Chapter 5

Simulating past land-use patterns: integrating natural and cultural factors: Article I

Simulating past land use patterns; the impact of the Romans on the Lower-Rhine delta in the first century AD

Abstract
This article introduces a modelling framework to simulate past land-use patterns. The simulation framework can be used to test hypotheses on human interactions with the natural landscape in the past and is able to address the interrelationship between various socio-cultural drivers and the biophysical environmental. The framework simulates land-use patterns based on estimated regional demands for various types of use and local assessments of suitable locations for these uses. 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. The proposed model is used to test the impact of the Roman military and vici inhabitants on the land use for the Lower-Rhine delta. It re-evaluates the hypothesis that 50% of the cereals consumed by the Romans in AD 70 and AD140 were produced locally. The results show that for AD 70 it is likely that the cereals could be produced locally, but for AD 140 this is less probable. The research, furthermore, provides interesting leads that could inform new hypotheses for the region.

Keywords: simulation modelling, land-use change, Roman period, Rhine Delta, spatial modelling

1. Introduction
By the end of the first century BC the military conquest of the Romans had brought their armies to the Lower-Rhine delta in the present-day Netherlands. In the following centuries the river Rhine became the northern Limes or border of the Roman Empire. To protect these borders, but also to regulate trade with the Germanic tribes to the north, the Romans established fortifications alongside the Rhine (Zandstra and Polak, 2012; Polak et al., 2009). The arrival of the Romans in the Lower-Rhine delta is accepted to have had a significant impact on the local inhabitants and their surrounding landscape (Willems, 1986; Bloemers, 1978; Vos, 2009; Kooistra et al., 2013; Van Lanen et al., 2015). Not only have they constructed road networks and a series of forts and watchtowers, they have also impacted the use of the land for the production of food. Previous studies have shown that part of the food was imported and part of it was locally produced (e.g. Groot et al., 2009; Heeren, 2009; Van Es, 1981; Willems, 1986). This meant

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8 This chapter is submitted as De Kleijn, M., Beijaard, F., Koomen, E., Van Lanen, R.J. Simulating past land use patterns; the impact of the Romans on the Lower-Rhine delta in the first century AD.
that farmers, who had until then been mainly producing for themselves, had to increase their production to generate sufficient surplus to meet the demands of the Roman army. However, relatively little is known on the extent of this local production potential and regional-scale impacts on the landscape. The scarce and isolated character of the available archaeological evidence makes it problematic to estimate the extent of local food production.

Van Dinter et al. (2014) and Kooistra et al. (2013) are the first to attempt to systematically research the land-use impact of the Roman military and vici inhabitants in the Lower Rhine delta. They analysed whether the local population could supply the Roman army in AD 70 and AD 140 in a diptych of articles. For this they have, through extensive calculations, estimated the required food and wood and translated these demands into hectares of land. By confronting these with available land resources for three sub-regions in the Lower Rhine delta (figure 1), they have reconstructed the impact of the Roman presence on the land use.
and concluded that the rural population and the landscape could meet the reconstructed additional demand for food.

In this article we explore the impact of Romans on the land use in the Lower Rhine by introducing a spatial simulation modelling framework that integrates economic and demographic factors with physical-environmental factors to simulate past land use on a regional level. For this we have re-examined the study of Van Dinter et al. which we extended with spatial interactions and economic competition. More specifically we have looked at the regional potential for food production.

Van Dinter et al. assume that 50% of the cereals consumed by the Romans was locally produced and that the remaining half was imported. These shares are rough estimates that are not supported with other sources. In order to understand whether this percentage is feasible, we formulate a set of scenarios with varying percentages of assumed local cereal production. Through these scenarios we aim to generate an understanding on the maximum capabilities of the landscape and labour force to meet the demand for food. We analyse which share of the Roman food demand may have been produced locally and thus test the feasibility of the 50% proposed by Van Dinter and colleagues.

