements situated in unsuitable areas can end up with no arable farming at all. To address this issue we should define claim regions per settlement.
- The demand for land use now does not make a distinction between various types of rural settlements. It would be interesting to include typologies incorporating specialization and trade as well. This requires a structured reevaluation and classification of the archaeological data. This is currently done within the FFL project, thus offers a clear opportunity for the near future to do so.
- By defining the claim regions as fixed borders, the PLUS suffers from edge effects. This has influenced the allocation of land use for settlements at the edge of the claim regions. The required land use for the individual settlements have been forced to be within the claim region, where it could easily have been available just outside the border. This could have led to an unrealistic simulation. To correct for this problem, the approach proposed in the previous point of making claim regions for every settlement and thus also creating overlapping claim regions would be a suitable

solution. However, doing so must be done with care, since it could as well be that the next fort would also influence the demand.

- The simulation currently does not make a difference between wood used to harvest timber and wood to harvest as fuel. The two however are very different, requiring different types of wood that have different compositions on different palaeogeographical units. However, due to lack of data such a distinction could not be made, and more archaeobotanical research is needed for this.
- The time slices currently selected are uneven and have for AD 500 and AD 800 a large gap in between them, making it problematic to allow them to influence the modelling outcomes and thus to analyze path dependencies. For AD 500 and AD 800 we have for instance not been able to include the various regeneration scenarios for woodland.
- The PLUS modelling framework presented currently does not include economic relationships between settlements. It would be very interesting to include transport networks into the modelling framework such as presented by Groenhuijzen and Verhagen (2015, 2016) or Van Lanen *et al.*, (2015).
- A crucial aspect of the PLUS modelling framework is the balancing of the various suitability components. This is currently done based on expert judgement of the researchers themselves. For the LUS this issue has also been identified by Koomen *et al.* (2011). This specific aspect is very important for using the PLUS framework and requires more research, exploring the opportunities of sensitivity analysis (Brouwer-Burg *et al.*, 2016) and Agent Based Modelling. Especially the latter has the opportunity to produce knowledge on micro scale processes which can be scaled to regional settings using the PLUS.

The PLUS framework applied for this study must therefore foremost be seen a tool for testing hypotheses on past land use rather than as a tool that produces faithful reconstructions of the past. The framework therefore requires interactions with other studies on especially past demography, and ecological and archaeobotanical studies on vegetation. Furthermore, the knowledge that the PLUS produces can inform archaeological predictive models which fosters the management of the archaeological heritage.

4. The SoNaR model for Uppland.

Daniel Löwenborg, Kim von Hackwitz and Carole Crumley

As stated in the introduction, Work Package 2.3 aim to bring together a protocol for studying the long-term changes in cultural landscapes and spatial dynamic modelling frameworks and tools. In order to do so we have linked archaeological, historical, ecological and social data, in the Uppland areas represented by stone settings, reconstructed watersheds and the notion of *dialectical variations* (see below).

The Uppland case study deals with slow and long-term changes in the natural landscape can be recognized in social organization and the cultural use of the landscape. This illustrates the close and dynamic integration between human and natural systems. The SoNaR (Social Natural Regions) modelling framework is based on the theory that watersheds[4] functions as natural borders that may influence in the formation of social regions. The aim is to identify

[4] A water catchment area constitutes the area from which all run-off water comes together in a point or in a stream. A watershed is the boundary between two such areas. Typically, a watershed is a height where the rain falls on two different sides forming two different water catchment areas.

such social regions by extracting *dialectical variations* in the archaeological material, i.e. slight variations in the material culture, indicating different habits and practices within a wider cultural system.

4.1 Introduction to the SoNaR modelling framework

Uppland has undergone dramatic changes since the inland ice retreated around 12,000 BP where process has offered new land for occupation and at the same time changed waterways and access to places, influencing the choice of locations. In order to understand those changes and how people related to them, the SoNaR model takes into account the changes of the landscape as well as the changes in the material culture over time in order to simulate the ongoing dynamics between nature and culture.

The notion that topography such as rivers, eskers, and watersheds, influences communication networks, and thus the development of prehistorical regions and territories, has been pointed out previously (Wijkander, 1983; Löwenborg, 2007; von Hackwitz, 2009, 2012): based on the notion of topography, especially rivers, as important in communication network, Löwenborg (2007) created watersheds based on DEMs calculated from present day topography with estimated historical shorelines. The watersheds were then compared to the medieval districts (*hundare*) as well as the present parishes. The study revealed that there is a clear link between the watershed areas and medieval districts in several cases, especially the larger areas. He further discusses how these borders can be traced back to 1,000 AD using rune inscriptions. The method was later tested on Neolithic stray find and settlement material in order to track long-term land use changes within one single watershed. Stray finds has proven to be a powerful material in determine prehistoric movements in the landscape as well as different "rooms" (see discussions in von Hackwitz 2009). In the mentioned study, stray finds belonging to different time periods and different material cultures over the time period of approx. 4000-2000 BC were mapped and projected onto reconstructed landscapes showing differences in the shore level as well as in the depositions of the stray finds. The results suggested that there was a historical awareness in the movements in the landscape between different sites within the watershed, as well as in the use of them. This historical awareness and the continuous use of different waterways and inland paths along the eskers over 2,000 years, even as the landscape changed due to land uplift with for example cut off waterways, supports the idea of topographical boundaries as an active part in landscape formation such as river-based communities (von Hackwitz, 2009, 2012).

However, in order to understand the long-term development and to get a correct outline of these topographically based regions, it is necessary to account for the changes of the actual topography of the landscape over a longer time period, that is, to calculate the prehistorical watersheds in relation to the isostatic uplift as well as the eustatic variations causing great differences within the area and between different time periods. For that reason this study will consist of two parts:

1. The first step is to show how the isostatic uplift and the eustatic variations transformed the watersheds in Uppland over a time period of almost 5,000 years. Over this time period the water withdraws from 32.2 – 56.5 m.a.s.l. (5,750 BP) to 4 – 8.5 m.a.s.l. (1,000 BP)

2. Since previous studies suggest a strong path dependency for SoNaR regions in Neolithic times as well as Medieval times, we chose here to use Iron Age graves to test the model on an intermediate period.

Models and methods

The first step in this model is to calculate the topography for a set of time periods; 5,750 BP, 5,000 BP, 4,500 BP, 3,150 BP, 1,950 BP and 1,000 BP, using a regression equation published by Sund (2010). This is based on a mathematical model using the location of archaeological sites and information about when they had contact with the sea. This material was complemented with analyses of soil geochemistry to identify when lakes were isolated from the sea. The benefit of using a regression equation is that the method considers both the isostatic uplift and the eustatic variations. This means that the shoreline reconstructions will be more accurately calculated, especially for larger areas, as the uplift is uneven between different land areas. Further, the shoreline can be modelled from any given BP value, which means that a site can be put in its specific time context in terms of shoreline displacement as long as there is a valid BP value (Sund, 2010).

Based on the reconstructed historical DEM a set of historic watershed catchments can be calculated for each period using a set of hydrological functions in a GIS. Relevant pour points are selected, considering the modelled shoreline for each period, and from the pour points a number of drainage basins can be calculated to identify the upland area that is hydrologically joined at the pour point. The pour points can also be understood as potentially important social nodes in the landscape, connecting everyone using the upstream watercourses, and thus forming a natural region that would be easily recognized in the landscape (cf. Llobera *et al.*, 2011). If there is a pronounced isostatic land rise in the area, this will affect the location of shorelines, thus making different pour points relevant at different periods. In areas with level terrain this might also cause the inland boundaries of the watersheds to shift as the land surface is tilting. It is therefore necessary to use a DEM that has been modified to the relevant time period using a method like the one described above. Also the quality of the DEM is important, where poor quality of the DEM might make it impossible to use for hydrological modelling. In the Uppland study area, a high resolution DEM has been produced by the Swedish Cadastral Agency (Lanmäteriet) using LiDAR technology. Since the DEM also has been edited to account for bridges, overpasses etc., this makes the data very suitable for hydrological analysis.

These datasets will then form the basis for further analyses of a range of archaeological artefacts and features, and their distribution in the landscape and over the different catchment areas, interpreted as potential regions. Through a comparative analysis of historical remains a diachronic analysis of regionality can be performed. This will address questions of how these topographic regions can be traced back in time, and how they are influenced by the changing landscape that is transformed from a highly fragmented archipelago to a more homogeneous flat plain dominated by clay with extensive areas of moraine.

4.2 Implementation of SoNaR in Uppland

Description of case study landscape

The study landscape consists of a tableland with inland and coastal plains, shaped by the ice sheet of the last Ice Age. The landscape is flat, with no higher formations. The glacial ridge of Uppsalaåsen running through the city of Uppsala reaches an elevation of about 75 metres in its highest places. Eskers and moraines are very common. With several major rivers, an extensive lake system and the seashore consisting of various bays, the topography of Uppland is strongly linked to water bodies and their forces.

The historic development of the landscape in Uppland is highly influenced by the marked regressive shoreline displacement after the Holocene. Today, the land is rising by about 5 millimeters per year, but since this process is slowing down it has historically been faster and has altered the character of the landscape considerably. This creates a horizontal stratigraphy in the landscape where prehistoric sites that were once shore-bound are now found further inland. The changing landscape also meant that the characteristics of the landscape changed, and new land with different geological characteristics became available for occupation. Since subsistence strategies changes over time, with different land use and landscape preferences, this means that long-term settlement patterns become complex and an understanding of the changing shorelines is fundamental for understanding long-term landscape use.

The region has been occupied since the withdrawal of the ice sheet about 10,000 years ago and the area is well known for its many remains from the Iron Age, especially the Old Uppsala site.

The archaeological material

The archaeological material that will be used to test the SoNaR model consists of 102,455 graves, so called *stone settings* (swe: *stensättingar*) from the Iron Age period (2,450 to 900 BP / 500 BC to 1,050 AD). The material is extracted from the digital database from the National Heritage Board (Fornsök) and the choice of material is based on temporal aspects in relation to previous research (see above), and on the internal differentiation in shape - round, square, rectangular, triangular, oval, ship shaped, tri radial and irregular (Figure 14). Round stone settings are most common and represent over 91% of the material. The different shapes have been interpreted as reflecting variations over larger geographical areas where the natural resources differ a lot (i.e. northern and southern Sweden etc.). Variations in smaller regions have been mentioned, but have not been investigated (Gräslund, unpublished). Here, we will test an approach where the different shapes will reflect *dialectical variations* appearing in different areas defined by watersheds, in turn reflecting different social areas. Similar interpretations have been done regarding Neolithic pottery, where variations in decor, form etc., can be used to identify a communicative context (Holm, 2006).

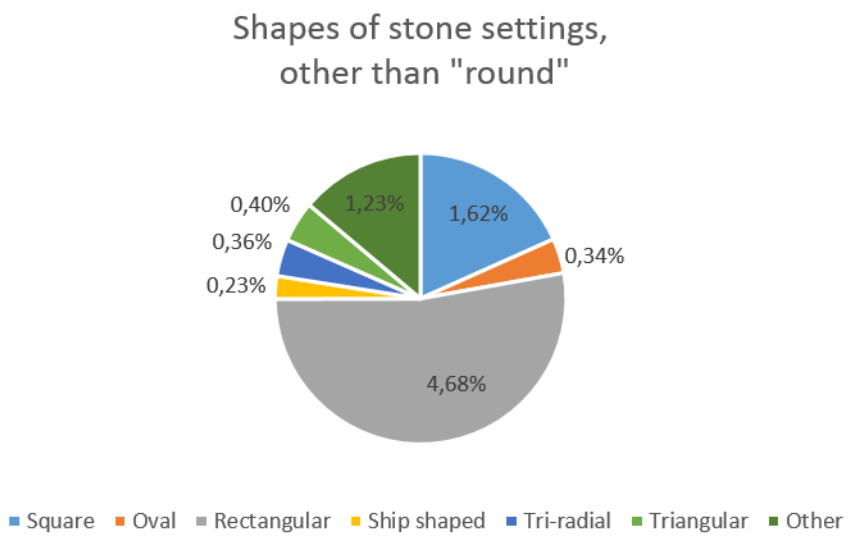

Fig. 14: The ratio of different types of stone setting shapes, excluding "round" shapes that represent the vast majority with over 91%

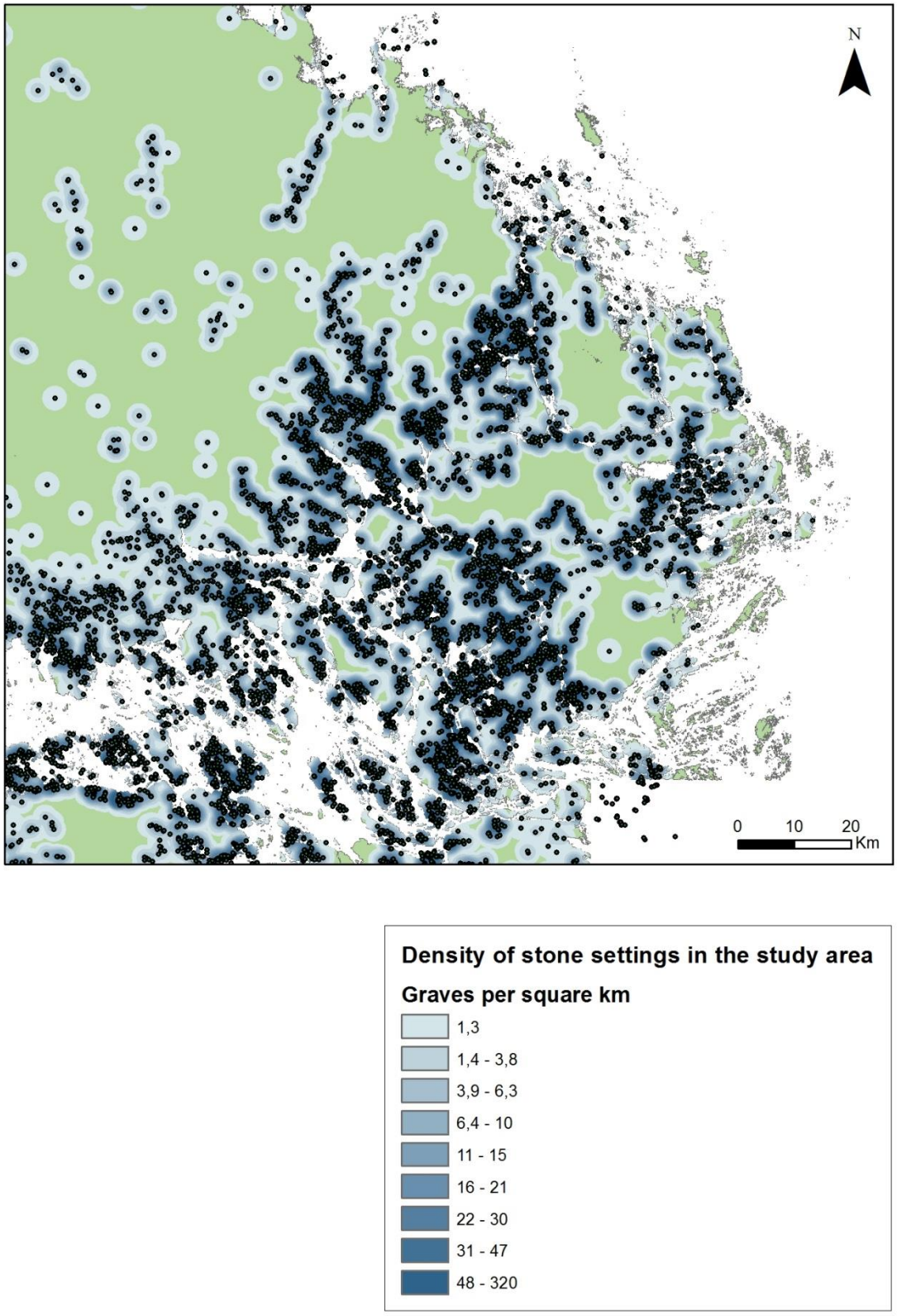

Fig. 15: The total amount of stone settings in the study area. A total of more than 150 000 individual graves

As with all archaeological material, there are some critical aspects to consider. Firstly, the material is collected from the digital database Fornsök where archaeologists with different experience have been adding information, resulting in uneven information. Secondly, as seen in figure 15, there are some areas appearing as "empty". Most likely this is a result of undeveloped areas in modern time, not unexplored during prehistoric times. And lastly, in this study the different types of stone settings will be treated as appearing simultaneous as a variation over time would not affect the outcome for this discussion as long as there is a clear difference between the different SoNaR regions.

SoNaR model implementation

To account for how the data sets used for the model have been created, a short step-by-step description of the process will follow. Using the regression equation published by Sund (2010), the corresponding elevation value is calculated for the desired BP value. These values are then interpolated into a continuous surface for the whole study area. The surface is subtracted from the present day elevation model to create an adjusted palaeotopography where zero equals the shoreline of the period at hand. For hydrological modelling, the elevation model should first be modified to fill any hollows, which generally are errors. After that a "flow direction" layer is calculated, that gives the runoff direction of the surface. From the "flow direction" surface it is possible to calculate a "flow accumulation" surface. The flow accumulation can be used both to calculate the watersheds, and also to find streams and reconstruct river networks for the adjusted topography. To get a more reliable topographic surface it would be necessary to account for more aspects of the geomorphological processes over time, such as rifts and uneven uplift due to the different plasticity of the geology. This would require extensive geological sampling and analysis.

In order to facilitate the calculations for multiple time periods it is useful to create a model in ArcGIS Model Builder that easily can iterate the same set of tools for any number of datasets, as illustrated in figure 16.

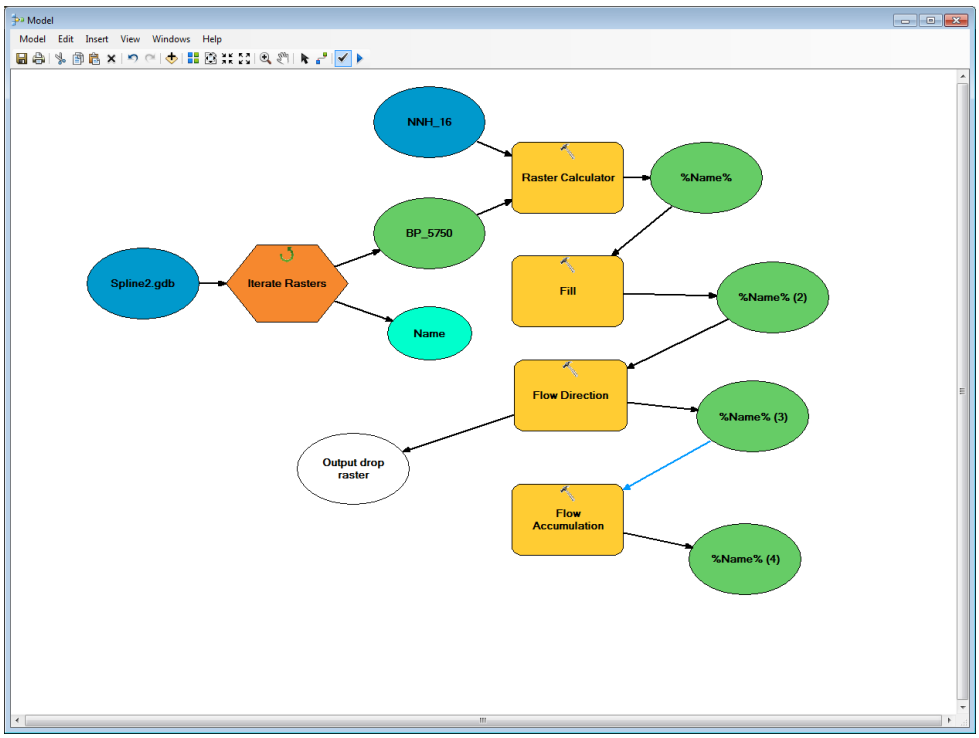

Fig. 16: ArcGIS Model Builder set up to calculate watersheds for each period. Using Model Builder enables the bulk calculations using a number of tools on a set of data files in sequence

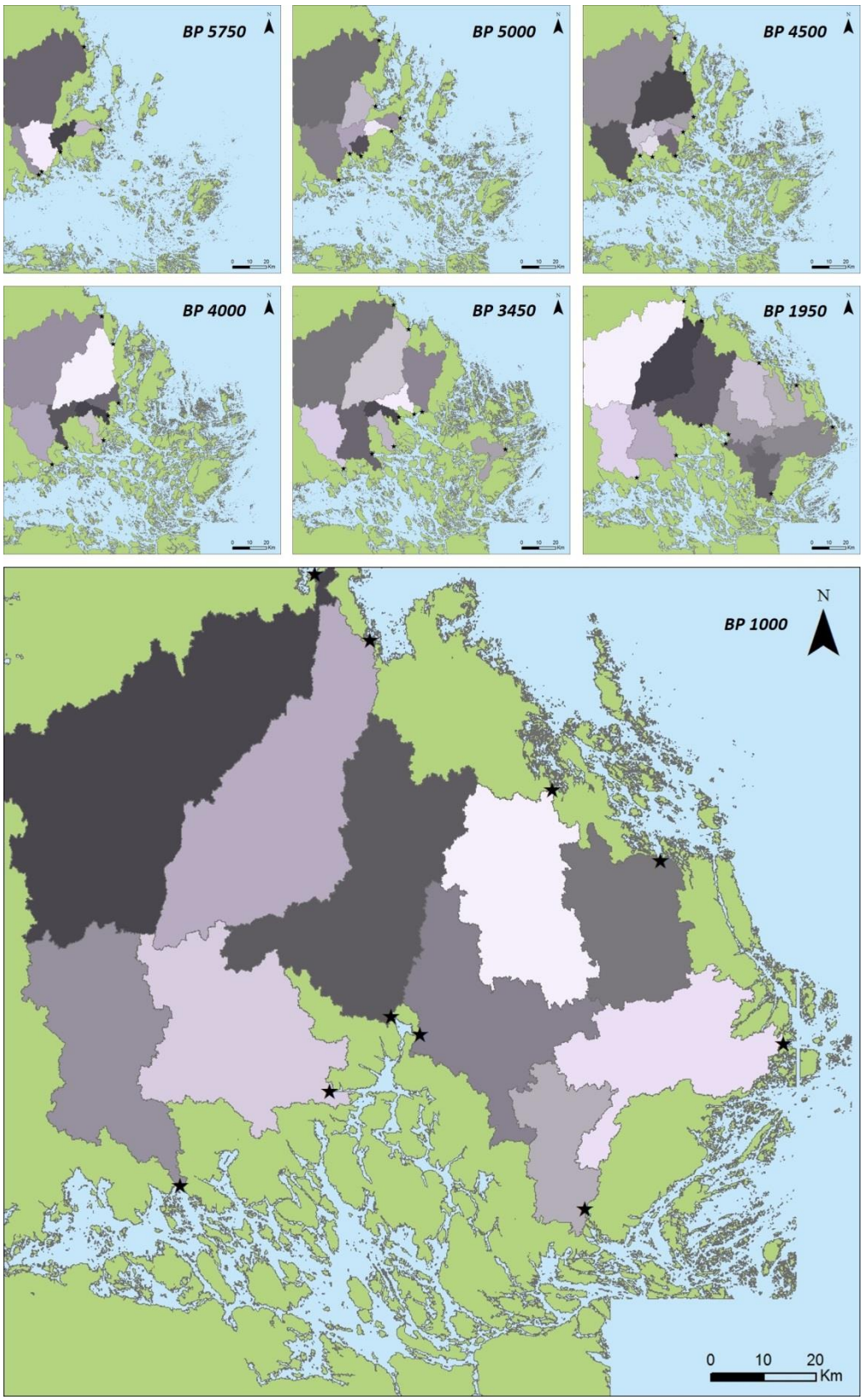

Fig. 17: The calculated watersheds, shorelines and pour points used for each period. Pour points are created manually where the recreated river networks drain to large bodies of water, but the exact number of watersheds to be created is depending on the research question at hand

The result is a series of watersheds for each of the periods used in the analysis, as can be seen in Figure 17. The data layers are available on the HERCULES Knowledge Hub where they can be compared to any other data. In addition to the watersheds calculated with the tools for hydrological modelling, a set of regions that was defined arbitrarily to cover the remaining parts of the landscape was created by hand. These are primarily the coastal areas, where no large watersheds exist. Here the water drains out to the larger waterbody through a large number of small drainage areas that would be of no use to calculate individually since they would be too small. Instead these areas were aggregated to larger "coastal" zones, that probably are internally very strong as they have a stretch of the coast in common. However, it is more uncertain where to separate one from the other, and this is something that needs to be decided in a case by case fashion as seen relevant. A formal criteria might have been formulated using average areas in square kilometers of potential regions, but this would require the calculation of a large number possible areas. This was not performed now and instead regions were defined in a arbitrary fashion as they seemed to make the most sense. On the other hand, this will highlight some differences between coastal and inland areas.