The spatial simulation modelling framework that is introduced in this article and that we refer to as the Past Land Use Scanner (PLUS), integrates economic and demographic factors with physical-environmental factors to simulate past land use on a regional level. The modelling framework has its roots in economic theory and simulates the allocation of land-use change by mimicking the competition for land among different types of use. The modelling framework has originally been developed to simulate land-use development in the near future and is known as Land Use Scanner (Hilferink and Rietveld, 1999; Koomen and Borsboom-van Beurden, 2011). For the present study this modelling framework has been rethought and operationalized in order to simulate past land-use change. Land-use simulation is based on estimated regional demands for various land-use types combined with local assessments of suitable locations for these uses. The regional demands are based on a combination of economic and demographic scenarios. The local suitability for certain land-use types is based on distance relations, physical characteristics of the landscape, limitations resulting from military and political processes and available techniques to work the lands. To balance the demand for land of different types of use with the supply of suitable locations a logit-type approach is applied.

Within simulation models the real world is translated into a collection of variables linked by mathematical or logical conditions (Lake, 2014). As identified by Lake (2014) one of the major challenges is the integration of sociological factors. Especially on site catchment and household-level various researchers have effectively attempted to integrate complex cultural and sociological factors (e.g. Van der Leeuw and McGlade, 1997; Goodchild and Witcher, 2010; Whitley et al., 2010; Danielisová et al., 2015). Besides some remarkable examples (e.g. Kohler et al., 2000; Kohler and Varien, 2012), the integration of sociological factors in simulation models that perform on a larger, regional area are scarce. This article aims to contribute to this research field by presenting a model that allows integrating socio-
cultural and natural factors at a regional scale. The model can be used to simulate the
interrelationships between socio-cultural and bio-physical factors and test hypotheses on
human interactions with the natural landscape in the past.

The article is structured as follows. First the simulation modelling framework is described in
section 2. The configuration and methodological steps to operationalise the simulation
model for the Lower-Rhine delta in the first two centuries is presented in section 3. In
section 4 the main results of the simulation model are presented, followed by a discussion
in section 5 and a concluding section 6. Section 7 provides an outlook for future research.

2. The Past Land Use Scanner Simulation framework
2.1. Conceptualizing the land-use simulation framework
At the core of the PLUS modelling framework a distinction is made between regional
demand for land for different types of use and a local definition of suitability for these uses.
To understand how demand and suitability are determined and translated into different
scenarios, several main driving forces are distinguished. For this we propose a conceptual
framework that is based on Bürgi et al. (2004) and Diogo et al. (2015) who distinguish the
following interrelated components which we translated to past situations:

- **economic factors**, provide the demand for goods (e.g. food, wood) based on
  estimates of the demographic characteristics of rural settlements and larger
  entities, such as cities or military units for which a local production surplus is
  required.
- **socio-cultural factors**, such as diet, traditions and religion that can limit or
  stimulate areas to be used or result in modification of a demand.
- **technological factors**, relating to, for example, tools or strategies (e.g. crop
  rotation systems) that allow different types of terrain and (marginal) land to be
  cultivated.
- **spatial and environmental factors** that we separate into spatial relationships
  between entities in the region (e.g. site catchment parameters as described by
  Higgs and Vita-Finzi (1972) and travel time through the landscape such as
  proposed by Groenhuijzen and Verhagen (2015) and physical environment factors
  such as soil type, geomorphology, wetness etc..
- **political factors**, for example territorial restrictions and trade agreements.