Studying the regions, they illustrate how the landscape available for settlement and use develops over time as the shoreline is retracting. The flat and level landscape of Uppland emerges as a scattered archipelago with only a small number of regions of limited size in the northwest. The SoNaR regions expand and often merge as more land becomes available, changing the connectivity of the landscape. Towards the end of the sequence there are larger regions forming, that join large parts of the land to a few central nodes by the pour points. One hypothesis is that these large regions could play are role in the social development, with focal points for power and control, and an increased sense of unity. In addition to that, there also emerges a division in the direction the regions are facing, where some are directed outwards to the coast, while others are directed inwards towards the emerging Lake Mälaren, that is becoming an important unifying factor and communication route.

To exemplify the relevance of the SoNaR regions, the example of Iron Age graves was chosen, where the shape of the stone settings could be understood as regional "dialects" in how to construct graves (see above). Figure 18 illustrates the result of a distribution map of the different types of stone settings that are available in the Uppland area. The westernmost areas were excluded since they contained so few graves. This might be the result of different settlement patterns, but might also be the result of a large number of graves being destroyed by agriculture over the centuries, as there are large areas of intensely cultivated areas there (Löwenborg, 2010). There are clear patterns of distribution of the different types of graves in the area, and when these are aggregated to the watershed and coastal regions for BP 1,950, there are some distinct differences between the SoNaR regions.

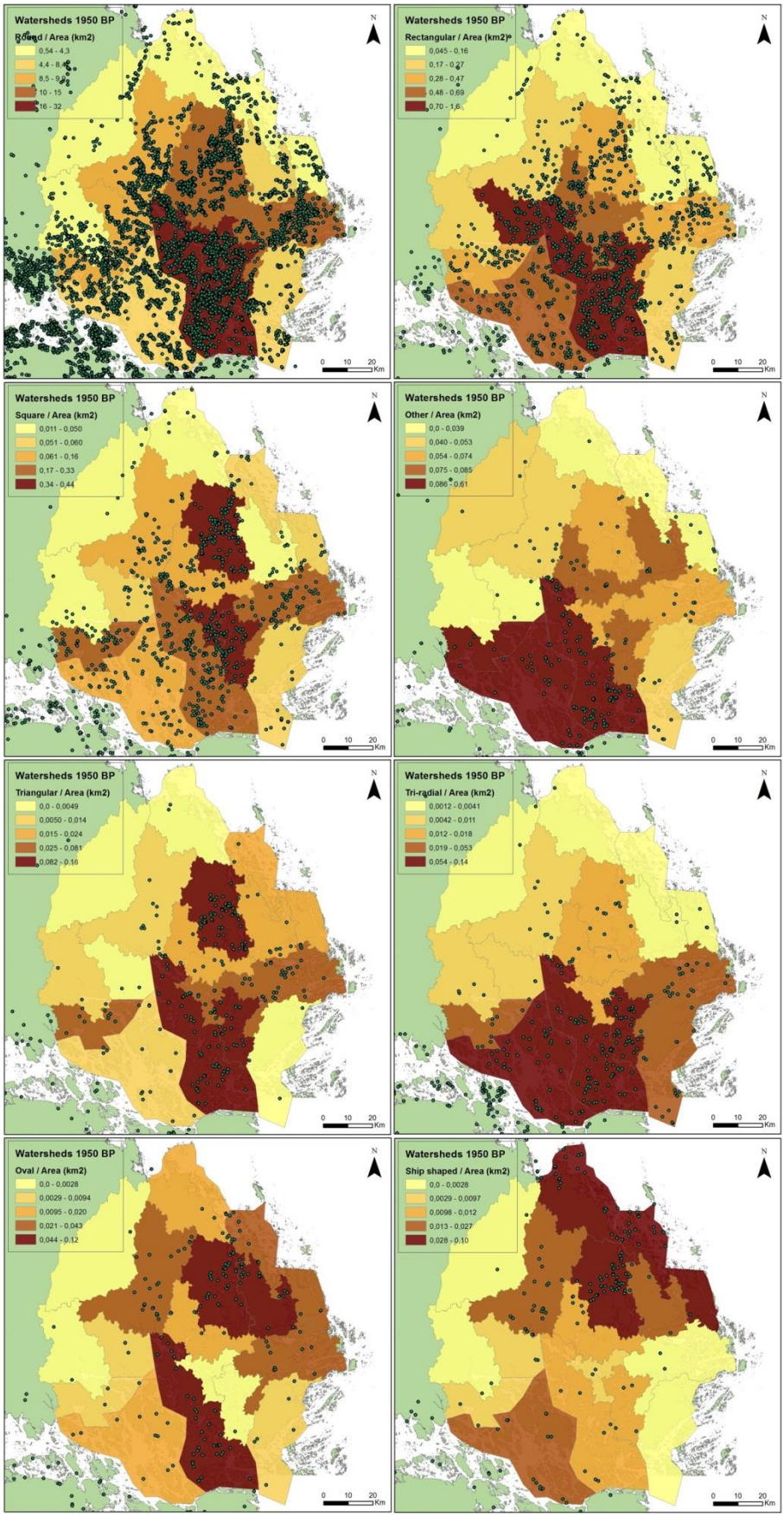

Fig. 18: Distribution of different stone settings in relation to the SoNaR regions of BP 1,950 in Uppland, shown both as actual point patterns, and aggregated numbers per square kilometer for each area. The regions have been classified using quantile classification to highlight the differences in concentration of sites

4.3 Modelling results of SoNaR in Uppland

The distributions of sites in figure 18 reveal several interesting patterns. Here we will only discuss a few brief examples of these to illustrate some implications of the SoNaR approach to understanding dynamic long-term landscape change and the formation of socio-cultural regions. The ship-shaped stone settings are concentrated to the coastal zones, but while frequent in the northern part of the coast, they seem to be fairly rare in the southern coastal zone. Oval shapes are concentrated to a few clusters that are not bordering each other. Square shapes are concentrated to a few areas, where other parts of the landscape are largely missing them. There seem to be some clear correlation between the dialectic traits in burial customs and the SoNaR regions, that could well indicate underlying social patterns. The results thus support the thesis that natural borders may influence the formation of social regions, especially since the same pattern of path dependency have been indicated from both previous and subsequent periods in analyses based on different archaeological and historical materials.

The results also show that the model can be a powerful tool in reconstructing prehistoric dynamic landscape as well as to understand why archaeological material show different, regional patterns. The SoNaR model should however be combined with other analyses, relevant for different areas and different time periods, in order to understand why the "dialects" appear and what they represent. It can also be improved as suggested above under SoNaR *model implementation.*

5. Modelling results as input for the Knowledge Hub SDI

As stated in D2.2, the Spatial Data Infrastructure that is available as part of the HERCULES Knowledge Hub has various advantages for presenting the results for the study of long-term landscape change.

- First, the SDI offers functionalities to integrate digital spatial data (also from different repositories e.g. different universities, governmental institutes etc.);
- Second, the SDI offers functionalities to communicate historical and heritage spatial data to various stakeholders ranging from history and heritage experts to the people of the place for purposes of validation. The GI literacy of these stakeholders varies a lot;
- Third, the SDI offers functionalities to process and/or download data into specialist software with which complex long term landscape change models can be developed and executed.(e.g. ArcMap, QGIS, GeoDMS, NetLogo, R etc.);
- Fourth, the SDI offers functionalities to share the models and the outcomes of long term landscape change models dynamically, allowing changes to the data to automatically update the model;
- Fifth, the SDI can offer functionalities to disseminate the research results as services which, in this case, will be done as part of the Knowledge Hub developed in HERCULES WP7;

For the Uppland region we have decided to make the modelling results available as viewing and download services. The watershed data is available at the Knowledge Hub SDI, and can be used as input for analysis of any cultural trait for the time periods. Since they represent regions defined from purely natural features of the landscape that have social implications, they are useful for analyses and study areas where modern boundaries are irrelevant. For the Uppland region we have thus foremost made use the second and third options listed above.

Like the Uppland case we will also made the data of the Lower Rhine region case available through the Knowledge Hub SDI[5]. Furthermore we will make the various scripts and configurations of the PLUS available as well. For the case study we will thus make use of the second, third and fourth option. Additionally we have, in close collaboration with WP7, developed a story telling GI by which we make use of the fifth option as well. Since within this story telling GI services from other sources are included as well, we will also use the functionalities of the first point described above.

5.1 Story telling webGIS for Lower Rhine case study

When presenting results of complex spatial modelling analysis to other scholars it is often difficult for other´s to reproduce the steps taken. This problem has been described in De Kleijn *et al.* (2014) and has over the last decade resulted in various infrastructural initiatives where researchers can upload their research results in a sustainable way (e.g. DANS EASY data archive for the Dutch research (https://easy.dans.knaw.nl)). However, the services work foremost as repositories and are more seen as digital appendices.

Since within the HERCULES project a complete WP has been dedicated to the development of a Knowledge Hub (i.e. WP7) we have made use of the opportunity to develop a story telling webGIS as a digital version of the modelling activities for the Lower Rhine Delta. This story telling webGIS will be part of the Knowledge Hub Labs http://labs.kh.hercules-landscapes.eu/. The main purpose of the story telling webGIS will be to allow other researchers that are interested in our modelling framework to interactively browse through our modelling results. By including interactive maps of the datasets, instead of printed static maps which is often the case in reports and academic papers and articles, we are able to present our research in a more scientific transparent way. The interactive maps will allow readers to overlay various data layers and offers possibilities to integrate more data layers then is normally done in research reports and papers (since not every data layer or table needs to be a printed map). Readers will thus be able to browse through directly through the data and are offered the possibility to check for the conclusions drawn.

Additionally to the possibility of sharing the modelling results to other researchers, the story telling webGIS also offers the opportunity to present the research results to heritage managers and a broader public. In order to do so we have develop a script with a main storyline with the steps of our modelling activities explained on a general level accompanied with boxes with additional information more meant for experts, but leaving it open for heritage managers and a broader public to access this information as well.

5.2 Story script

The story telling webGIS developed for WP2 mostly follows the structure of this report (D2.3) chapter 3. It initiates with an introduction to the protocol after which it sketches the opportunities of applying spatial dynamic modelling methods to analyze long term land use change. It then introduces the PLUS modelling framework. For more expert readers this section provides links to more details on the used algorithm. This is followed by an introduction to the case study landscape including interactive maps with which the reader can

[5] Making the data available as viewing services is scheduled for September 2016. Making the data available as download services is scheduled after a peer reviewed scientific article for the PLUS framework has been published.

browse through the archaeological datasets, the palaeogeographical reconstruction for AD 100 and some basic maps from other sources such as the Dutch elevation model.

Each time slice will constantly refer to separate boxes in which short descriptions on the situation in these time slices will be described. At that point the two hypotheses will be introduced after which the construction of the suitability maps and demand for land use per hypothesis will be extensively described. The user will be able to browse interactively through the different tables and resulting maps, making it possible to understand whether he or she would draw the same conclusions based on the results that the PLUS framework applied.

A schematic overview of the script that has been developed for the story telling webGIS Knowledge Hub lab is presented in figure 19.

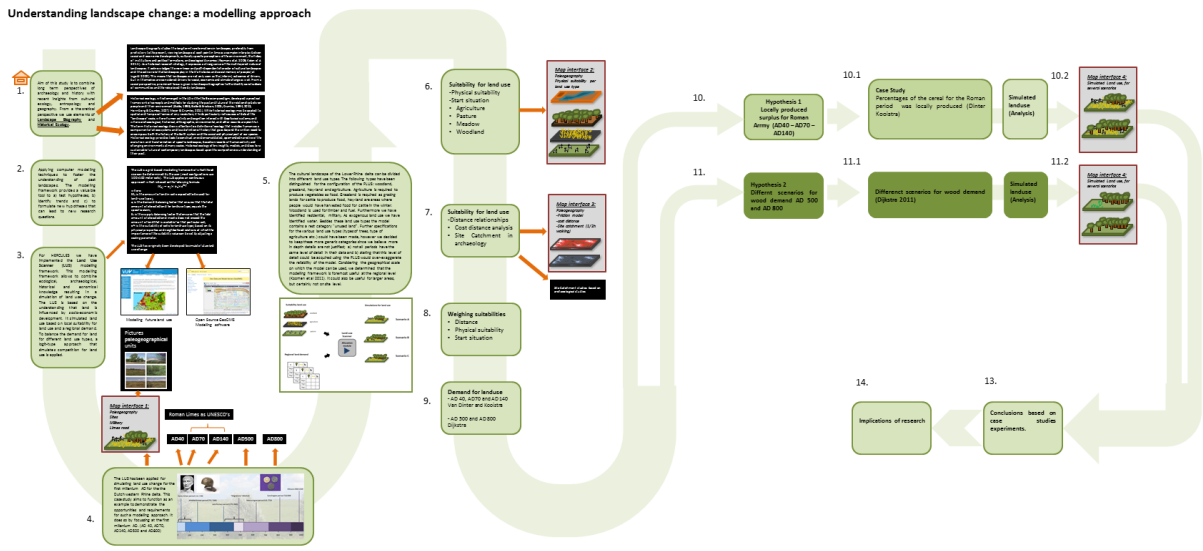

Fig. 19: The storyboard for the storytelling webGIS Knowledge Hub for WP2 (a readable version has been included as appendix D)

5.3 Story telling webGIS as a dynamic service

Together with WP7 we have decided to approach the content of the story telling webGIS to be dynamic. We have therefore integrated the content of the story telling GI using Geopedia services. This allows the member of WP2 to dynamically adjust the various textual sections without additional involvement of WP7 Knowledge Hub developers. By approaching the story webGIS as such the tools remain usable for other purposes as well.

For the layout of the story telling webGIS we have used the following link as inspiration. (http://clear3.uconn.edu/viewers/bears/). Like this site we have given our story a navigation pane on the left side allowing visitors to scroll through the story and constantly understanding where they are in the story.

The interactive maps have been organized as such that the users can go through all of the datasets and sub products (layers and tables) that the PLUS framework uses as input and produces. Furthermore interactions have been developed that link tables, descriptions and map layers as such that it will always remain clear which layers are related to each other.

Screenshot on the story telling webGIS Knowledge Hub lab are given in the figures 20, and 21. At the moment of publication of this (D2.3) report, the Knowledge Hub is not yet fully

operational. The finalizing and launch of the story telling webGIS Knowledge Hub are scheduled for the final event of the HERCULES project fall 2016.

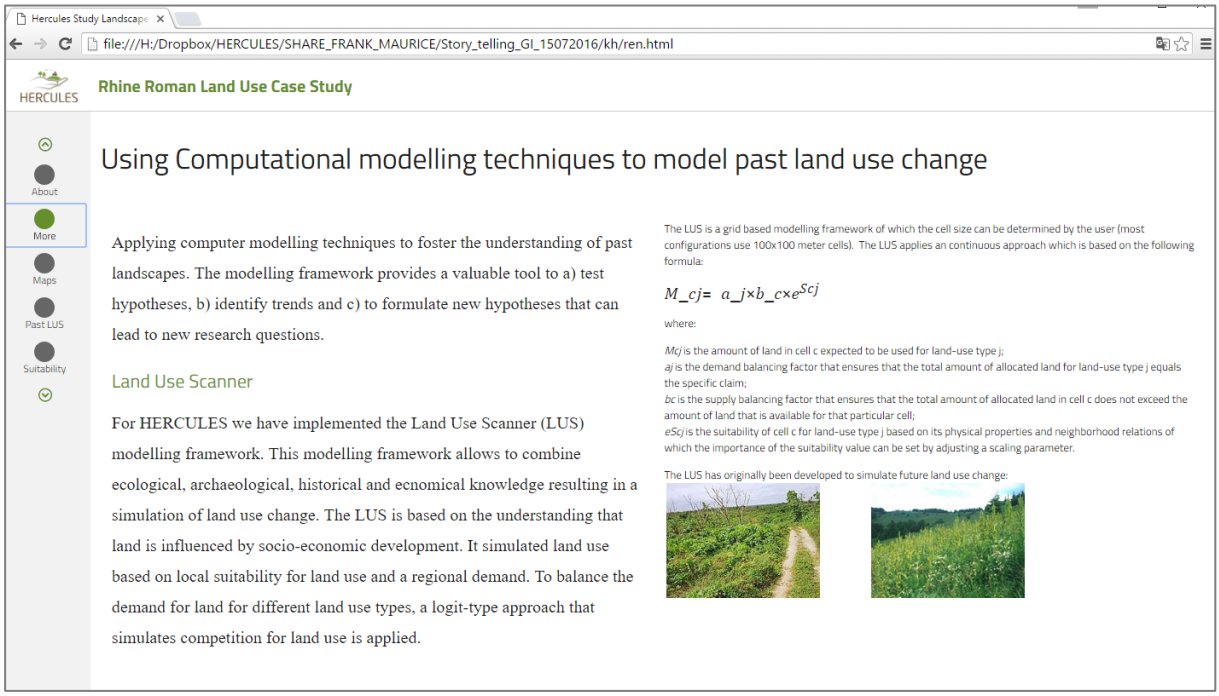

Fig. 20: Screenshot of storytelling webGIS Knowledge Hub that shows an explanation of the PLUS modelling framework

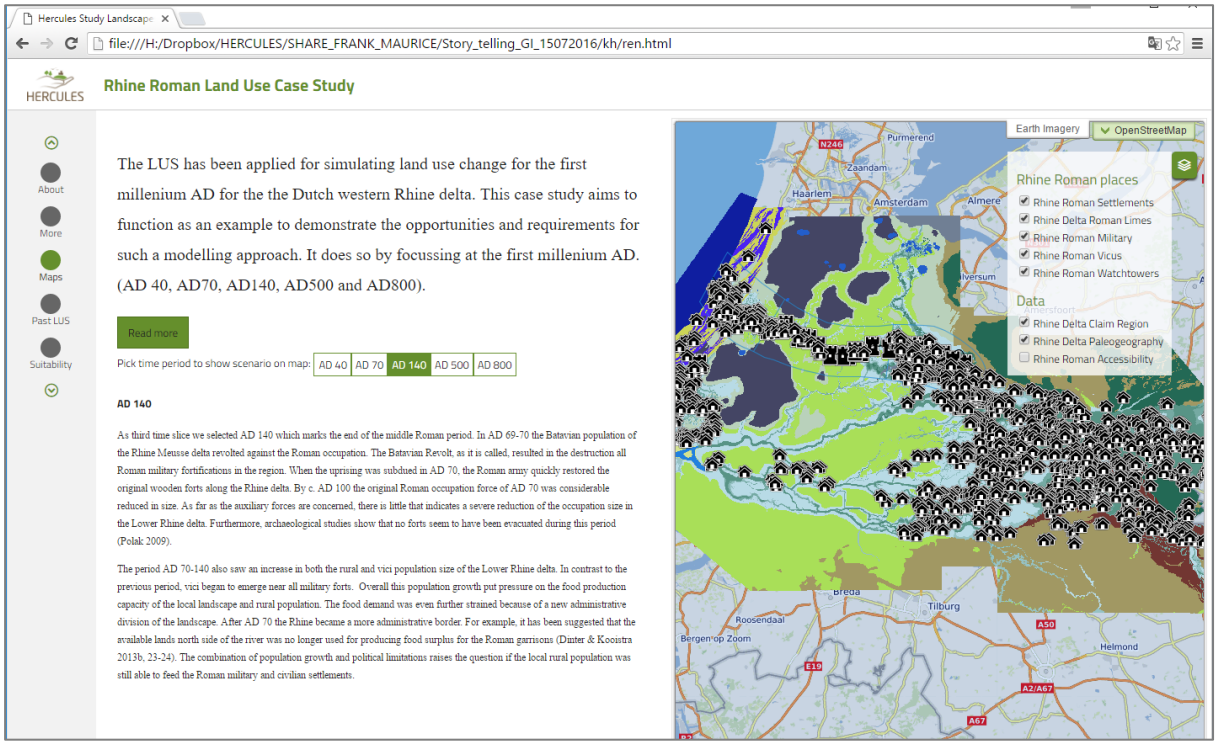

Fig. 21: Screenshot of storytelling webGIS Knowledge Hub that shows the interactive maps for input data for the various periods

5.4 Opportunities of Storytelling GI for HERCULES Knowledge Hub labs

The storytelling webGIS that is developed for WP2 provides a state-of-the-art example on how complex modelling research can be published. It allows researchers to share all their research data in a more comprehensible way. It therefore facilitates scientifically transparent enriched publications.