While regional land demand is expected to be mainly dependent on economic and socio-
cultural factors, local suitability is assumed to be mostly influenced by technological,
spatial, environmental and political factors. An important aspect in defining local suitability
is the balancing of those factors. To determine which factors are more influential, a relative
weighing of the different data layers describing these factors is necessary. There are several
examples in which such weighing methods in the archaeological domain has been applied
(Verhagen et al., 1999; Robb and Van Hove, 2003; Kohler et al., 2007; Whitley, et al., 2010;
De Cet et al., 2015).
The model can integrate socio-cultural factors that influence land-use patterns by integrating thematic layers related to the assumed suitability of locations. For past situations, spatially explicit information is often lacking on the spatial implications of beliefs, customs and traditions that may have limited local people in the use of their landscape (Lake, 2014). This void may partially be filled by integrating outcomes of small-scale simulation modelling studies and translating these into multiple, regional-level scenarios. In the context of this article we mainly focussed on including economic and agricultural production oriented aspects and understanding how these would reflect on regional simulations of land use.

The combination of local suitability and regional demand form the input for the allocation procedure which is based on McFadden’s discrete choice theory (see figure 2 for a schematic overview). The probability that an actor chooses a certain alternative is dependent on the utility of that specific alternative in relation to the total utility of all alternatives (McFadden, 1978). Translating this into land use, the model bases the probability of occurrence for a certain land-use type at a location on the suitability of that location for that type of use in relation to the total suitability of all possible uses at that location (Hilferink and Rietveld, 1999). Recent validation efforts have indicated that current, observed land-use patterns can be reproduced by this modelling approach if sufficient information on regional demand and local suitability is available (Loonen and Koomen, 2009; Koomen et al., 2015; Diogo et al., 2015).

Figure 2. Schematic overview of conceptual modelling framework (based on Bürgi et al. (2004) and Diogo et al., 2015)
2.2. Operationalizing the simulation framework
To operationalize the PLUS framework, software GeoDMS has been used (www.objectvision.nl/geodms). This specialized free and open source GIS modelling software is highly efficient for raster based calculations and allows for the efficient and fast simulation of multiple scenarios at a high resolution (Lavalle et al., 2011).

The allocation process of the various land-use types is operationalized using the following formulation (see Koomen et al., 2011):

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

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 demand;
- \( b_c \) 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 neighbourhood relations of which the importance of the suitability value can be set by adjusting a scaling parameter.

The values of \( a_j \) are determined in an iterative approach that simulates a competitive bidding process between different types of users for their preferred type of land use. The model assumes that every type of user will attempt to get their desired amount of land – the demand – allocated at their preferred locations but can be outbid by another user if the relative suitability for that land-use type is higher at that specific location. Allocation follows suitability values but is constrained by overall demand, so little to no land will be allocated to fairly suitable locations if more suitable alternatives exist. Moreover, land-use types may not be allocated to their most suitable locations if these locations are more suitable for other types of use or if very few suitable alternatives exist for these other types of use.

3. Model implementation for Lower-Rhine delta
3.1. The land-use system
The PLUS framework is set up to model multiple land-use scenarios for AD 70 and AD 140. Within PLUS we simulate three types of land use related to the production of food: arable farming, meadow and pasture (table 1). In addition the model includes woodland, water, residential and military. Woodland is approached as a passive land-use type, allowing it to be replaced by the food producing land-use types. We refrained from simulating changes in woodland coverage as we lacked accurate data and reconstructions on the spatial distribution and composition of woodland. The other land-use types are considered to be exogenous in the model, meaning that they are approached as static elements in the simulation process.
3.2. Suitability for land

The local suitability for endogenous land-use types in PLUS is determined by physical characteristics, spatial relationships and political and military aspects. For the physical environment characteristics, the cultivation options per land-use type depend on the available technologies and land-use management strategies combined with the physical characteristics of the landscape. For the physical landscape the palaeo geographical reconstruction for AD 100, developed by Groenhuijzen 2015 based on Cohen et al., (2009), Vos and De Vries (2013), Van Dinter et al., (2014) is used. This reconstruction is valid for both AD 70 and AD 140. To determine the suitability of the various palaeo geographical units for different types of land use we apply a relative scoring method developed in collaboration with Marjolein Gouw-Bouman (palaeo-ecologist, Utrecht University) that quantifies the land use potential of different palaeogeographical units. Every landscape unit received a suitability score on a 0-5 scale with 0 representing unsuitable and 5 representing very suitable (see Appendix A).

<table>
<thead>
<tr>
<th>Land-use type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>arable farming</td>
<td>This land-use type produces crops and cereals for food.</td>
</tr>
<tr>
<td>pasture</td>
<td>Pasture is used as grazing land for cattle to produce food (i.e. meat and dairy products).</td>
</tr>
<tr>
<td>meadow</td>
<td>Meadows are used to harvest hay as food for cattle during winter.</td>
</tr>
</tbody>
</table>

A second aspect in the definition of local suitability is the inclusion of spatial relationships. We apply site catchment theory (Higgs and Vita-Finzi, 1972) to obtain the area people could reach within one hour walking time from a settlement. The friction model of Groenhuijzen and Verhagen (2015) was applied to incorporate the effect of physical characteristics of the landscape on walking speed. In line with the seminal work of Von Thünen (1842) on the pre-industrial spatial configuration of agricultural areas we assumed the efforts related to travelling to the fields and transporting produce to influence local suitability for the different types of agricultural land use. Arable farming requires most effort in care for crops, harvesting and transporting the raw products to the markets and is thus assumed to be located closest to the settlements followed by pasture and meadows.

The different components comprising suitability are added up after applying weights reflecting their assumed importance. This deductive approach was informed by relative scores that are presented in Appendix A. For instance, for arable farming we expect the distance to settlements to be more important than physical suitability. Based on site catchment theory we assume that people would not have been willing to walk more than one hour to their lands and would at least have a certain minimum suitable land around their settlement. We have therefore configured the relative attractiveness of arable farming within half an hour walking distance and one hour walking distance to be higher...
than the physical suitability. To avoid unsuitable areas near to settlement to be used for arable farming, we have included the condition that excludes all locations with a physical suitability score of 0. The final suitability for the various land-use types is thus a weighted sum of all suitability factors reflecting an integration of the knowledge on the different forces that drive land-use choices that is available amongst different groups of experts (i.e. Groenhuijzen and Verhagen for distance relations and Marjolein Gouw-Bouman for the physical suitability). Appendix A describes the exact suitability definitions for the different types of land use.

3.2. Demand for land and required labour force
To study the impact of different assumptions on the share of food that could be produced locally we formulated several scenarios and applied our modelling framework to simulate the corresponding landscape. By doing so, we test the validity of their hypothesis and explore the limits of the landscape to produce the required amounts of food. In addition, we check whether this amount of food can be produced by the workforce available in the settlements.

For each time slice we defined eleven scenarios in which we vary the amount of the local food surplus as share of the total amount of required food in the region in steps of 10 from 0 to 100%. To estimate the total land area needed to produce these amounts of food per sub region (i.e. western coastal region, central peat area and eastern river area) we have used an updated archaeological dataset in which locations of known archaeological sites and find spots from the Archaeological Information System of the Netherlands (Roorda and Wiemer, 1992; Wiemer, 2002) have been re-looked at resulting in cleaned dataset minimizing errors such as multiple points of one site. The demand for food has been calculated based on the the assumptions on daily diets and typical sizes of settlements, forts and vici as reported by Van Dinter and colleagues (2014). To translate the food demand into a demand for land we applied the food production per hectare estimates by Van Dinter et al. (2014) (see Appendix B for the calculations). In addition they calculated that rural settlements on average could manage 12.8 ha of arable farming. Assuming that a two-field rotation system in which half of the land would be fallow was applied, this equals a maximum area of 25.6 ha each settlement could manage (see table 2 for the calculated labour force per region and time slice). Additionally, for AD 140 the sub regions have been split in a northern and southern part, following the hypothesis that the Roman army and vici only obtained their resources south of the border (Kooistra 2009; Van Dinter et al. 2014).
### Table 2. Maximum capacity of arable land that the labour force from the rural settlements can handle