Besides the story webGIS as a tool to interactively present research results for other researchers, since it works with a main story line with extras for experts, the tool is also usable to present the research to a broader public and heritage and landscape managers. To test the added value of the tool for these purposes the research presented by De Kleijn *et al.*, (2016) would be as a good starting point for the design of an evaluation framework.

The way in which the tool has been set it also allows for other cases to be integrated as such. Other case studies from HERCULES thus might benefit from the generic tools developed for WP2.

6. Conclusions

Within the HERCULES project, WP 2 focuses on the study of long-term landscape change. The principal aim of the study is to enhance methodologies, to collect data and to enhance existing knowledge on the long-term dimensions of cultural landscape change. To accomplish this aim, the WP has presented a landscape protocol focused at long-term perspectives (D2.1). This protocol has subsequently been used as the basis for the development of modelling frameworks to study long-term landscape change and includes recent insights from geography, landscape archaeology, (historical) ecology, anthropology and information science. This has resulted in two modelling frameworks that have extensively been discussed in this deliverable.

Both modelling frameworks presented here show that the main problems for simulating past cultural landscapes are the quality and detail of available data, and the uncertainties in the assumptions. Interpreting and using the modelling results must therefore be approached with care and accompanied by sensitivity analyses

The uncertainties in available data and the careful approach of the results make the modelling frameworks presented here rather an academic tool for the sole purpose of supporting other scholars. HERCULES's Knowledge Hub can to that extent be used as a tool which can be used as a bridge between heritage landscape experts and the general public. WP 2 therefore aims to use the Knowledge Hub as a tool which can be used for the integration of long-term landscape perspectives in planning and design practices. Planning and design frameworks like Geodesign (Steinitz, 2012; Lee et al., 2014) can be adapted to create a suitable workflow for planning and design sensitive to the long-term landscape histories and heritage values.

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Appendix A

Table A1: Physical suitability for arable farming

Palaeogeographical unit	Physical Suitability Agriculture	Reasoning and source
sea	na	classified as water, exogenous
residual gully	na	classified as water, exogenous
estuary	na	classified as water, exogenous
lake	na	classified as water, exogenous
tidal flats	0	High flood risk, makes it unsuitable for agriculture
dune	3	Dunes are suitable for agriculture, however the soils are less fertile compared to other palaeogeographical units (see Van Dinter *et al.* (2014)). This palaeogeographical unit has therefore been scored with a 3.
high levee	5	High Levees are considered to be very suitable for agriculture (Van Dinter *et al.* (2014))
moderate levee	3	Based on expert judgment of Gouw-Bouman, supported by Brinkkemper (1991): various cereal types suitable to be grown on moderate levees.
low levee	1	Based on expert judgment of Gouw-Bouman, supported by Brinkkemper (1991): a few cereal types suitable to be grown on on low levees.
river dunes	3	River dunes are considered to be suitable for agriculture, however since the soils are less fertile compared to other palaeogeographical units (see Van Dinter et al., 2014). This palaeogeographical unit has therefore been scored with a 3.
fluvial terrace	5	Based on expert judgement of Gouw-Bouman, fluvial terraces are very suitable (5) for agriculture. This palaeogeographical entity is however not present in the study area.
covered alluvial ridge	4	Based on expert judgement of Gouw-Bouman, covered alluvial ridges are considered to be suitable for agriculture.
high floodplain	0	High flood risk, makes it unsuitable for agriculture
low floodplain	0	High flood risk, makes it unsuitable for agriculture
eutrophic peat	0	For this period, peat areas are not suitable for agriculture.
mesotrophic peat	0	For this period, peat areas are not suitable for agriculture.
oligotrophic peat	0	For this period, peat areas are not suitable for agriculture.
high pleistocene sands	4	Based on expert judgement of Gouw-Bouman, high pleistocene sands are suitable (4) for agriculture. This palaeogeographical entity is however not present in the study area.
cover sand	4	Based on expert judgement of Gouw-Bouman, cover sands are suitable (4) for agriculture. A distinction could have been made between cover sands with a low nutrient level and a high nutriciet level, however, since this is very difficult to distinguish in a palaeogeographical reconstruction, we have given it a give an average score. Since the rich areas are believed to have been more present the score was set to 4.
post-Roman erosion	0	Post-Roman erosion processes made it impossible to provide a palaeogeographical reconstruction. We have therefore set this palaeogeographical unit to 0 excluding it from the analysis.

Table A2: Physical suitability for pasture and meadow

Palaeogeographical unit	Physical Suitability Pasture (Hay-land / Grassland)	Reasoning and source
sea	0	classified as water, exogenous
residual gully	0	classified as water, exogenous
estuary	0	classified as water, exogenous
lake	0	classified as water, exogenous
tidal flats	3	Van Dinter *et al*. (2013) state that tidal flats would to some extent have been suitable for pasture. Their statement is supported by Brinkkemper (1991).
dune	4	Dunes are considered to be suitable for pasture, however since the soil of this palaeogeographical entity is considered to have a relative low nutrient level it has not been scored as very suitable but a little less (Van Dinter *et al.* 2013 and expert judgement Gouw-Bouman).
high levee	5	High levees are very suitable for pasture (Van Dinter *et al.*, 2014)
moderate levee	5	Moderate levees are very suitable for pasture (Van Dinter *et al.*, 2014)
low levee	5	Moderate levees are very suitable for pasture (Van Dinter *et al.*, 2014)
river dunes	5	Based on the soil this palaeogeographical entity is considered to be rich in nutrients making it very suitable for pasture (expert judgement Gouw-Bouman).
fluvial terrace	5	Based on the soil this palaeogeographical entity is considered to be rich in nutrients making it very suitable for pasture (expert judgement Gouw-Bouman).
covered alluvial ridge	5	Covered alluvial ridges are very suitable for pasture (Van Dinter *et al.*, 2014)
high floodplain	5	High floodplains are very suitable for pasture (Van Dinter *et al.*, 2014)
low floodplain	2	Low floodplains are only limited suitable. (Van Dinter *et al.*, 2014)
eutrophic peat	0	Eutrophic peat is not suitable for pasture (Van Dinter *et al.*, 2014)
mesotrophic peat	0 / 3	Mesotropic peat is only suitable as grassland (Van Dinter *et al.*, 2014: 10)
oligotrophic peat	1 / 0	Oligotrophic peat is only suitable as hay land and bordering floodplain (Van Dinter *et al.*, 2014)
high pleistocene sands	5	The soil map shows that high pleistocene sands are relatively nutrient, this nutrient level makes these relatively high suitable for pasture.
cover sand	5	Cover sands are considered as very suitable for pasture (www.geologievannederland.nl/landschap/landschappen/zandlandschap)
post-Roman erosion	0	Post-Roman erosion processes made it impossible to provide a palaeogeographical reconstruction. We have therefore set this palaeogeographical unit to 0 excluding it from the analysis.

Appendix B

Table B1: Balancing the suitability factors for the PLUS

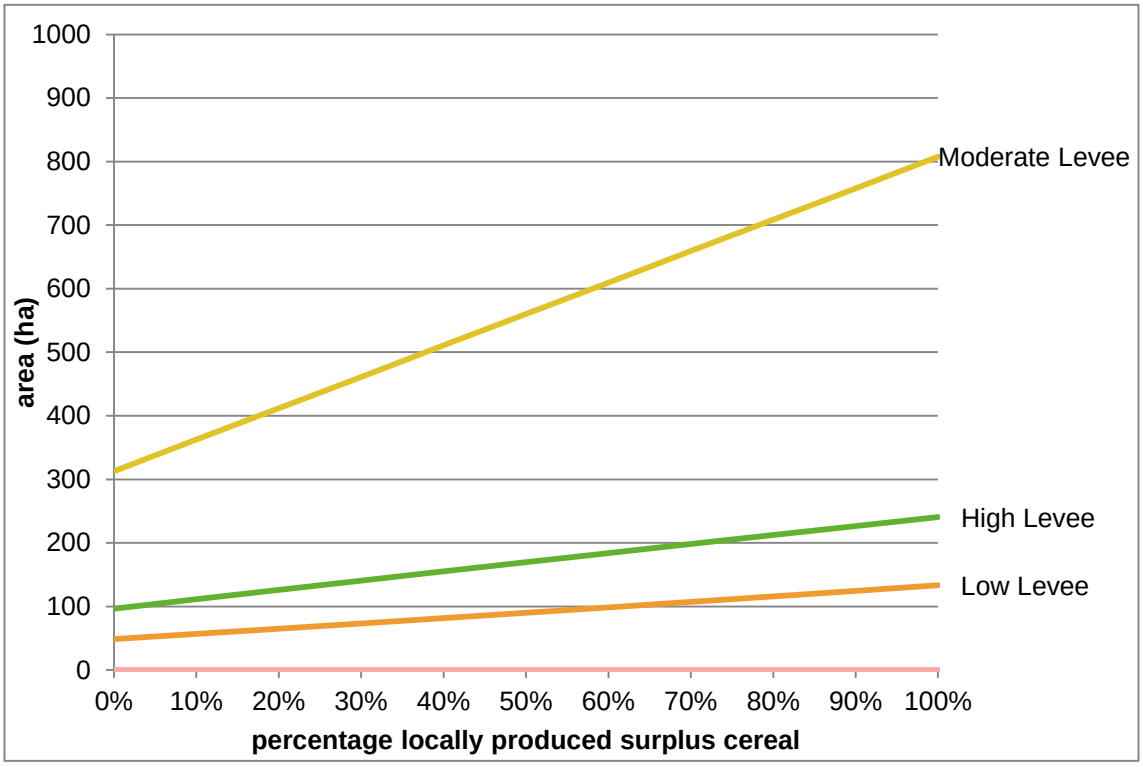
Land use type	Start situation		Physical suitability		Distance relationships	
	description	values	description	values	description	values
Residential*	For residential we have used the known archaeological sites. Since the locations won't change we have given the start land use an extremely high number	75	-	-	-	-
Military*	For military we have used the known archaeological sites. Since the locations won't change we have given the start land use an extremely high number	75	-	-	-	-
Water	water is defined as exterior and won't compete in the PLUS model	-	-	-	-	-
Arable Farming	For AD 40 this land use has been left empty. For AD 70 and AD 140 this land use type is assumed to be likely to have continued on the same locations. For AD 70 and AD 140 the output from the previous time slice has been reused and given a value of 20. For AD 500 and AD 800 we have not done so, since the time differences between the periods are assumed to be too big.	20	A score between 0 and 5 representing the physical suitability x2	0 - 10	A gradual scale of 1 hour walking from residential cells	0 - 10
					A gradual scale of 0,5 hour walking from residential cells	0 - 10
					Areas further than 1 hour walking distance have been made less attractive	-20
Pasture	As with arable land for AD 40, AD 500 and AD 800 this land use type has been left empty. For AD70 and AD 140 the land use from the previous time slice has been reused. A value of 20 had been given	20	A score between 0 and 5 representing the physical suitability x2	0 - 10	A gradual scale of 1 hour walking from residential cells	0 - 10
					A gradual scale of 2 hours walking from residential cells. This value is a little lower to increase the attractiveness of 1 hour walking	0 - 5
					Areas further than 2 hours walking distance have been made less attractive	-20
Meadow	see pasture	20	A score between 0 and 5 representing the physical suitability x2	0 - 10	A gradual scale of 1 hour walking from residential cells. Has been made less attractive to allow pasture to be place nearer to residential cells	0 - 5
					A gradual scale of 2 hours walking from residential cells. This value is a little lower to increase the attractivity of 1 hour walking	0 - 3
					Areas further than 2 hours walking distance have been made less attractive	-20
Woodland	see woodland, with a little difference giving it a value of 10 instead making it slightly less important	10	-	-	A gradual scale of 1 hour walking from residential cells	-5 - 0
					Distance of 300 m to limes road (only for AD 70 and AD 140)	-15
					Distance of 500 m to military sites (only for AD 40, AD 70 and AD 140)	-40
Unused land	all cells from this category has been given a value of -1 ensuring the PLUS will use this category to fill the remaining cells with	-1	-	-	-	-
Infrastructure	exterior	-	-	-	-	-

*Residential and Military could also have been configured as exogenous, thus not participating in the competition for the various land use types, however in order to allow the PLUS to be reused for APM purposes we have kept these as endogenous

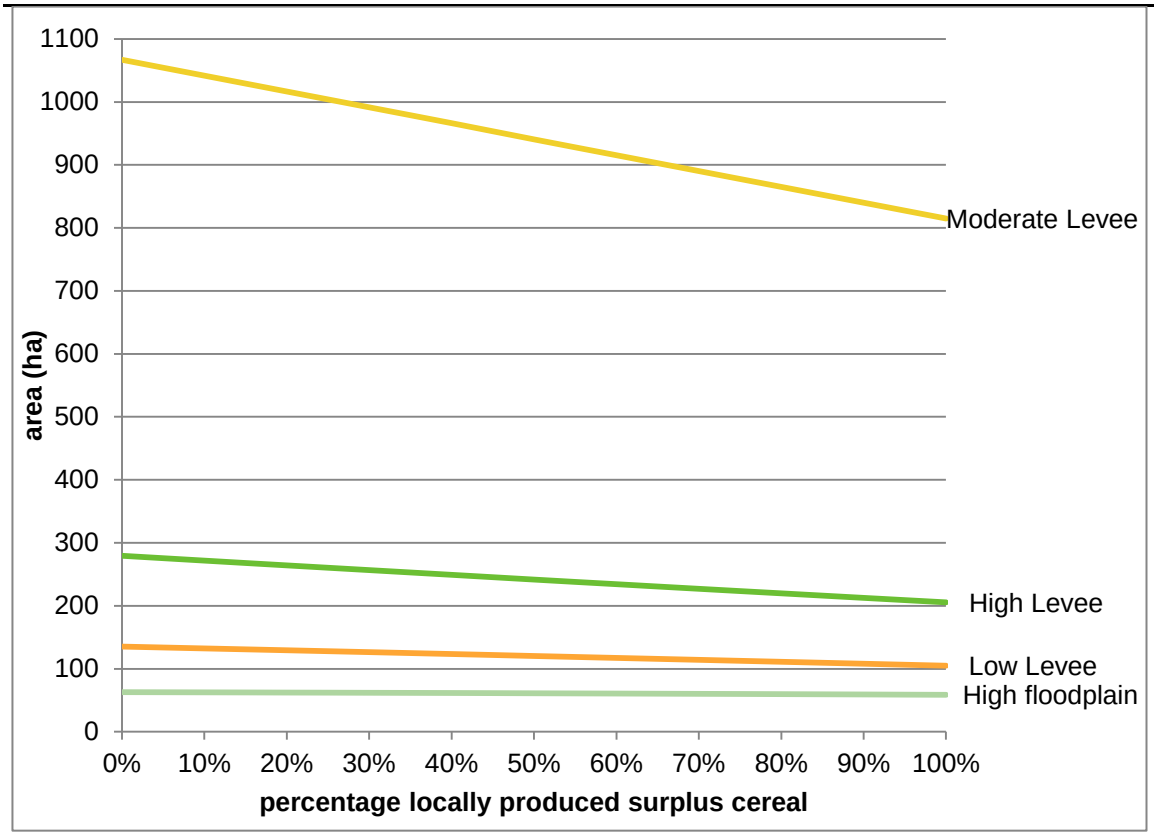
Appendix C

This appendix contains graphs showing the number of hectares (y-axis) allocated per land use type per palaeogeographical unit per percentage of cereal surplus locally produced. For AD 40 we only included graphs for the eastern claim regions, since the other regions do not have a demand for land use influenced by Roman presence. Palaeogeographical units that did not became higher than 15 ha have been excluded.

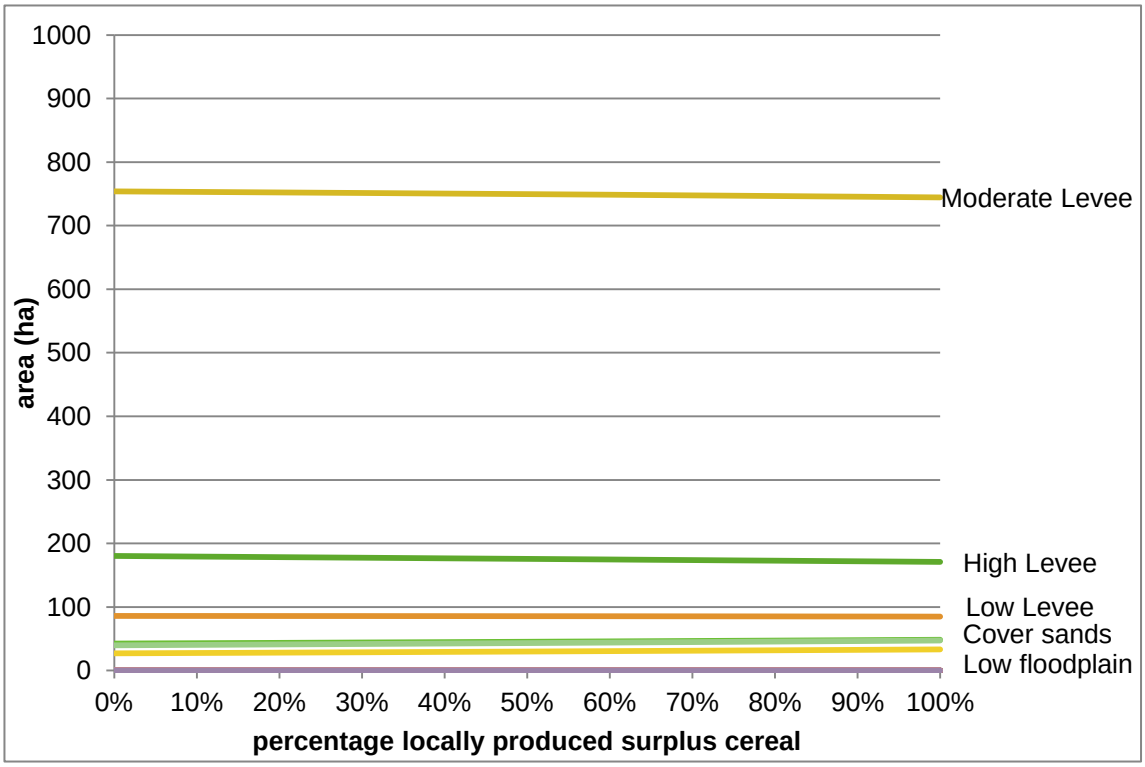
AD 40



C 1.1: Area arable farming per palaeogeographical unit eastern river area AD 40

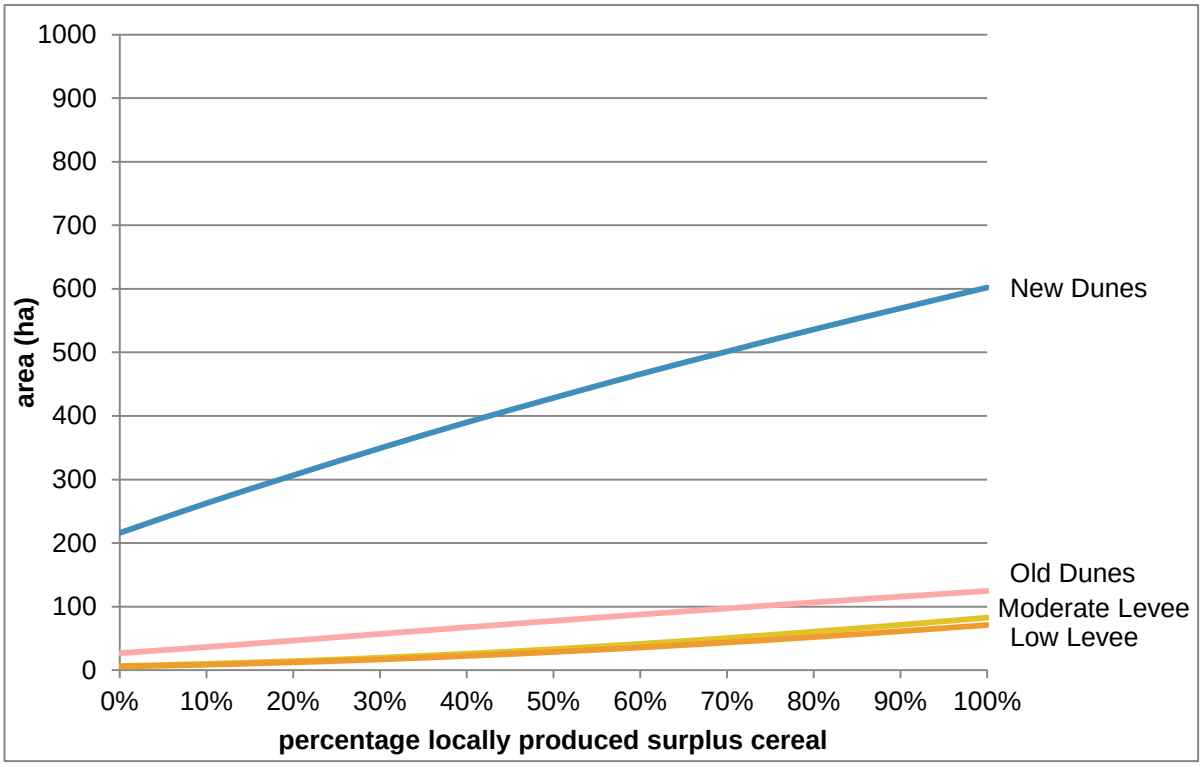


C 1.2: Area pasture per palaeogeographical unit eastern river area AD 40

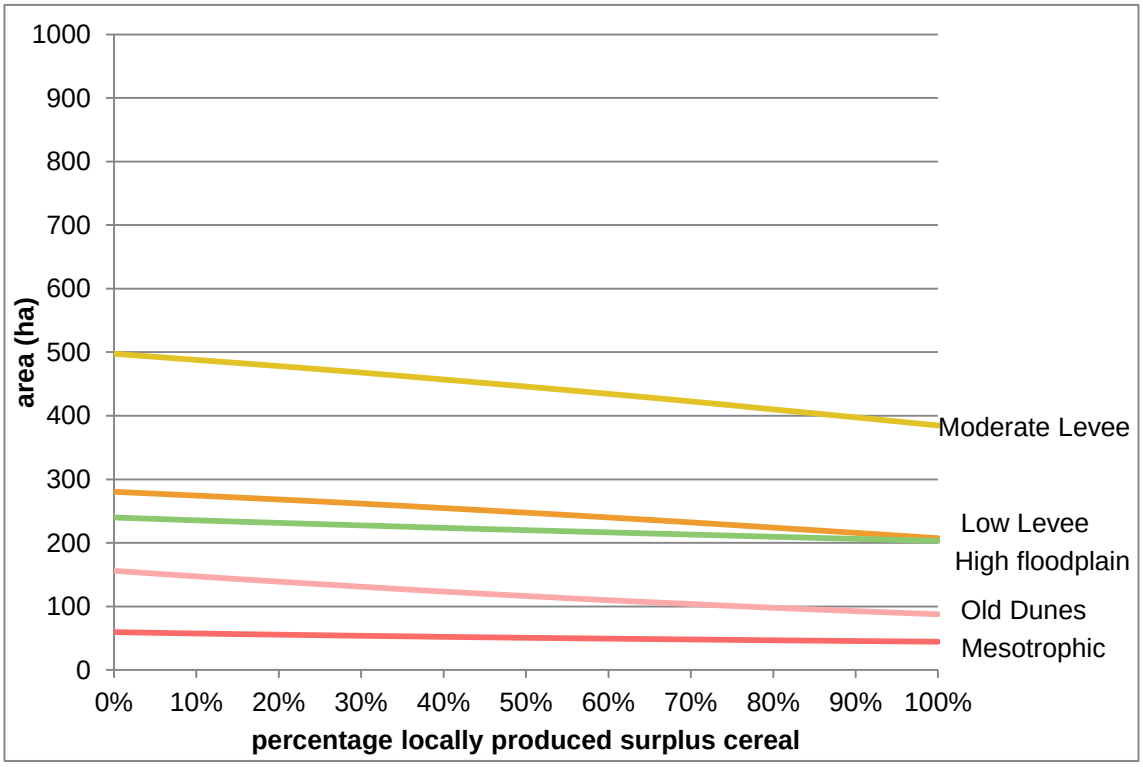


C 1.3: Area meadow per palaeogeographical unit eastern river area AD 40

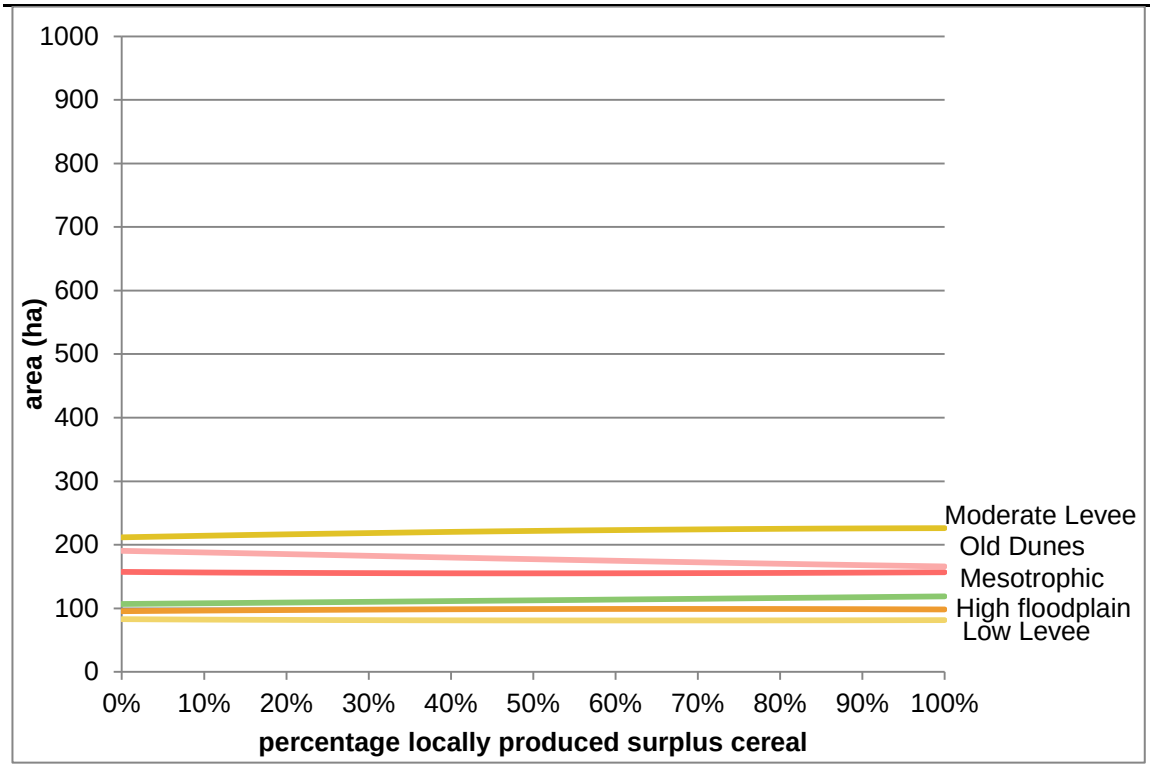
AD70



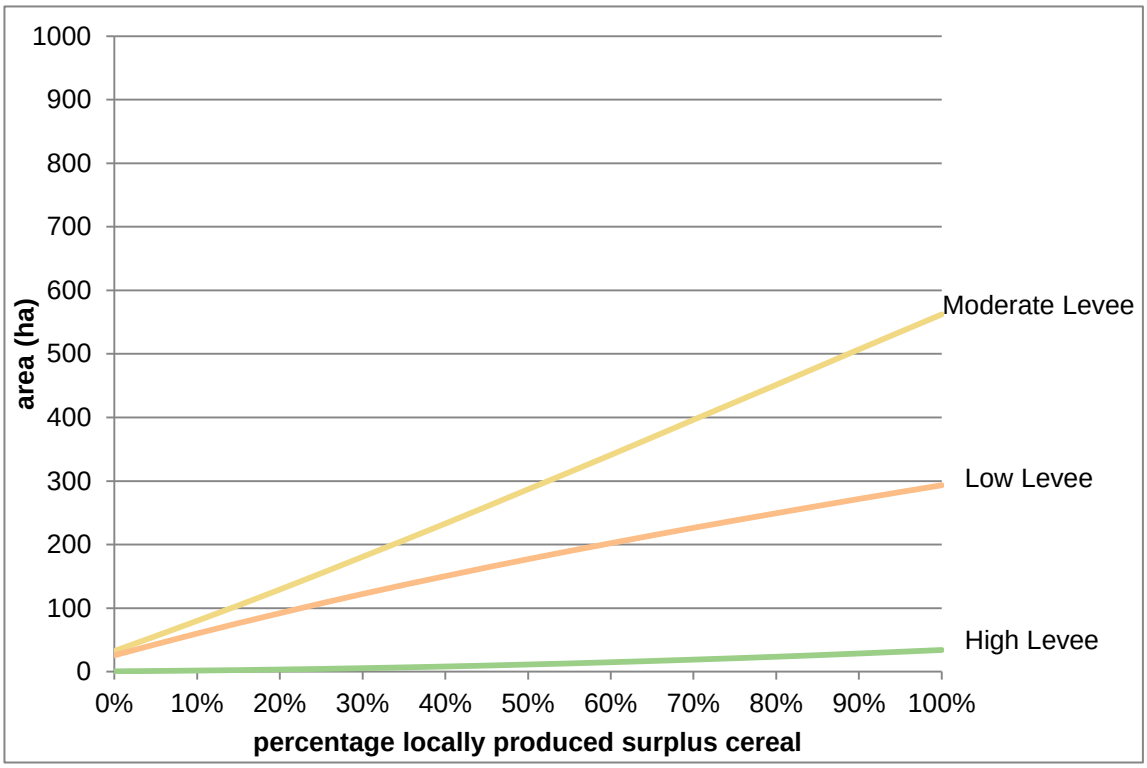
C 2.1: Area arable farming per palaeogeographical unit western coastal region AD 70



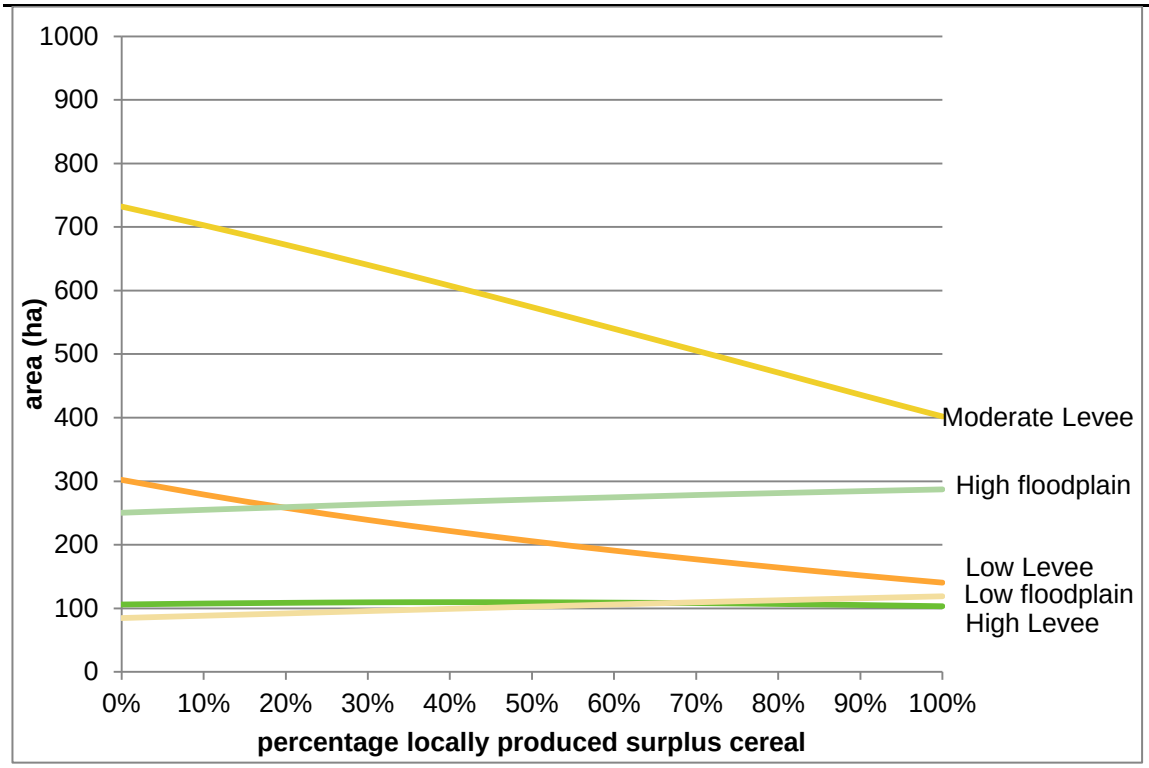
C 2.2: Area pasture per palaeogeographical unit western coastal region AD 70



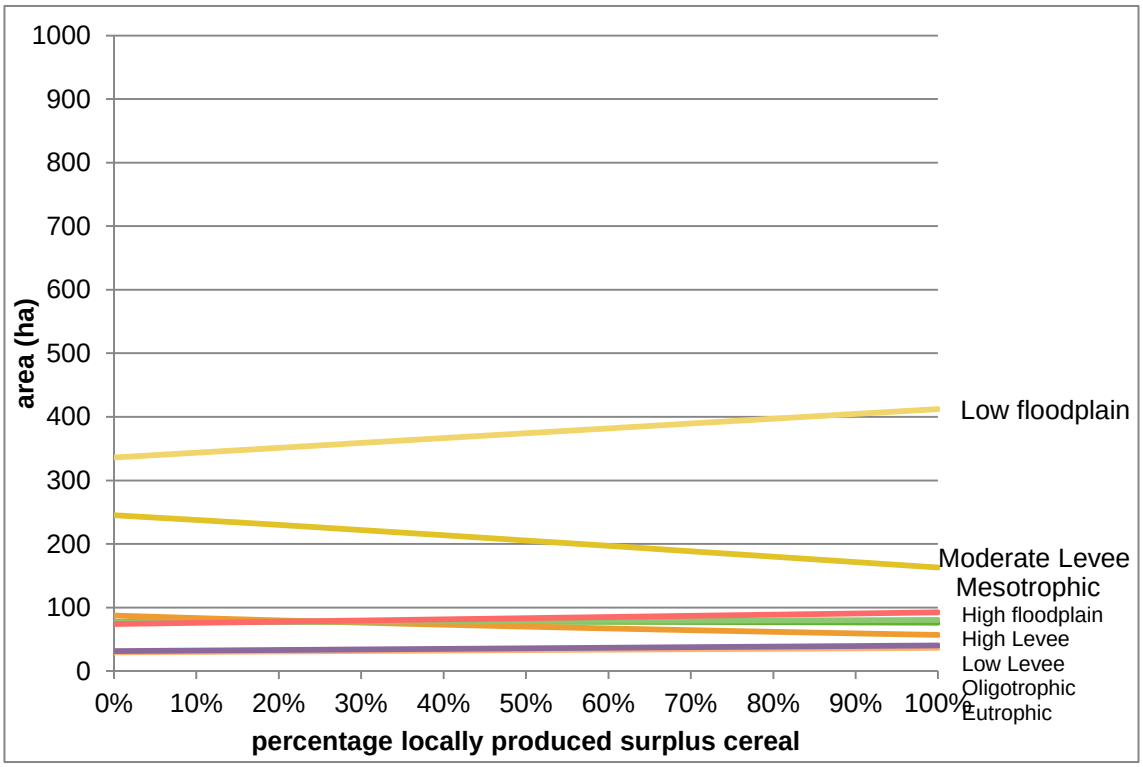
C 2.3: Area meadow per palaeogeographical unit western coastal region AD 70



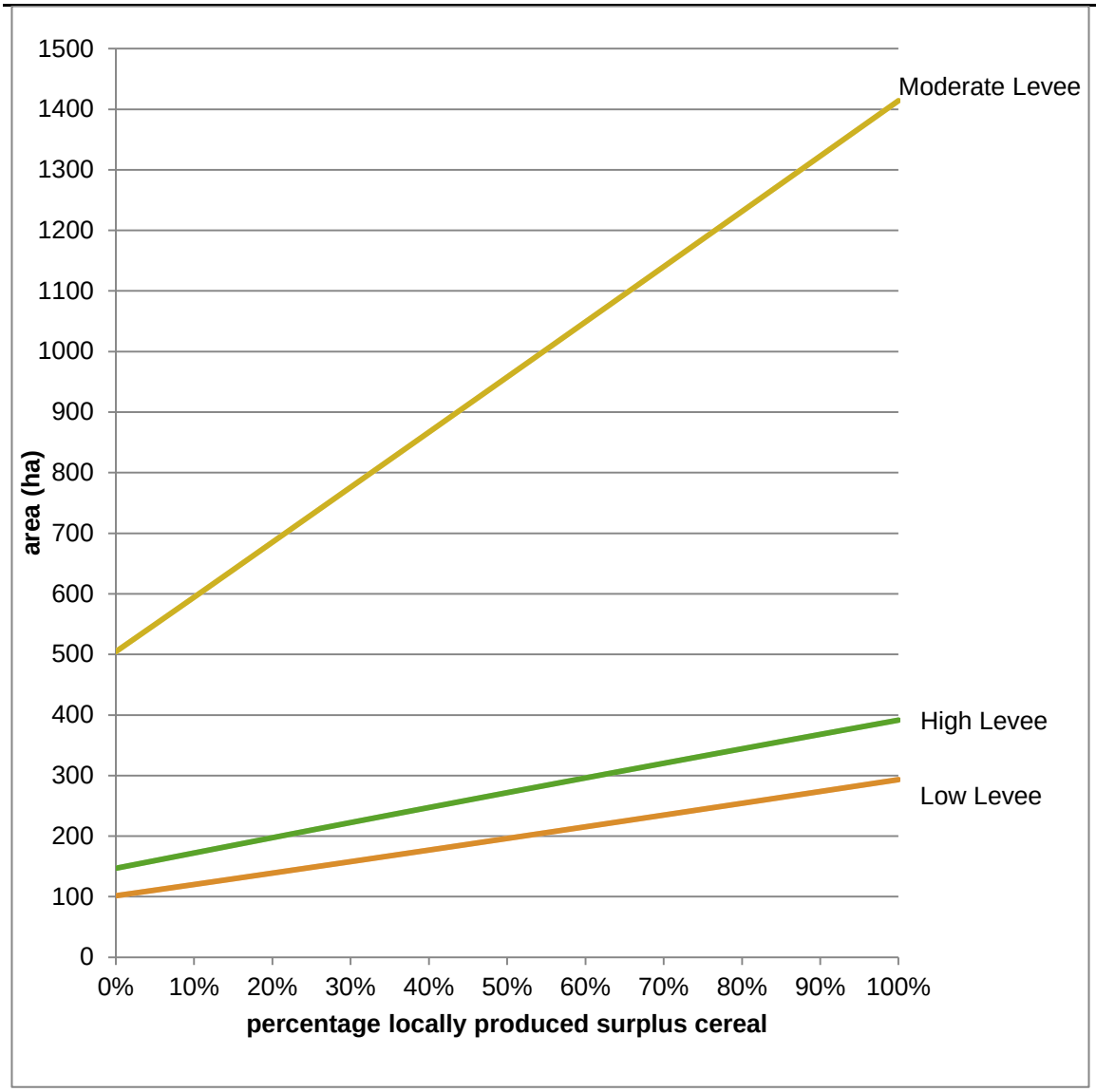
C 2.4: Area arable farming per palaeogeographical unit central peat area region AD 70



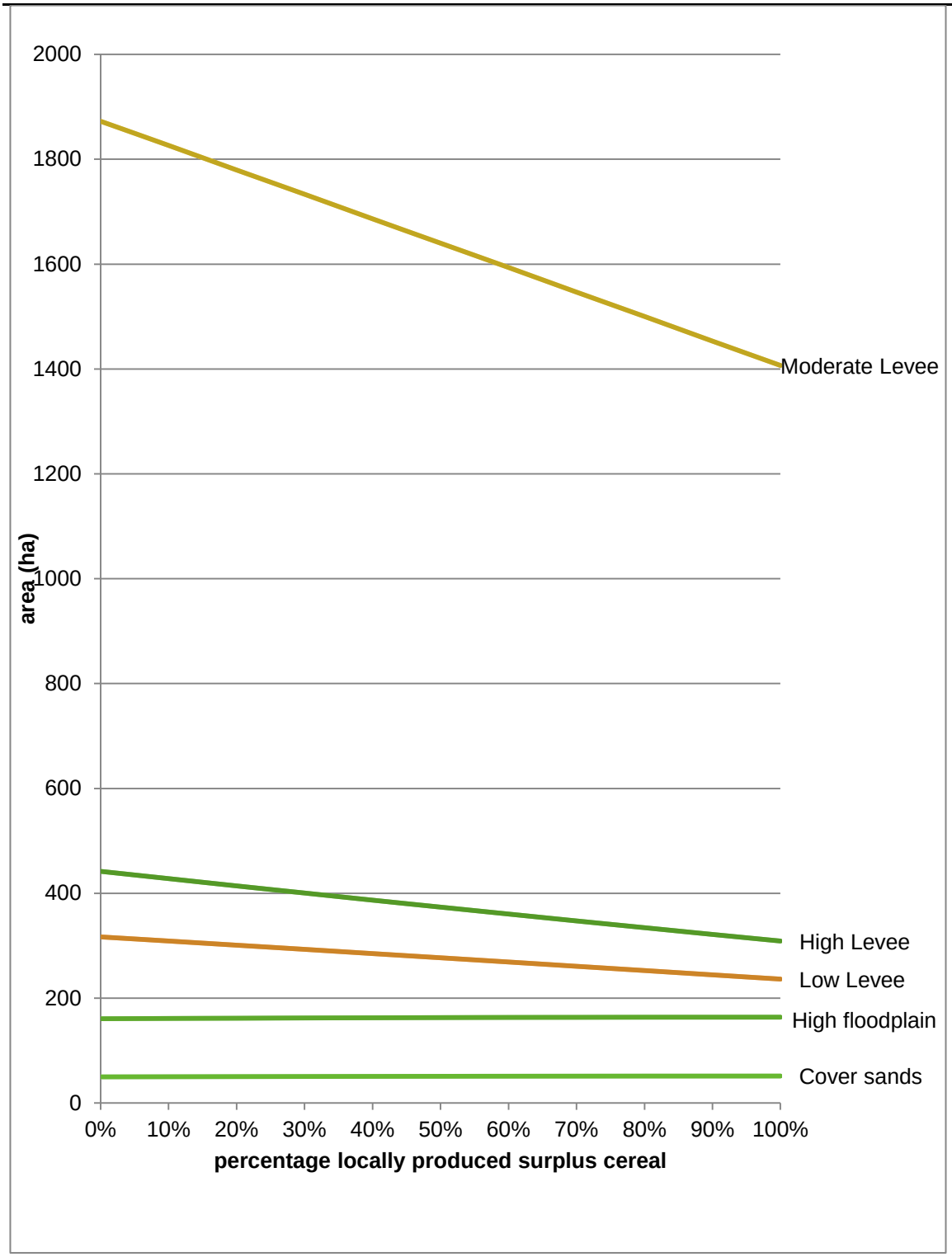
C 2.5: Area pasture per palaeogeographical unit central peat area AD 70