<table>
<thead>
<tr>
<th>Region</th>
<th>AD 70</th>
<th>AD 140</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>western coastal region</td>
<td>central peat region</td>
<td>eastern river region</td>
<td>western coastal region</td>
<td>central peat region</td>
<td>eastern river region</td>
</tr>
<tr>
<td>Number of rural settlements</td>
<td>39</td>
<td>9</td>
<td>115</td>
<td>48</td>
<td>16</td>
<td>132</td>
</tr>
<tr>
<td>Maximum capacity of arable land for settlements (ha)</td>
<td>998</td>
<td>230</td>
<td>2944</td>
<td>1229</td>
<td>410</td>
<td>3379</td>
</tr>
</tbody>
</table>

#### 4. Results

Figure 3 shows the predominant land-use types for the different food producing lands for AD 70 and AD 140 for 0%, 50% and 100% local production for the Roman military and vici inhabitants. In addition to the spatial representations we have performed an overlay analysis which allowed us to understand on which palaeogeographical unit the different food producing lands have been allocated. Figure 4 shows the results of this overlay analysis and includes the total land demand and the capacity of the labour force. Looking at these results the following observation on the simulation modelling outcome can be made (see appendix C for all the raw results, modelling software and configuration).

**Arable farming**

Except for the eastern river area, the demand for arable farming can in every scenario be met for AD 70. For the eastern river area the demand can almost be met. This indicates that the pressure for land is already very high for that region in that period. For AD 140 the demand for arable farming can in most scenarios not be realised. The simulation outcomes show that even at low percentages of local surplus production the land is the limiting factor to supply sufficient surplus.

Looking at the variation of the allocated uses of land by confronting it with the palaeogeographical unit it is simulated on it can be observed that for the western coastal region arable farming is placed in less suitable dune areas to fulfil the demand for food. This result suggests that we should carefully reassess archaeological and palaeo-vegetation studies for these areas or reconsider the assumptions in relation to the share of locally produced food. For the other regions arable land is most commonly allocated on the moderate levees, followed by the high and low levees.

Considering the labour force we can observe that for the western coastal region and eastern river area this is not a limiting factor. For the central peat area, the labour force seems to be a limiting factor after 30% of local surplus production. This accounts both for AD 70 and AD 140.

**Pasture**

For pasture a similar trend is noted as for arable farming when comparing AD 70 and AD 140. For AD 70 the demand can be met for almost every scenario, for AD 140 it cannot. The amount of pasture land decreases when the share of food surplus production increases.
Figure 3. Predominant land-use types for different scenarios for local production of cereal surplus for the Roman military and vici inhabitants for AD 70 and AD 140
Figure 4. Realisation of land use according to different local production scenarios (in percentages) for AD 70 and AD 140 for the different sub regions.
This is explained by the increase of required fallow land in the two-field rotation system as part of arable farming. Since fallow arable farming is assumed to be used as pasture as well, the areas for pasture do officially not decrease but are “hidden” under arable farmlands. Focussing at the variation in palaeogeography of pasture we observe that an increasing demand for arable farming forces pasture to less suitable areas, such as high floodplains. This is especially visible in the western coastal region. For other the central peat region at around 50% surplus production in AD 70, pasture is increasingly more found on floodplains than on the lower levees. In AD 140 the allocation of pasture on levees decreases drastically in favour of low and high floodplains. This strong competition for land 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.

**Meadow**

Like arable farming and pasture, also for meadow account that the AD 70 scenarios are able to realise the demand for land. For AD 140 the pressure is for land is too high and does not allow allocating all required land. Concentrating on the variation of meadows we observe that for AD 70 in the central peat area meadows are pushed to the less suitable low floodplains. In AD 140 a shift can be noted for the western coastal area. At 10% cereal surplus production high floodplains, moderate levees and mesotrophic peat areas are the most cultivated palaeogeographical units on which meadow appears. Increasing the demand for AD 140 forces meadows even further towards eutrophic and mesotrophic peat areas.