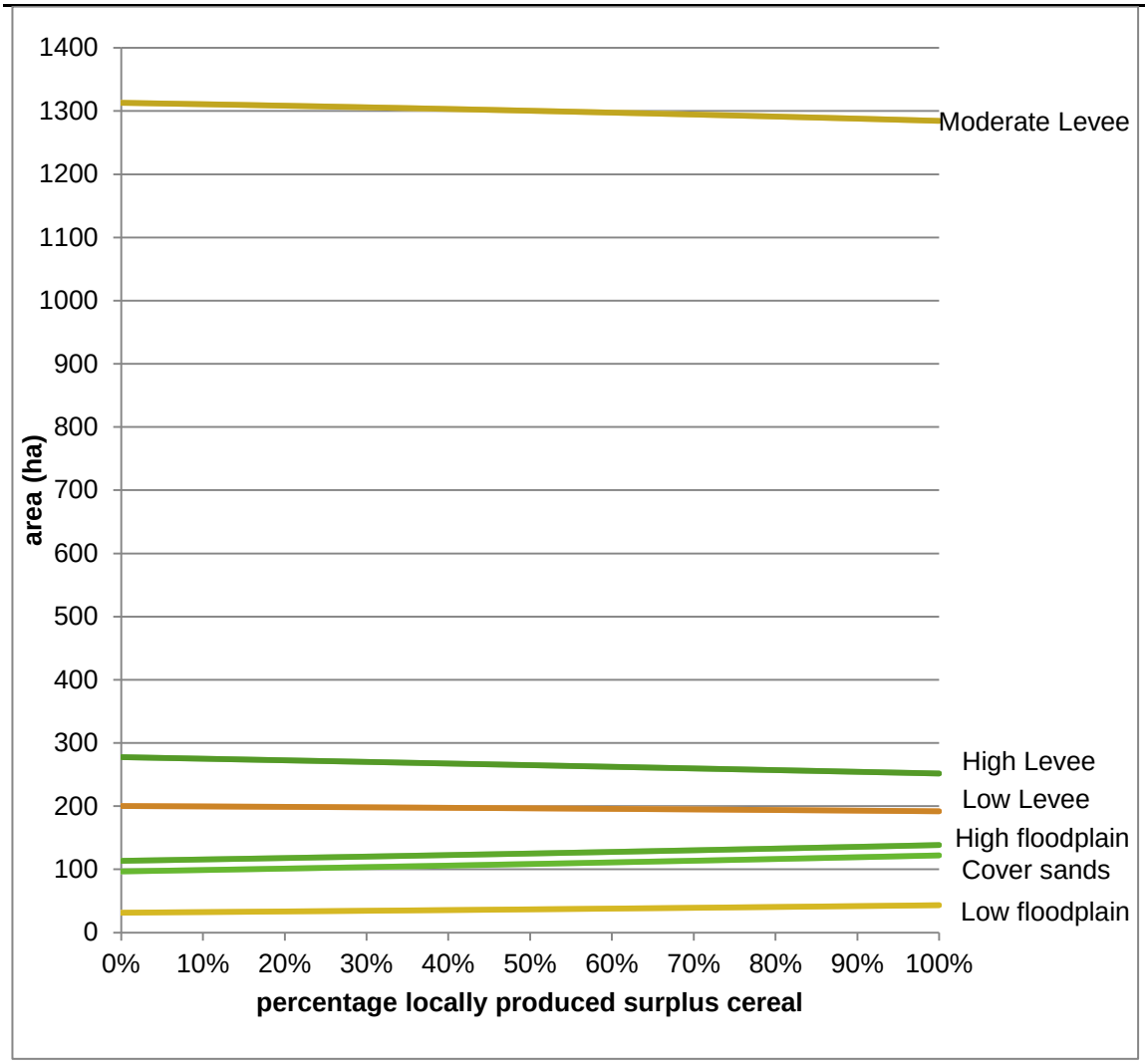
C 2.6: Area meadow per palaeogeographical unit central peat area region AD 70



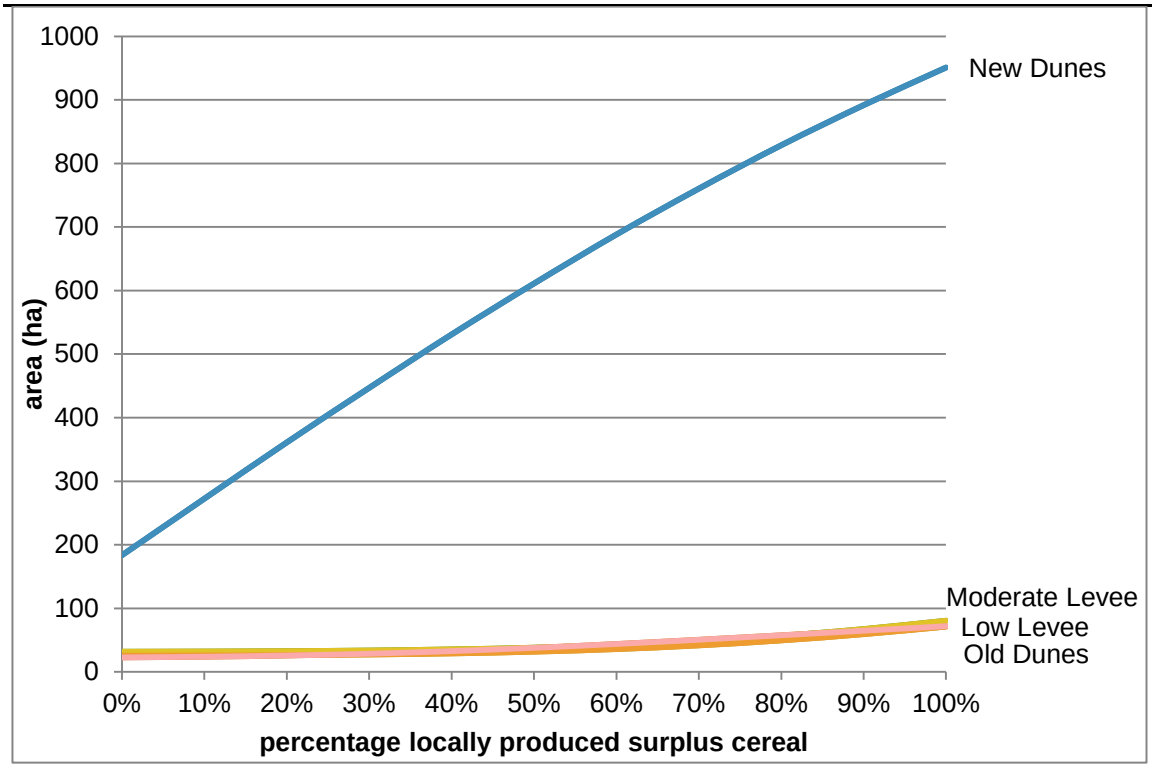
C 2.7: Area arable farming per palaeogeographical unit eastern river area AD 70



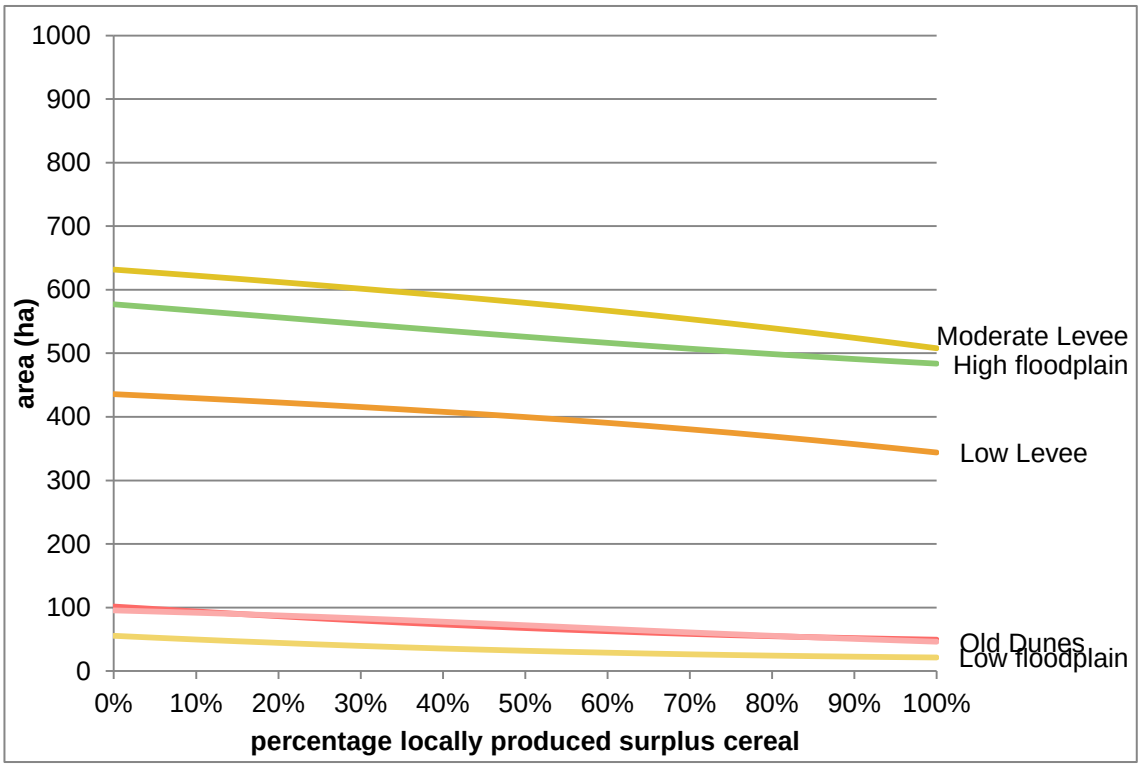
C 2.8: Area pasture per palaeogeographical unit eastern river area AD 70



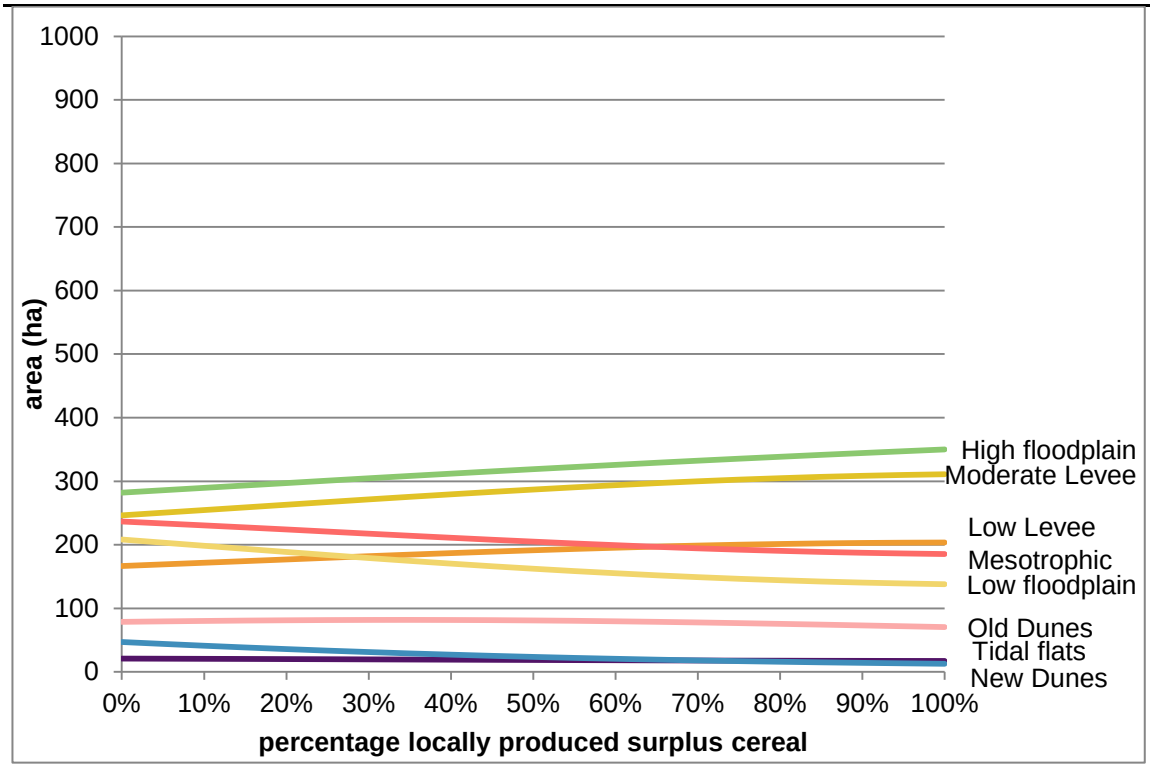
C 2.9: Area meadow per palaeogeographical unit eastern river area AD 70



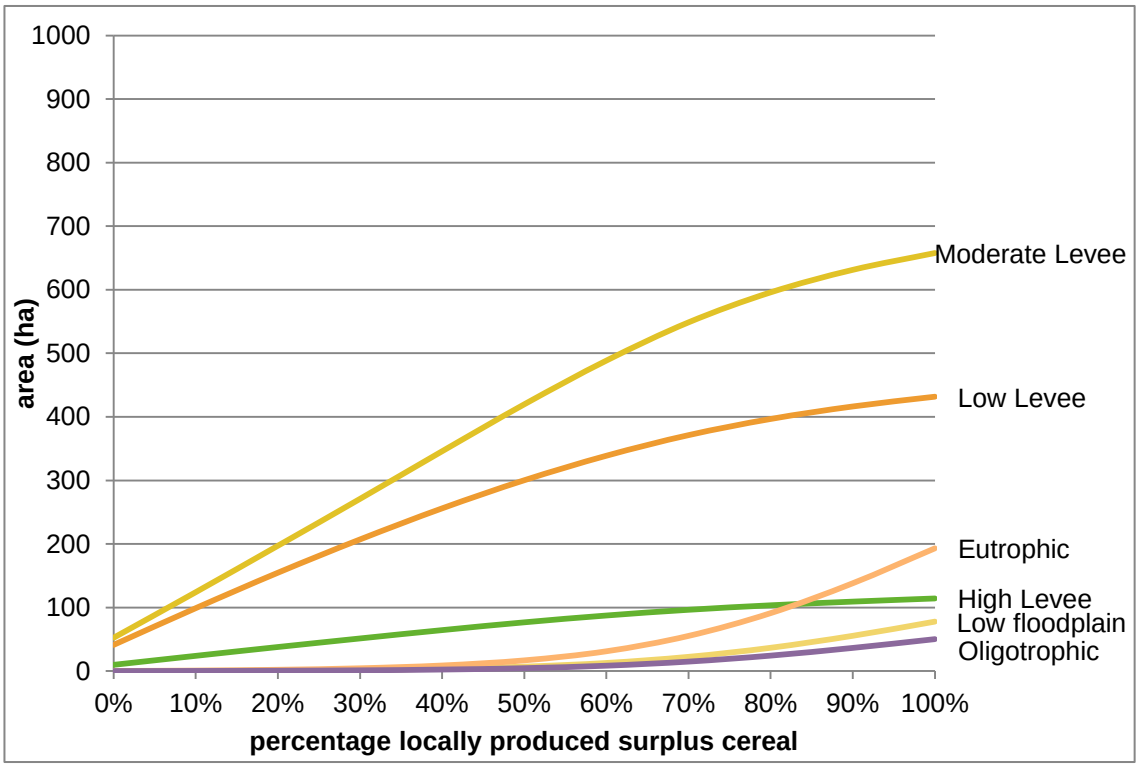
C 3.1: Area arable farming per palaeogeographical unit western coastal region AD 140



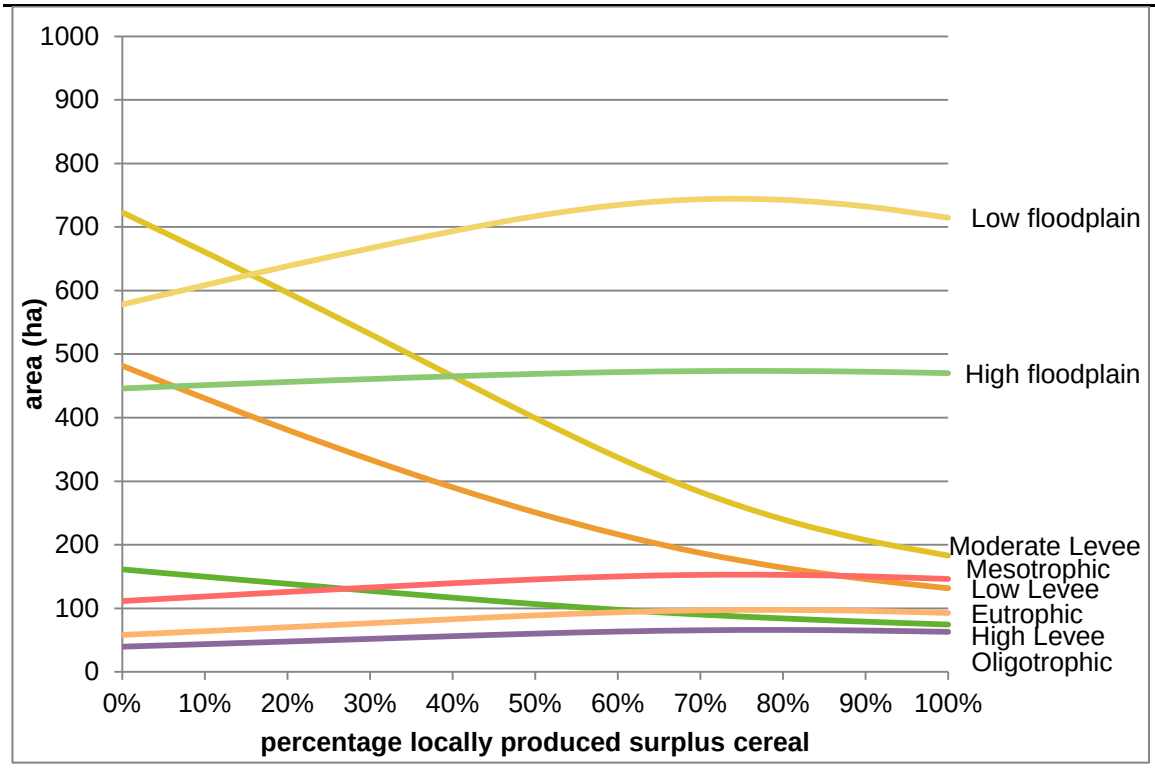
C 3.2: Area pasture per palaeogeographical unit western coastal region AD 140



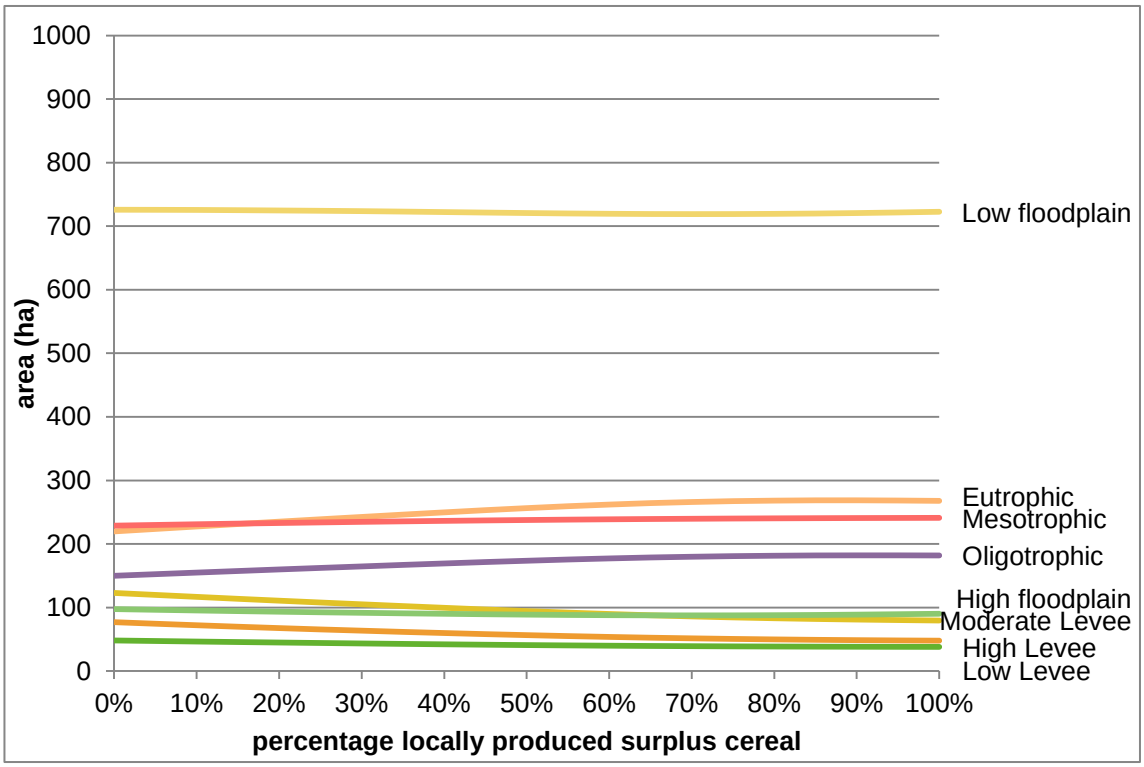
C 3.3: Area meadow per palaeogeographical unit western coastal region AD 140