5. Interpretation of results

Based on the results we can conclude that the hypothesis of Van Dinter et al (2014) that 50% of the cereal for the Roman military and vici inhabitants was produced locally seems to hold for AD 70. For AD 140 it is appears that their hypothesis does not. For this period the results point towards rejecting and re-evaluating the hypothesis of Van Dinter and colleagues.

Considering the availability of suitable land for AD 70 a local production would have been possible in the western coastal area and central peat area even when a much higher demand would be required. For the eastern river area in AD 70 there seems to be sufficient land, however it must be noted that it is pushed to its limits. For AD 140 it is clear that the region does not contain sufficient useful land to meet the demand for the various food producing land-use types. The results show that the area does not have sufficient suitable space for the food producing land-use types. There is not enough suitable land to meet the demand in almost every scenario.

For both AD 70 and AD 140 the labour force does not seem to be the limiting factor except in the central peat area. However, it must be noted that the adjacent regions do indicate to have had have plenty of labour force available, making it possible that people from that region might have helped them on for instance labour intensive periods.
Besides improving the understanding whether or not the landscape could provide enough suitable food producing lands and if the settlements have sufficient people to work the lands, this study also show patterns in land-use. This allows the exploration of the spatial distribution of various land-use types over different landscape types and palaeogeographical units. Doing so the simulation has revealed possible land-use patterns that are useful to indicate areas with potential archaeological value that have hitherto been under explored.

For arable farming in the western coastal areas it can be noted that it is mostly allocated on dune areas knowing that these soils are less fertile compared to other palaeogeographical units (see Appendix A). It is therefore fair to assume that people were also relying on other food producing activities like fishing; however exact figures on the amount of food this would produce are difficult to reconstruct. For meadow and pasture in the central peat area it can be noted that the model simulates significant parts to the less suitable low floodplains and mesotrophic peat areas. Identifying this could lead to reformulate the hypothesis of pasture and meadow in the area. The results could indicate for alternative economic activities or specialisation.

Inherent to any spatial modelling approach the PLUS has also simplified reality. In case of arable farming the simulation modelling framework is configured to simulate this land-use type to an area within one hour walking distance from a settlement. This rule has a significant impact on the results. It might have been that people were willing to travel longer to their lands or that arable farming was more systematically organized. Here the results thus provide interesting leads to formulate hypotheses considering the land organisation. Furthermore this study has not differentiated different types of settlements. The analysis could greatly benefit from having more detailed data on estimated sizes of individual settlements to provide more variation in associated land-use patterns and available workforce. Another aspect is that the settlements integrated in the model are all known sites from archaeological research activities (i.e. excavations, surveys and historical sources). However, obviously not all settlements are found or archaeologically traceable. Bult (1983) and Deeben et al. (2006) for instance estimate that 50% of the sites have not yet been found. For the central peat area in AD 70 this could mean that the labour force was not the limiting factor to produce sufficient food. For the eastern river area many more settlements would have an even more dramatic effect on the available land, which is already relatively scarce. In addition to these limitations, the simulation modelling is likely to suffer from edge effects. Settlements to the boarders of the sub-regions would have suitable land for use available nearby which are currently not available due to the fixed boarder.

6. Conclusions
The main contribution of this article is that is demonstrates that the PLUS can be used as a research instrument to test hypotheses and inform directions of further research. Especially the land-use patterns that the PLUS produces in for example the west where dunes seems to be fully cultivated for arable farming and the central peat area where
pasture must have been on peaty soils offer interesting insights that inform hypotheses for the use of the land. In addition the site catchment constraint of one hour walking distance to arable farming can be reconsidered and extended to for instance 1.5 hour walking distance. This however would for instance imply a more organized land system and cooperation, thus offering a ground for formulating different hypotheses considering land organisation.