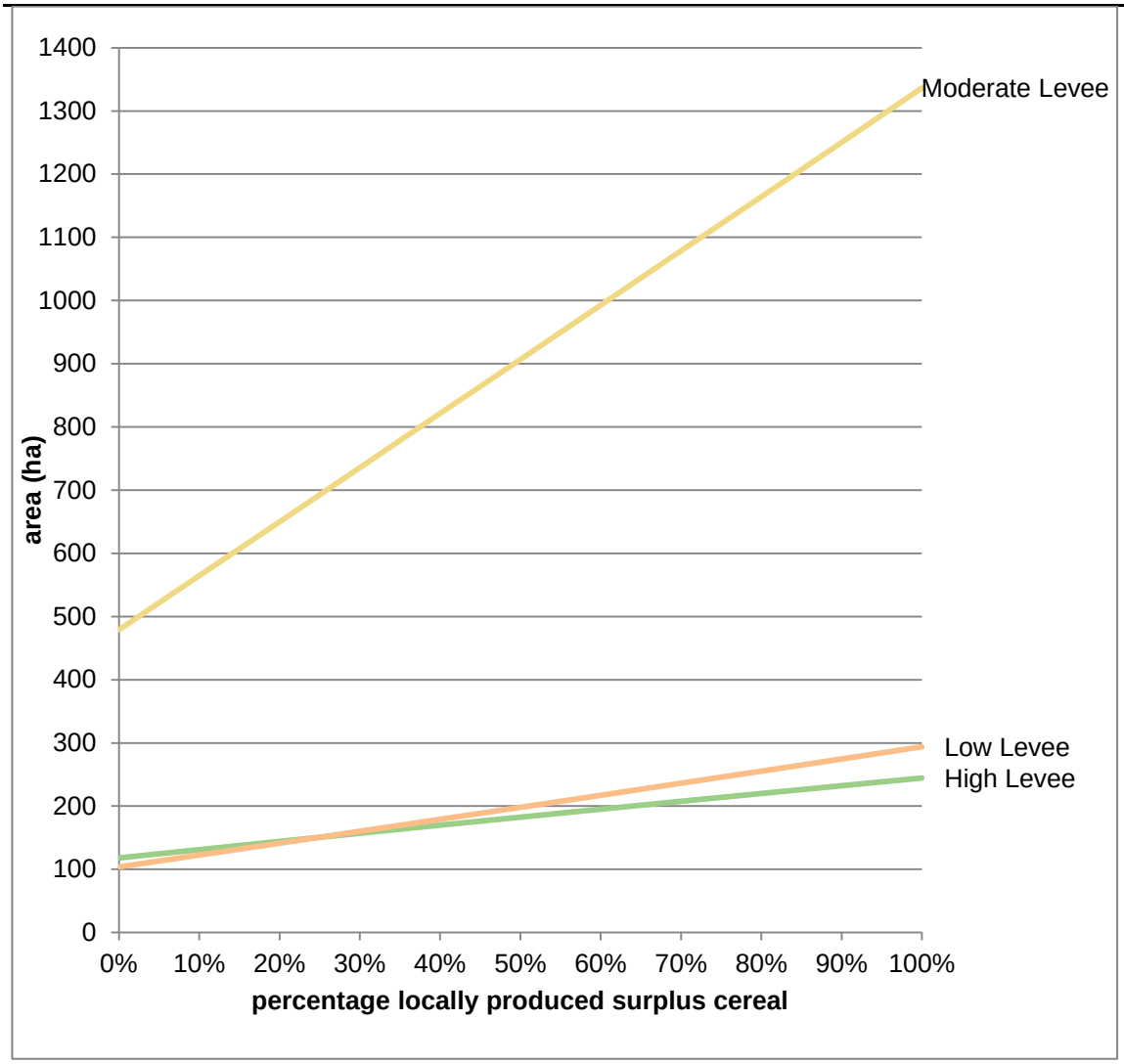
C 3.4: Area arable farming per palaeogeographical unit central peat area region AD 140



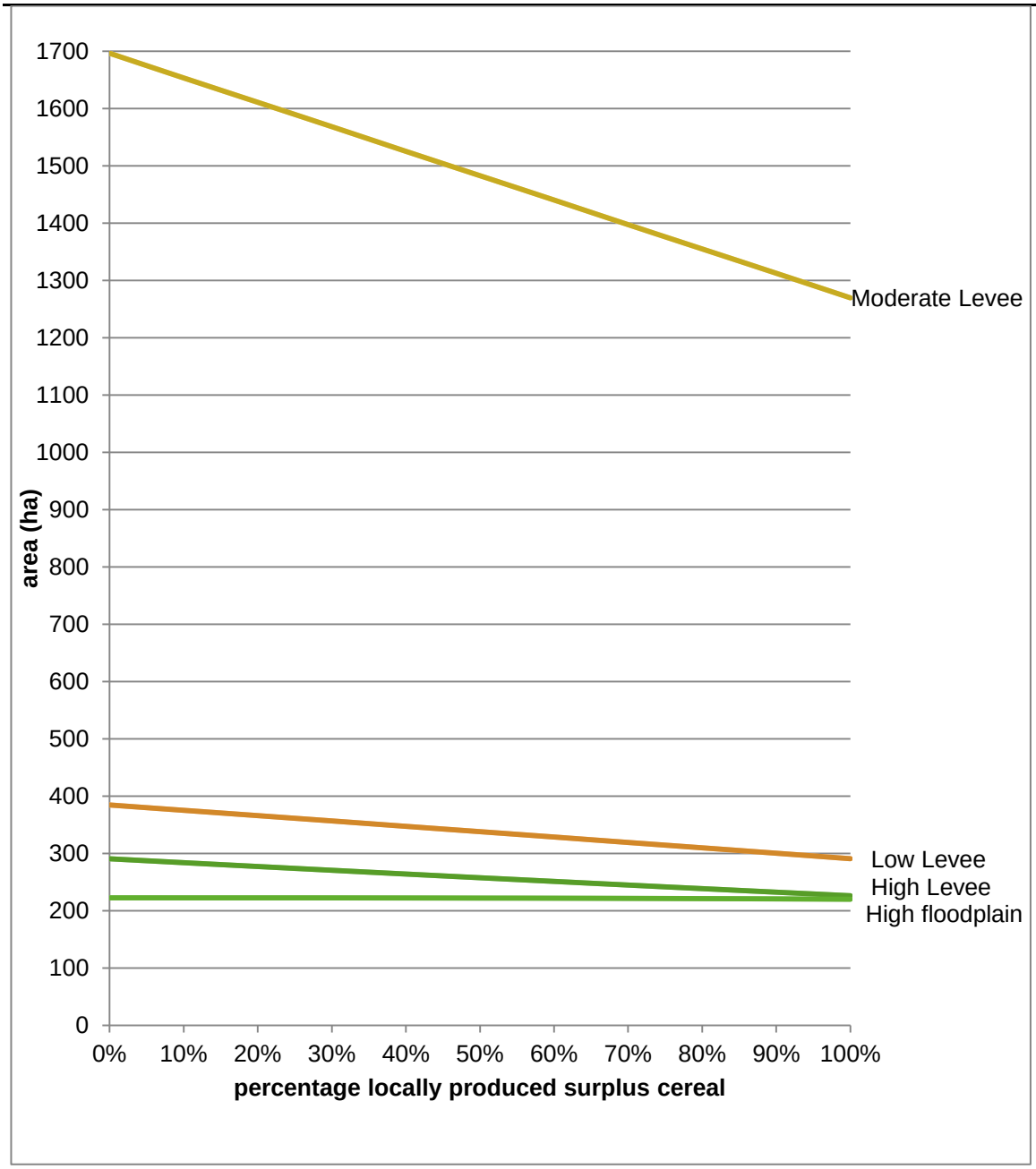
C 3.5: Area pasture per palaeogeographical unit central peat area AD 140



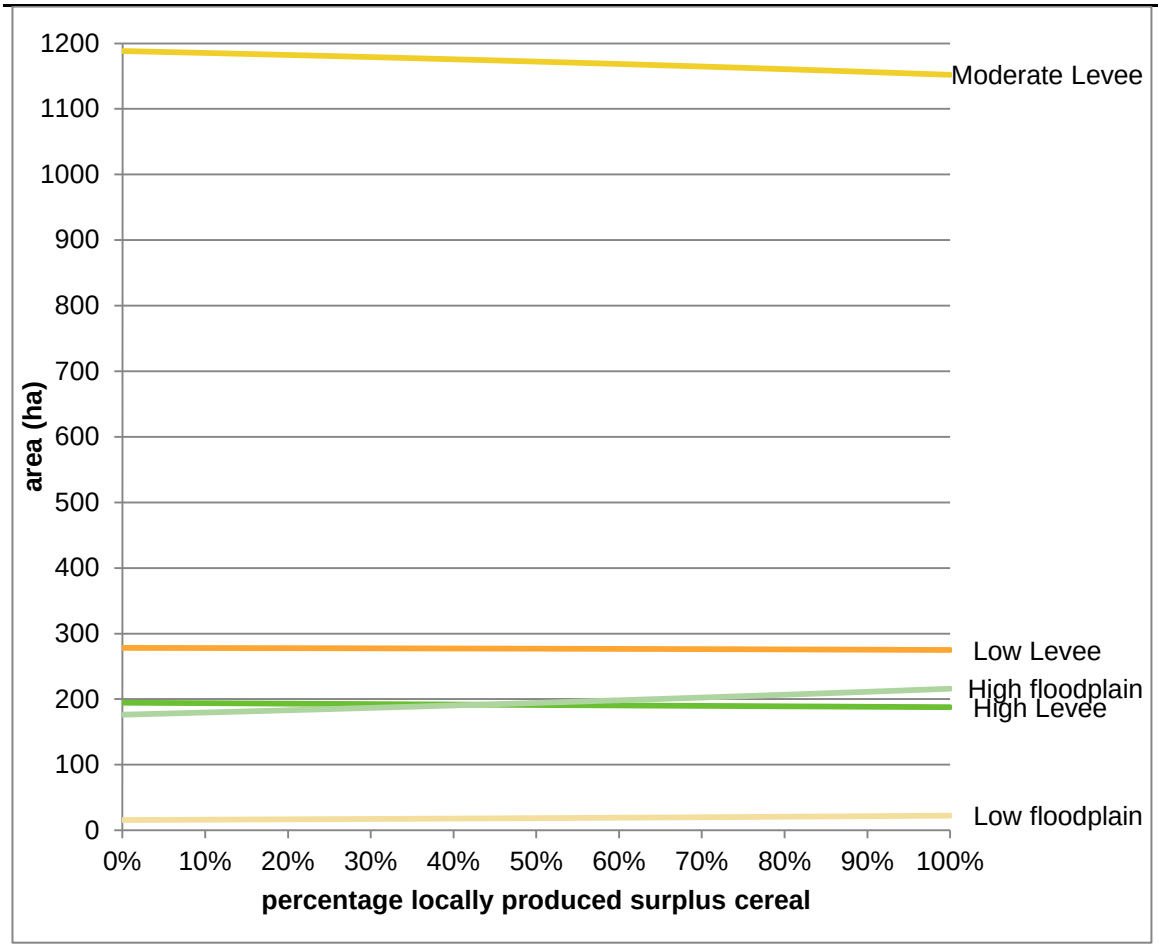
C 3.6: Area meadow per palaeogeographical unit central peat area region AD 140



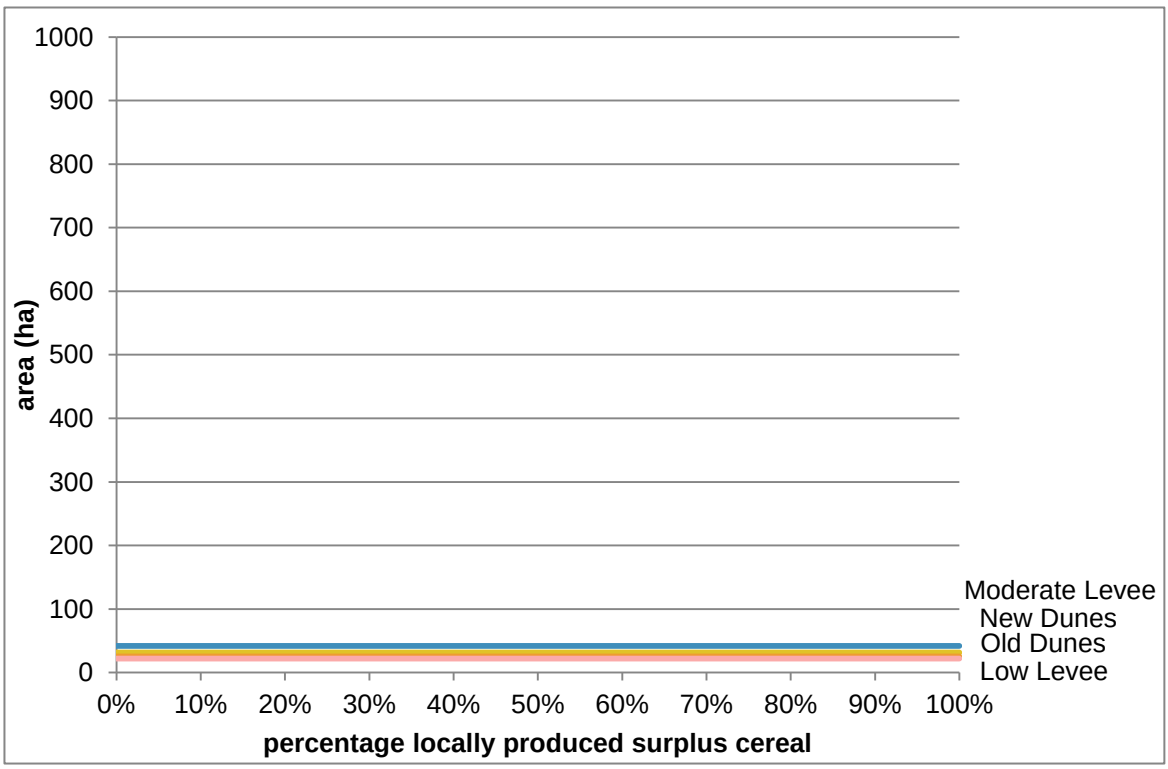
C 3.7: Area arable farming per palaeogeographical unit eastern river area AD 140



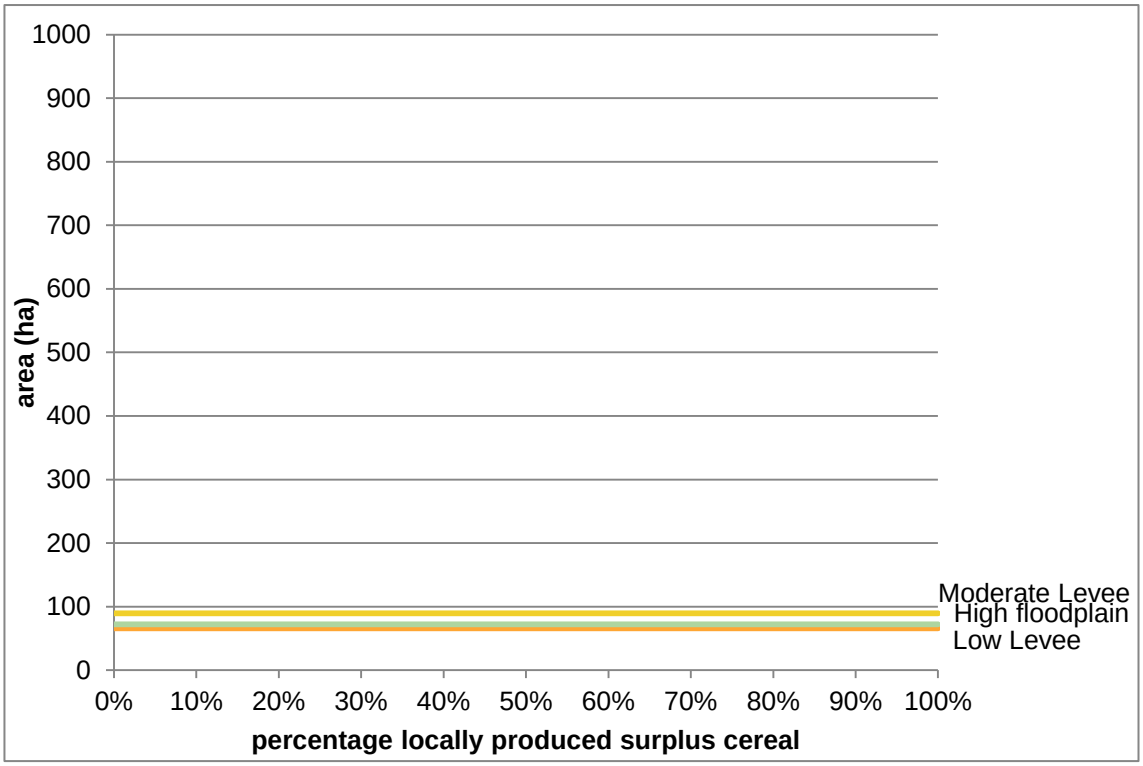
C 3.8: Area pasture per palaeogeographical unit eastern river area AD 140



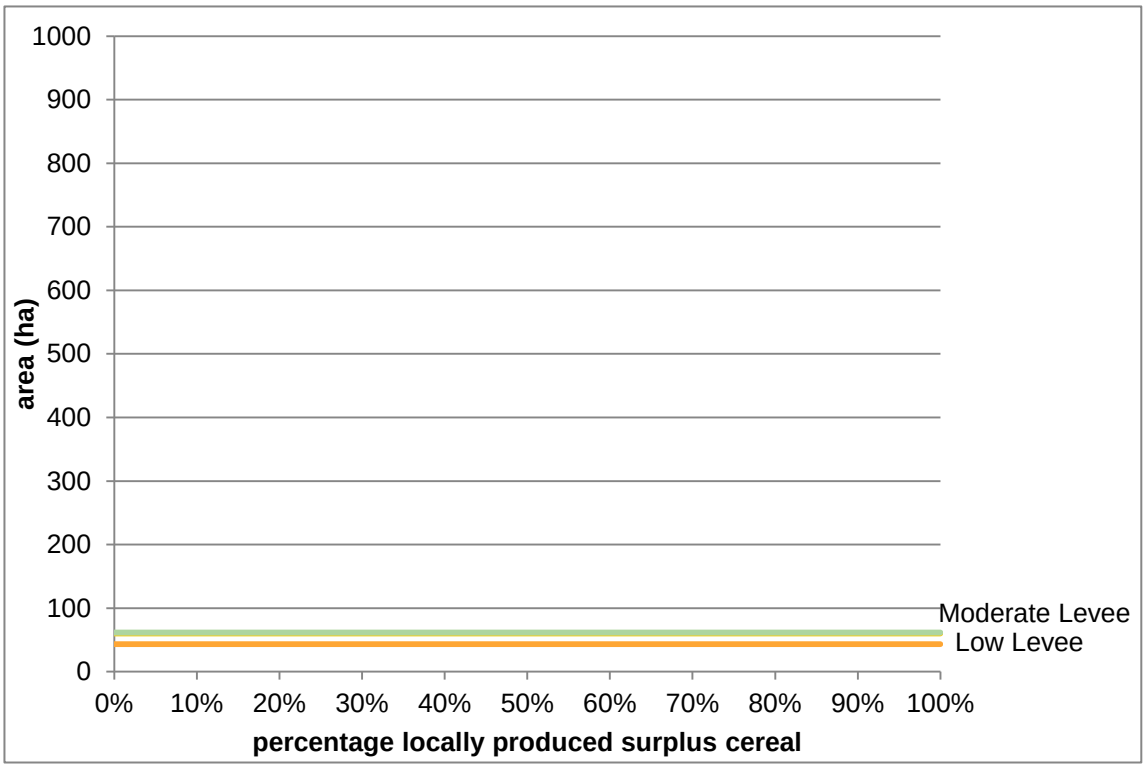
C 3.9: Area meadow per palaeogeographical unit eastern river area AD 140



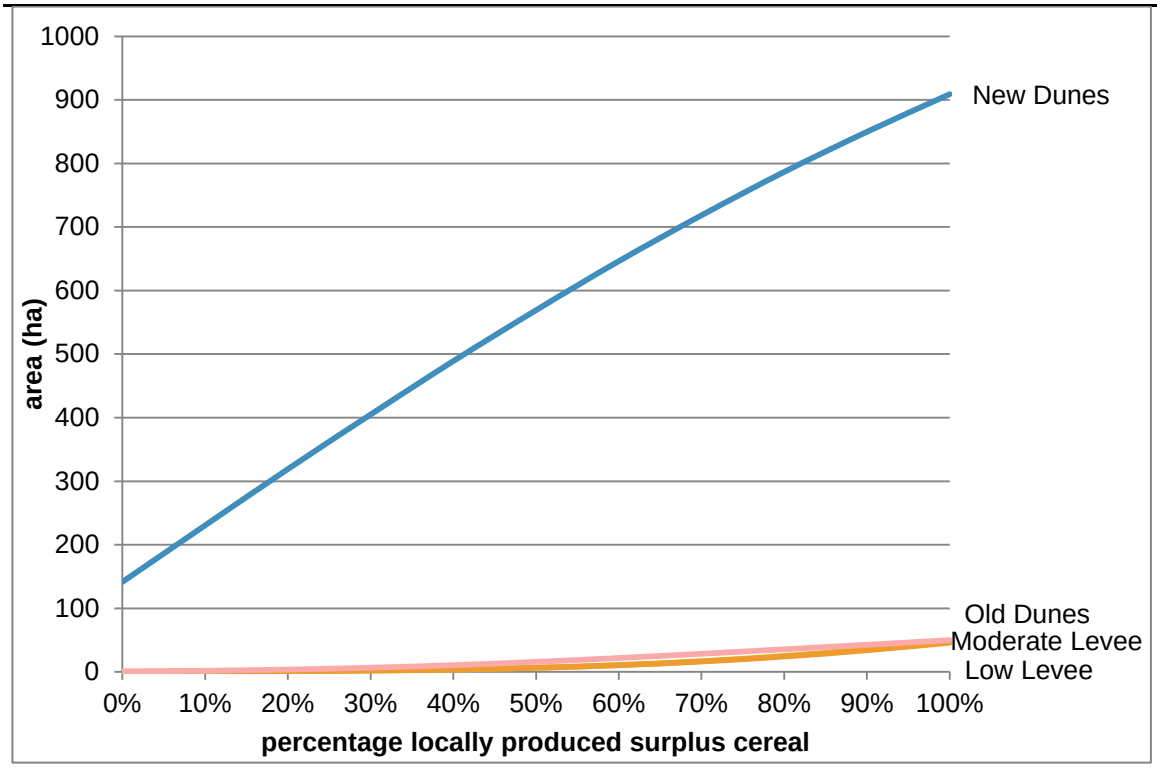
C 3.10: Area arable farming per palaeogeographical unit claim region 1 AD 140



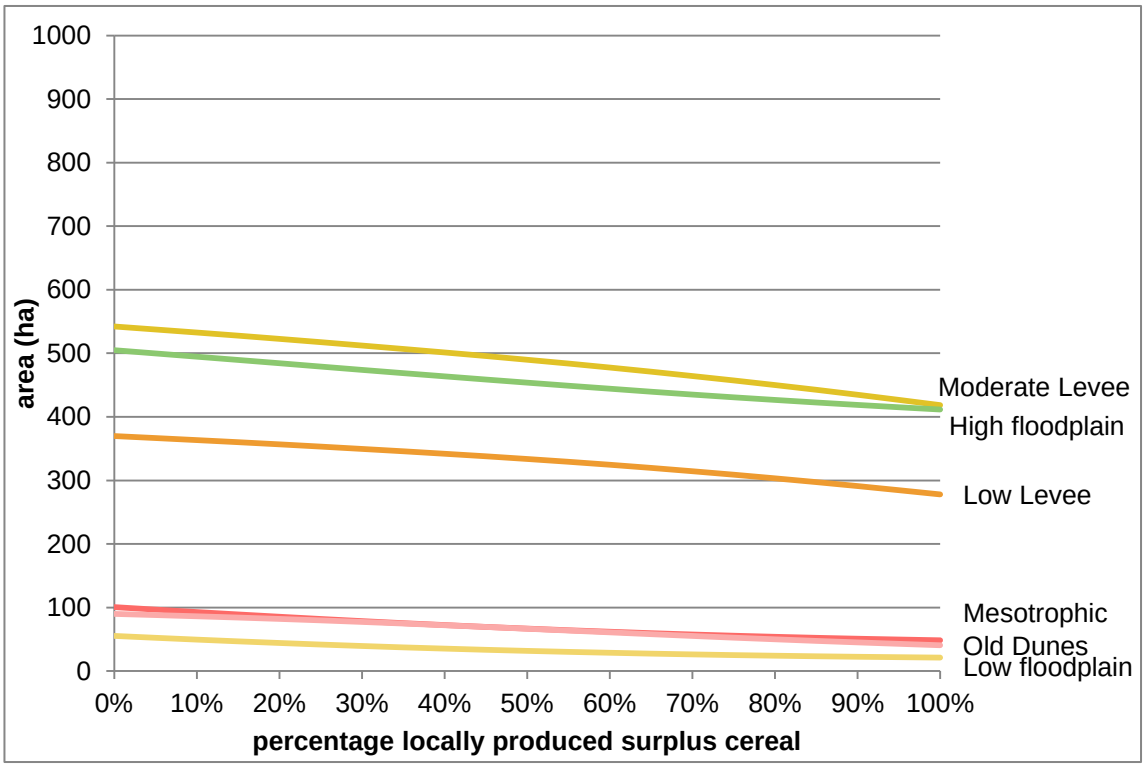
C 3.11: Area pasture per palaeogeographical unit claim region 1 AD 140



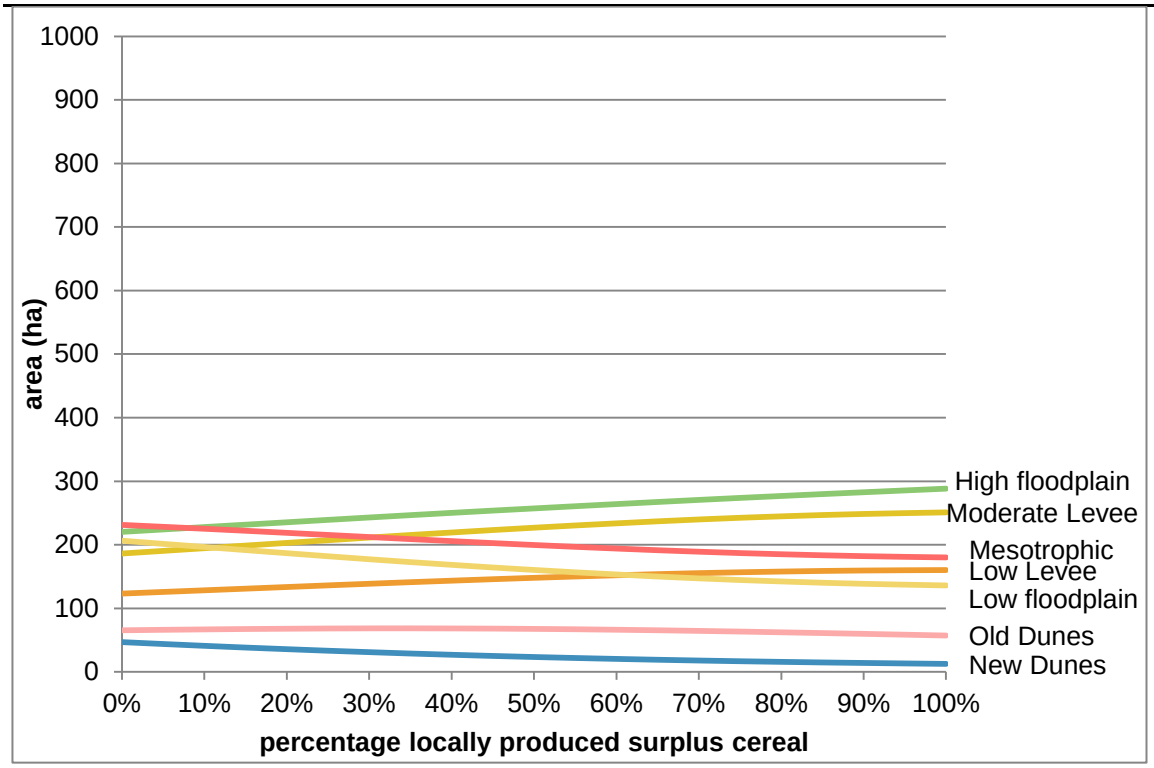
C 3.12: Area meadow per palaeogeographical unit claim region 1 AD 140



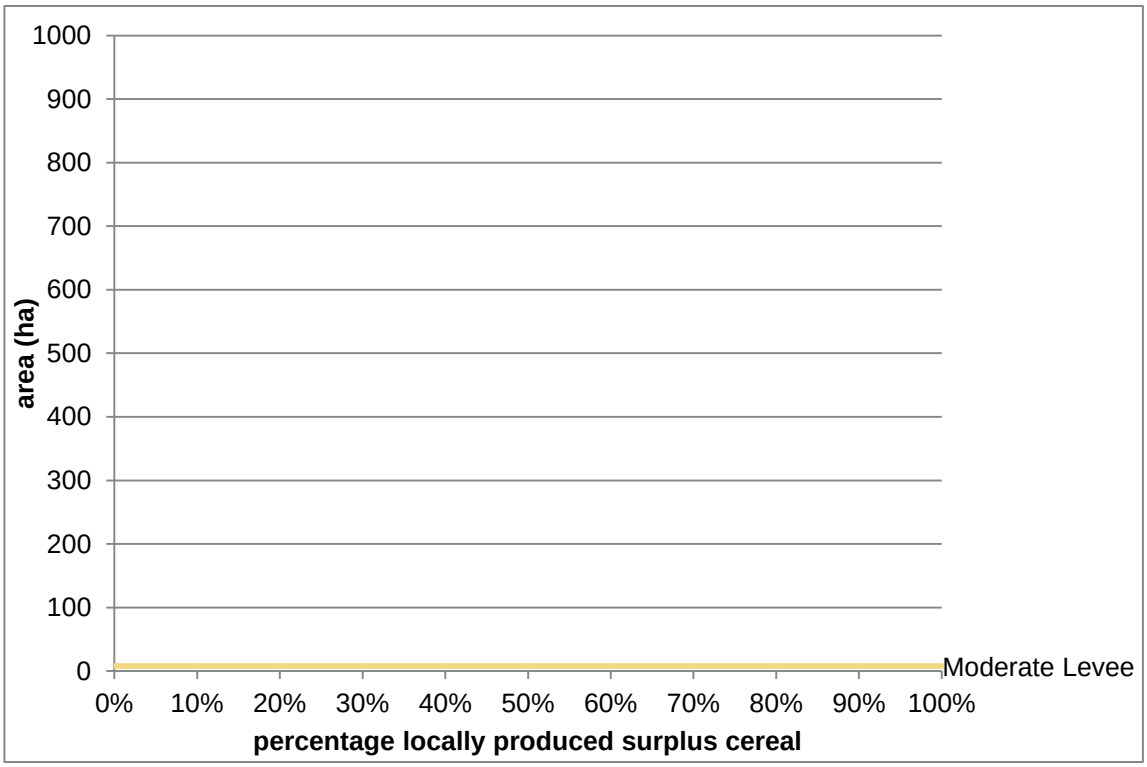
C 3.13: Area arable farming per palaeogeographical unit claim region 2 AD 140



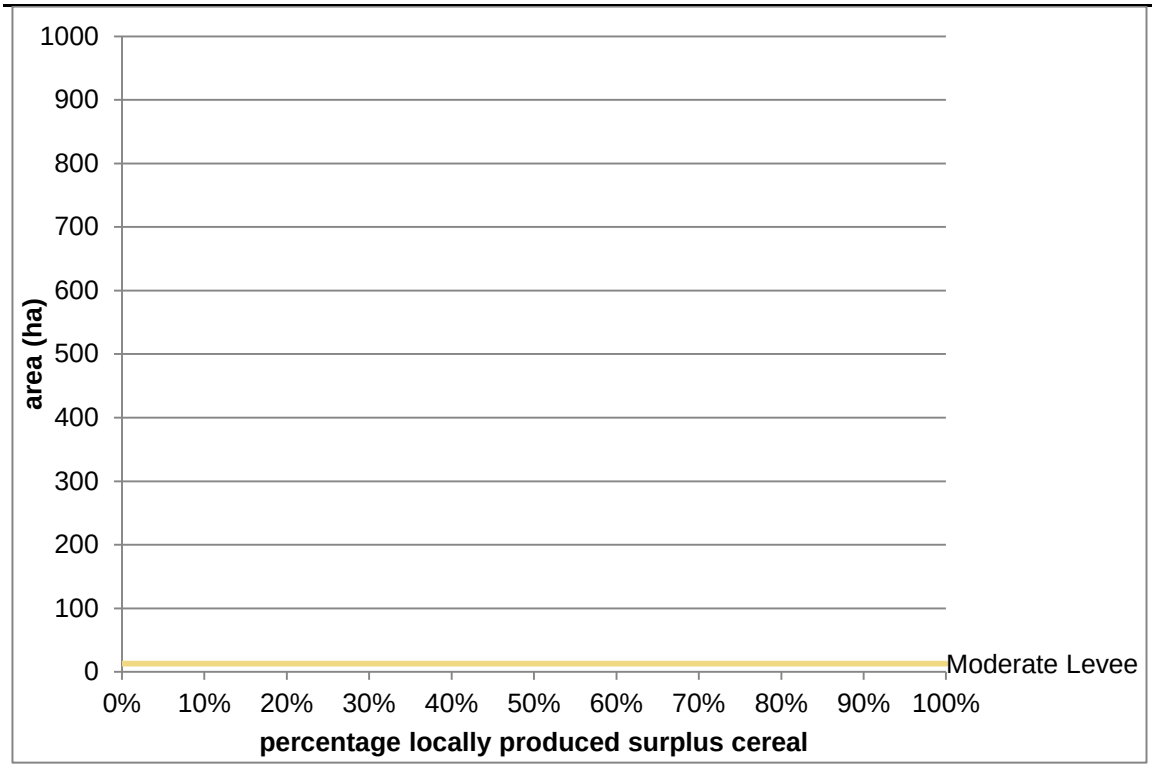
C 3.14: Area pasture per palaeogeographical unit claim region 2 AD 140



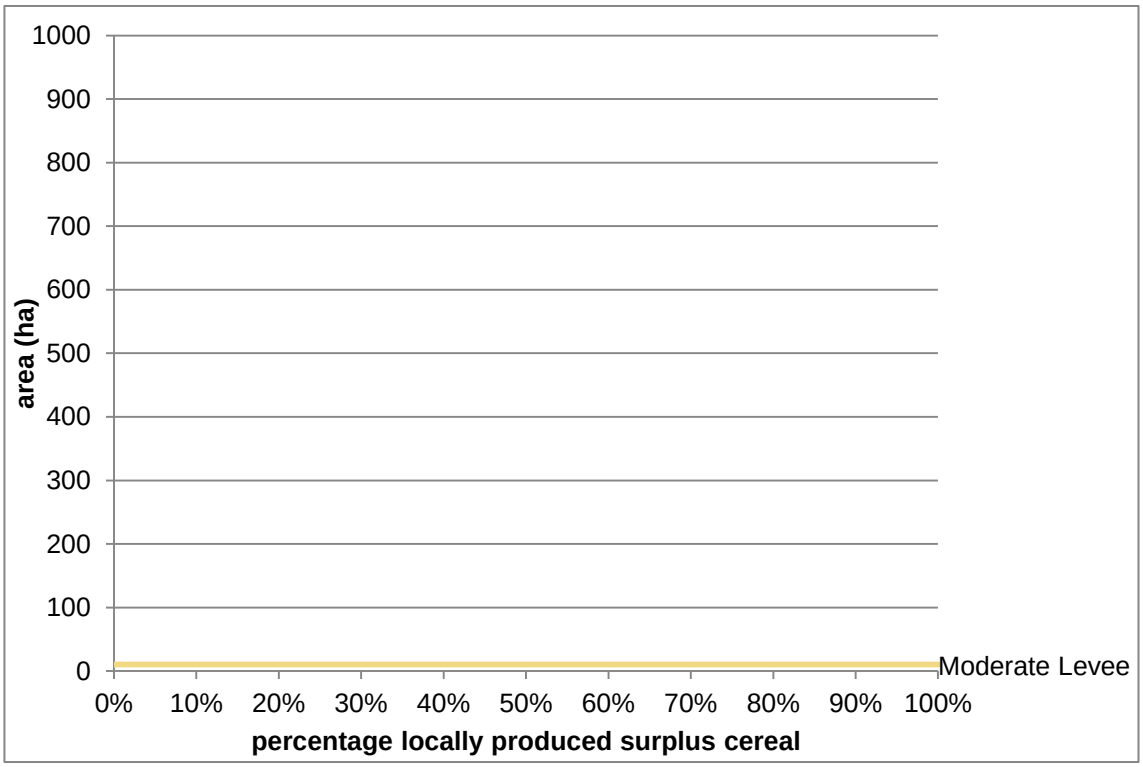
C 3.15: Area meadow per palaeogeographical unit claim region 2 AD 140



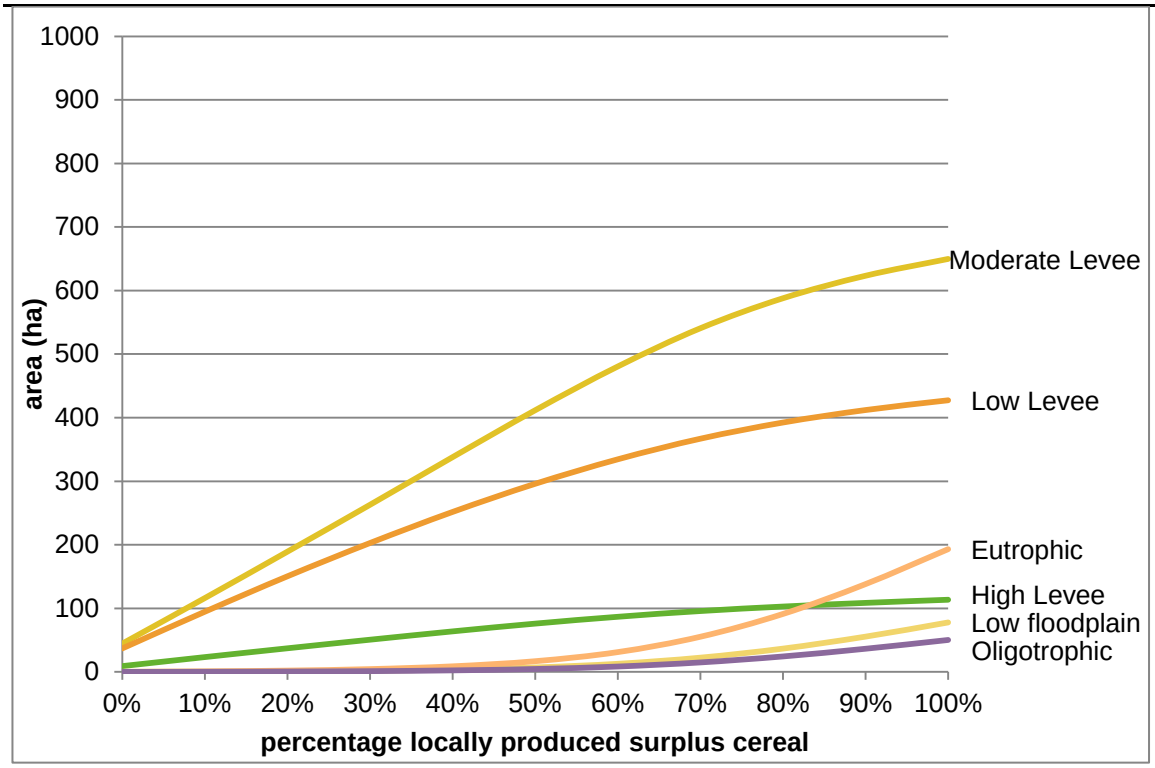
C 3.16: Area arable farming per palaeogeographical unit claim region 3 AD 140



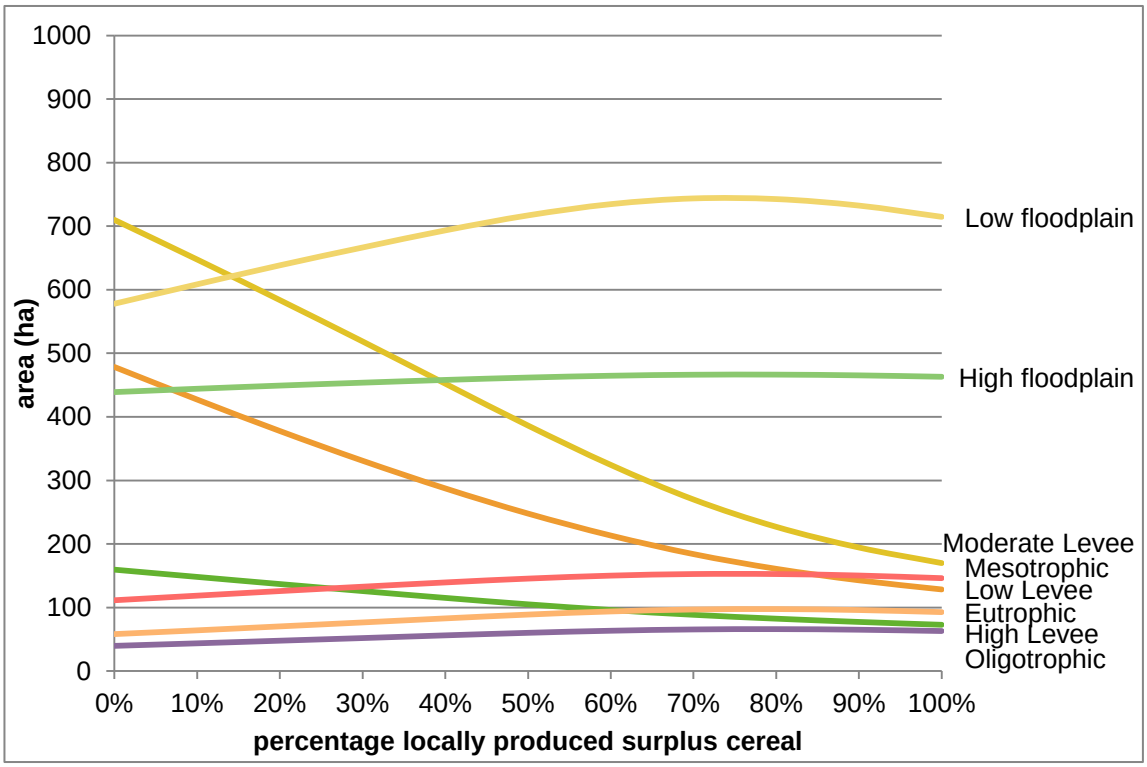
C 3.17: Area pasture per palaeogeographical unit claim region 3 AD 140