In order to deal with uncertainties, the modelling framework has worked with a range of scenarios. This approach especially proved to be valuable for testing hypotheses. The major strength of the presented simulation modelling framework is that it integrates knowledge from multiple research fields. In the presented case the PLUS has integrated economic aspects with physical environmental factors; the modelling framework presented would be capable of integrating sociological and cultural factors as well, as long as these can be translated into spatial constraints. The PLUS can thus potentially contribute to the challenge identified by Lake (2014) to integrate sociological factors. The PLUS is a dynamic research instrument that could be used for other regions and cases as well. The modelling framework would allow archaeologists to generate a better understanding of past spatial dynamics and the relationship between the people and the landscape.

7. Future research
As a way forward we have identified various opportunities with which the research could be extended and which would improve the modelling framework. First, the modelling framework would benefit from regional vegetation reconstructions to validate the simulation outcomes. In addition vegetation reconstructions would allow narrowing down the range of scenarios and would allow simulating closer to the historical reality. Second, in order to improve the empirical basis of the various suitability components used in the modelling framework, more archaeological fieldwork would be required producing a more complete archaeological datasets. When more archaeological evidence on (Roman-era) land-use patterns and underlying decision-making processes becomes available other, statistics or utility-based quantitative weighing methods (as applied in contemporary land-use models by, for example, Koomen et al. 2015) would be considered to define local suitability. In line with that the PLUS can considerably be improved by including settlement differentiation. This would allow providing an even more precise simulation of the historical reality and would allow testing hypotheses considering specialisation and size. Another aspect for which we believe the PLUS would be a suitable research instrument is to integrate different scenarios to simulate the use of woodlands. For the specific case presented in this article Van Dinter et al. did produce estimates on the demand of timber for construction and timber as fuel. These figures can be translated into a demand in hectares, which could be used as input for the PLUS. However, since little data is available of the composition of woodlands which are necessary since not every tree can for be used for construction purposes and since relatively little is known on possible different wood management strategies we refrained from integrating woodland scenarios in this study. It does however provide an interesting opportunity for follow up research to test hypotheses.
on wood import proposed by for instance Van Lanen et al. (2016). Finally, we see a clear opportunity of recent local-scale studies that use Agent Based Modelling (ABM) techniques (e.g. Joyce and Verhagen, 2016). It would be interesting to combine these with models like the PLUS that perform on a more regional scale. Research results from ABM on a local scale could be translated into various regional scenarios. The PLUS can validate the impact of the ABM modelling findings and ABM studies have the potential to inform the PLUS and fine-tune the modelling configuration.

Acknowledgements
This project received funding from the European Union’s Seventh Framework Programme for research, technological development and demonstration under grant agreement no 603447 (FP7, Collaborative Project: HERCULES http://www.hercules-landscapes.eu/). Furthermore researcher Rowin Van Lanen contributed as part of the project “The Dark Age of the Lowlands in an Interdisciplinary Light: People, Landscape and Climate in the Netherlands between A.D. 300 and 1000” funded by the Netherlands Organisation for Scientific Research (NWO, 360-60-110, Section Humanities, http://darkagesproject.com/).
We would like to thank Philip Verhagen, Jamie Joyce and Mark Groenhuijzen (Vrije Universiteit Amsterdam) for the valuable discussions and the use of their data as input. Furthermore we want to thank Marieke van Dinter (Utrecht University) and Laura Kooistra (BIA) for their valuable input and clarifications of their initial work. In addition we thank Bert Groenewoudt (Cultural Heritage Agency of the Netherlands), Marjolein Gouw-Bouman and Harm Jan Pierik (Utrecht University) for the development of physical suitability model. Finally we thank Jan Kolen (Leiden University) and Niels van Manen (Vrije Universiteit Amsterdam) for their input on the theoretical framework and Maarten Hilferink, Martin van Der Beek (Objectvision) and Bart Rijken (PBL Netherlands Environmental Assessment Agency) for advice on using the modelling software.
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### Appendix A. Suitability for land-use types