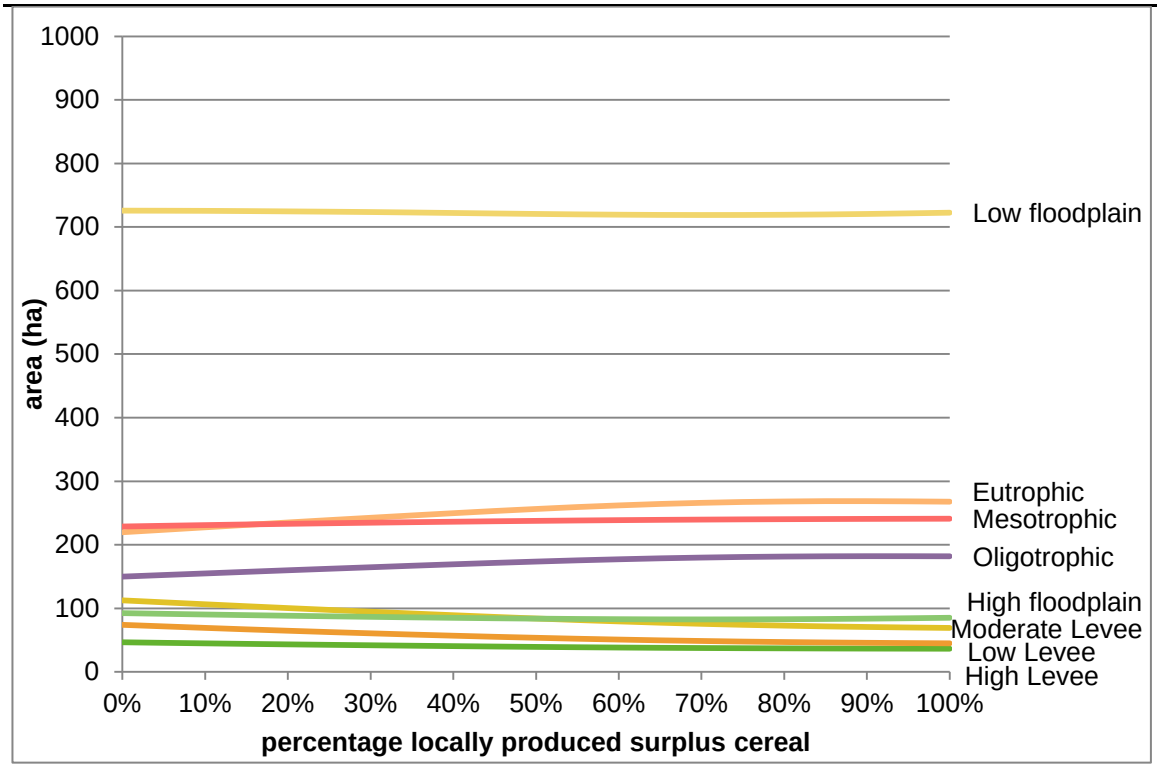
C 3.18: Area meadow per palaeogeographical unit claim region 3 AD 140



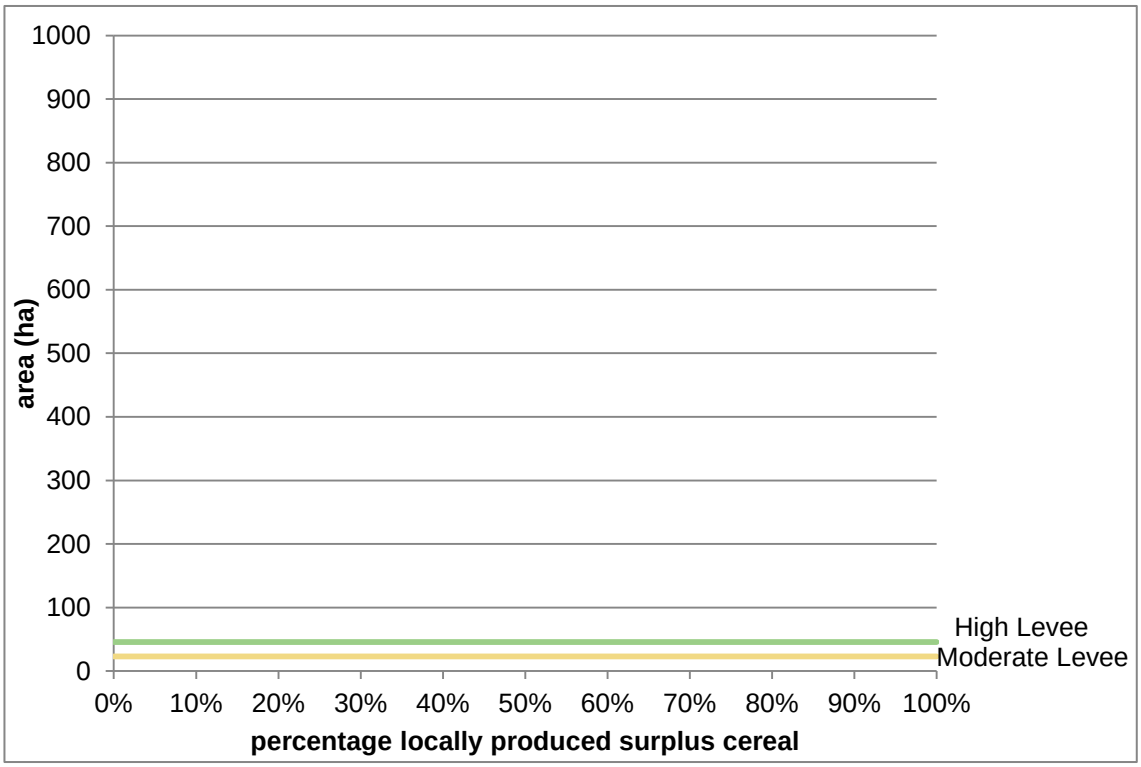
C 3.19: Area arable farming per palaeogeographical unit claim region 4 AD 140



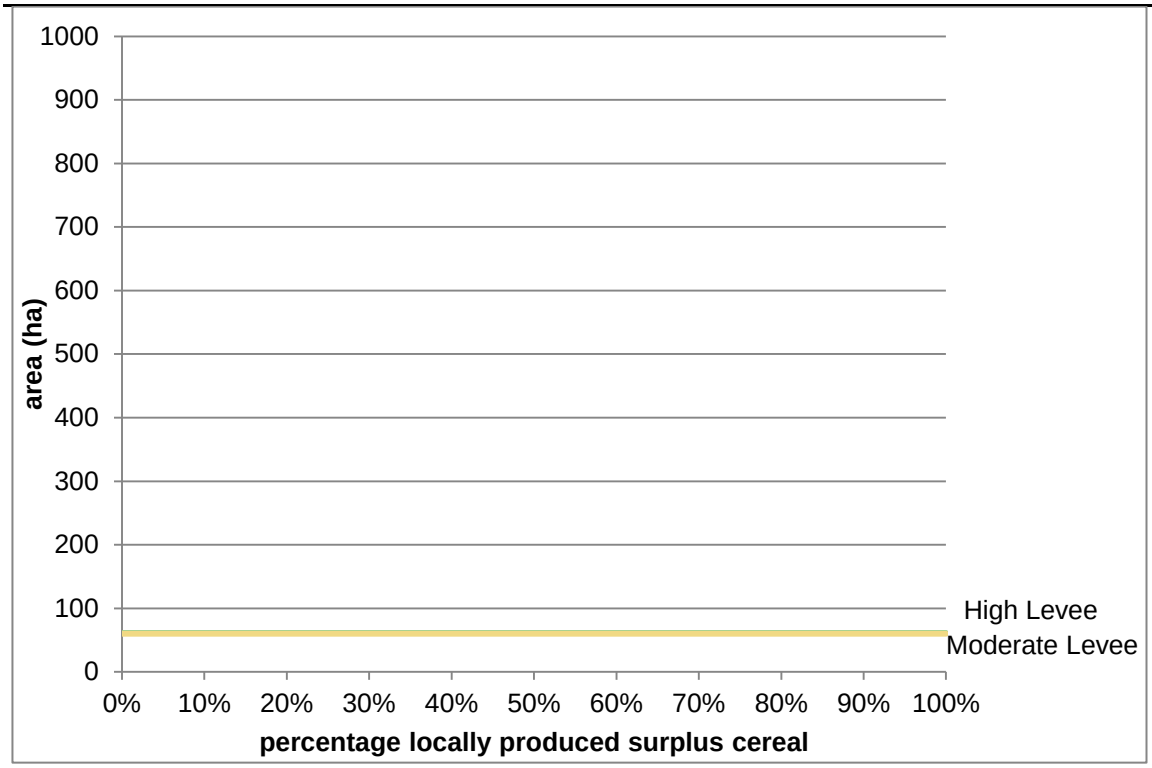
C 3.20: Area pasture per palaeogeographical unit claim region 4 AD 140



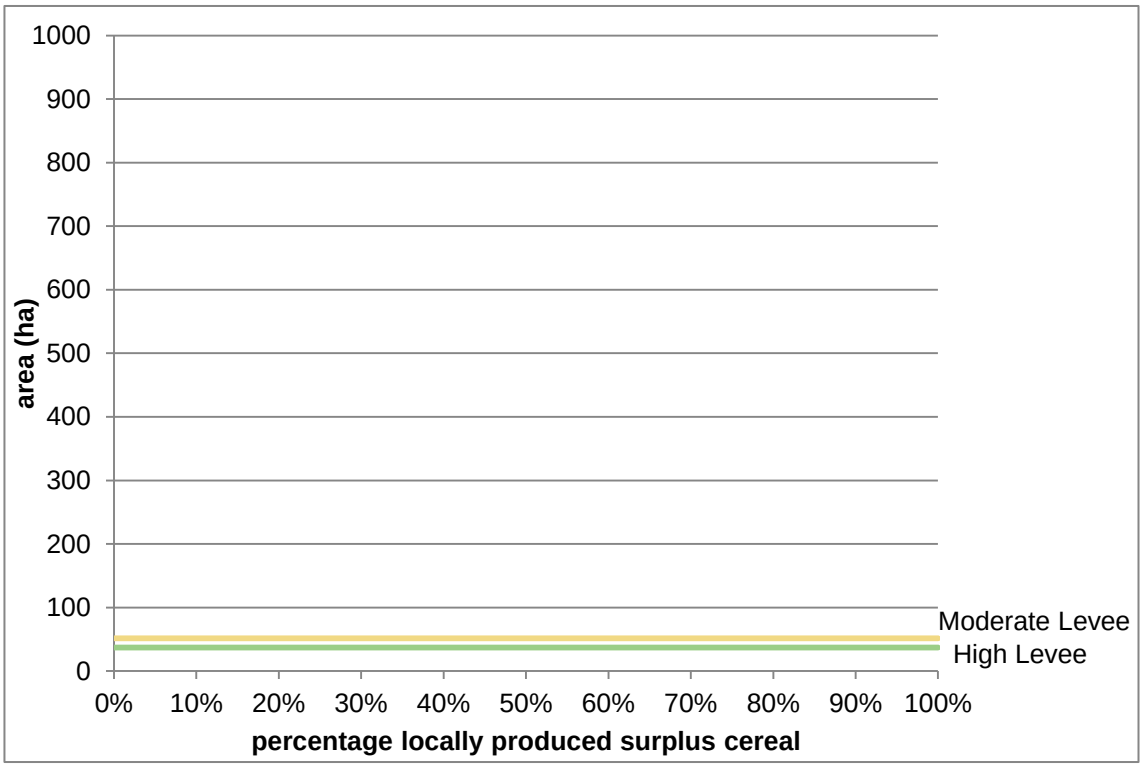
C 3.21: Area meadow per palaeogeographical unit claim region 4 AD 140



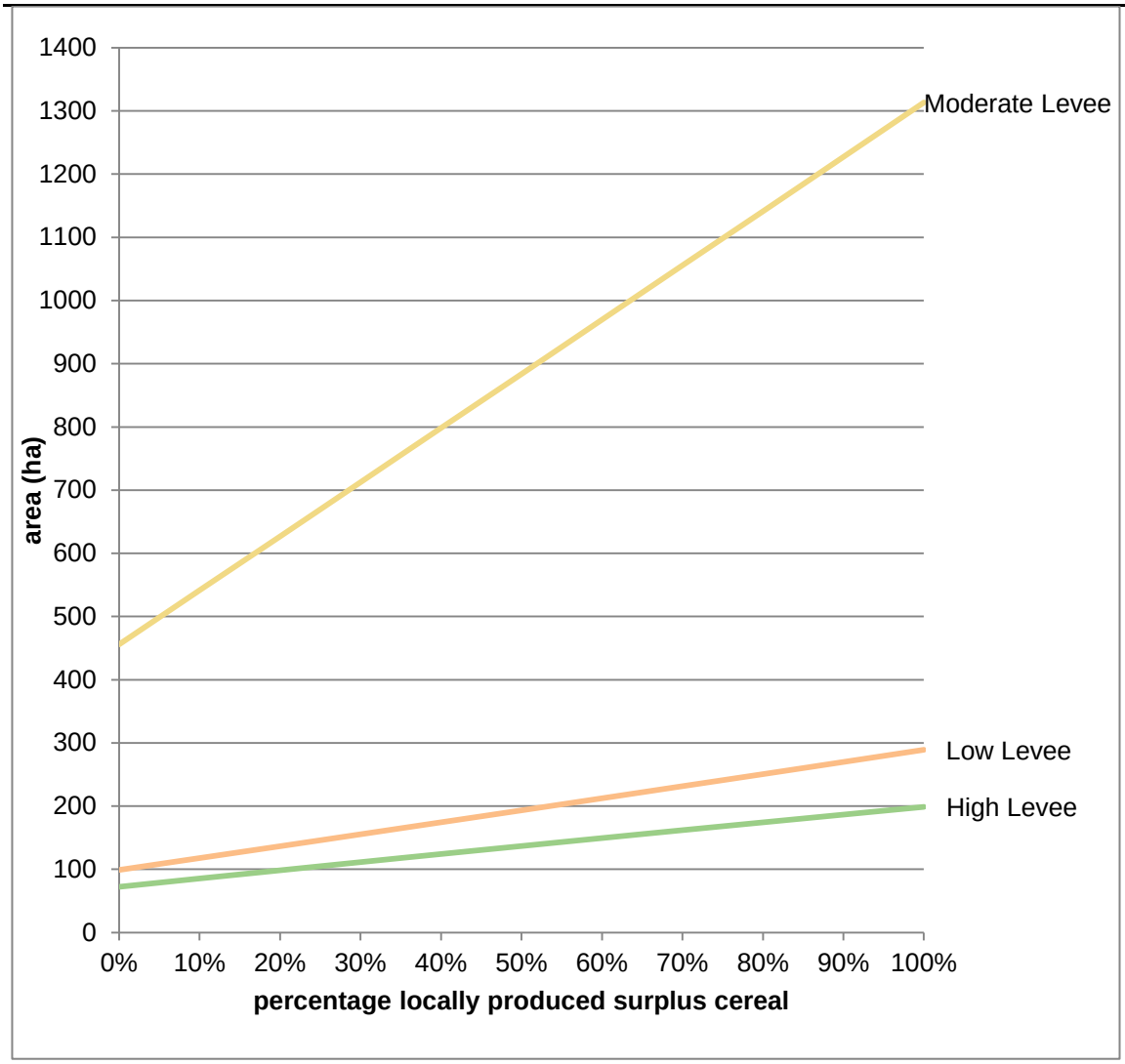
C 3.22: Area arable farming per palaeogeographical unit claim region 5 AD 140



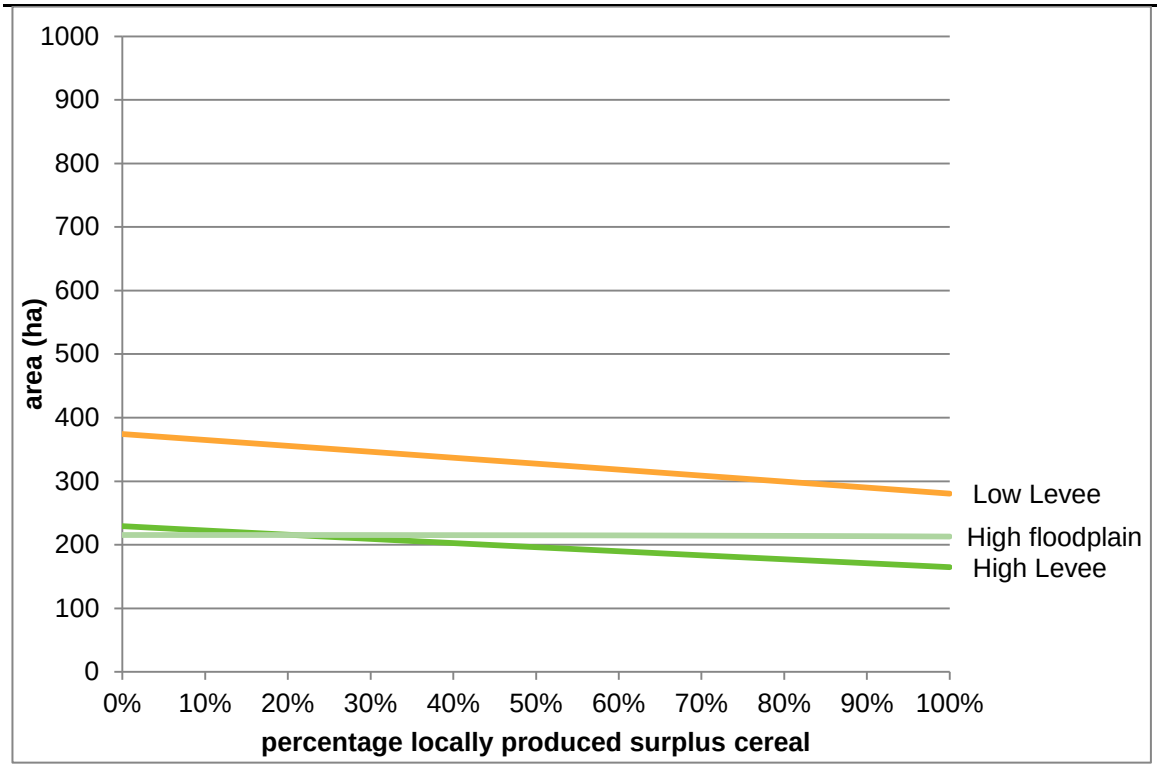
C 3.23: Area pasture per palaeogeographical unit claim region 5 AD 140



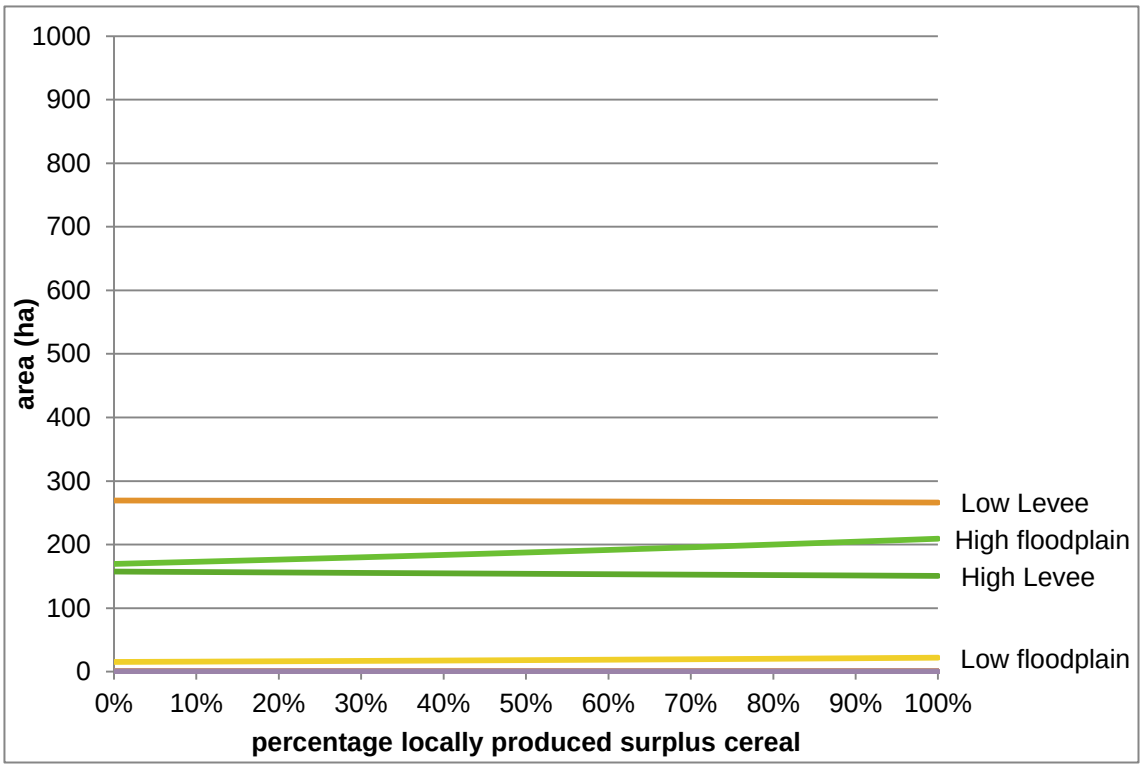
C 3.24: Area meadow per palaeogeographical unit claim region 5 AD 140



C 3.25: Area arable farming per palaeogeographical unit claim region 6 AD 140



C 3.26: Area pasture per palaeogeographical unit claim region 6 AD 140



C 3.27: Area meadow per palaeogeographical unit claim region 6 AD 140