**Table A1. Physical suitability for arable farming**

<table>
<thead>
<tr>
<th>Palaeogeographical unit</th>
<th>Physical Suitability</th>
<th>Reasoning and source</th>
</tr>
</thead>
<tbody>
<tr>
<td>sea</td>
<td>na</td>
<td>classified as water, exogenous</td>
</tr>
<tr>
<td>residual gully</td>
<td>na</td>
<td>classified as water, exogenous</td>
</tr>
<tr>
<td>estuary</td>
<td>na</td>
<td>classified as water, exogenous</td>
</tr>
<tr>
<td>lake</td>
<td>na</td>
<td>classified as water, exogenous</td>
</tr>
<tr>
<td>tidal flats</td>
<td>0</td>
<td>High flood risk, makes it unsuitable for agriculture</td>
</tr>
<tr>
<td>dune</td>
<td>3</td>
<td>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.</td>
</tr>
<tr>
<td>high levee</td>
<td>5</td>
<td>High Levees are considered to be very suitable for agriculture (Van Dinter et al. (2014))</td>
</tr>
<tr>
<td>moderate levee</td>
<td>3</td>
<td>Based on expert judgment of Gouw-Bouman, supported by Brinkkemper (1991): various cereal types suitable to be grown on moderate levees.</td>
</tr>
<tr>
<td>low levee</td>
<td>1</td>
<td>Based on expert judgment of Gouw-Bouman, supported by Brinkkemper (1991): a few cereal types suitable to be grown on on low levees.</td>
</tr>
<tr>
<td>river dunes</td>
<td>3</td>
<td>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.</td>
</tr>
<tr>
<td>fluvial terrace</td>
<td>5</td>
<td>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.</td>
</tr>
<tr>
<td>covered alluvial ridge</td>
<td>4</td>
<td>Based on expert judgement of Gouw-Bouman, covered alluvial ridges are considered to be suitable for agriculture.</td>
</tr>
<tr>
<td>high floodplain</td>
<td>0</td>
<td>High flood risk, makes it unsuitable for agriculture</td>
</tr>
<tr>
<td>low floodplain</td>
<td>0</td>
<td>High flood risk, makes it unsuitable for agriculture</td>
</tr>
<tr>
<td>eutrophic peat</td>
<td>0</td>
<td>For this period, peat areas are not suitable for agriculture.</td>
</tr>
<tr>
<td>mesotrophic peat</td>
<td>0</td>
<td>For this period, peat areas are not suitable for agriculture.</td>
</tr>
<tr>
<td>oligotrophic peat</td>
<td>0</td>
<td>For this period, peat areas are not suitable for agriculture.</td>
</tr>
<tr>
<td>high pleistocene sands</td>
<td>4</td>
<td>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.</td>
</tr>
<tr>
<td>cover sand</td>
<td>4</td>
<td>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 nutrient 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.</td>
</tr>
<tr>
<td>post-Roman erosion</td>
<td>0</td>
<td>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.</td>
</tr>
</tbody>
</table>
Table A2. Physical suitability for pasture and meadow

<table>
<thead>
<tr>
<th>Palaeogeographical unit</th>
<th>Physical Suitability Pasture (meadow / pasture)</th>
<th>Reasoning and source</th>
</tr>
</thead>
<tbody>
<tr>
<td>sea</td>
<td>0</td>
<td>classified as water, exogenous</td>
</tr>
<tr>
<td>residual gully</td>
<td>0</td>
<td>classified as water, exogenous</td>
</tr>
<tr>
<td>estuary</td>
<td>0</td>
<td>classified as water, exogenous</td>
</tr>
<tr>
<td>lake</td>
<td>0</td>
<td>classified as water, exogenous</td>
</tr>
<tr>
<td>tidal flats</td>
<td>3</td>
<td>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).</td>
</tr>
<tr>
<td>dune</td>
<td>4</td>
<td>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).</td>
</tr>
<tr>
<td>high levee</td>
<td>5</td>
<td>High levees are very suitable for pasture (Van Dinter et al., 2014)</td>
</tr>
<tr>
<td>moderate levee</td>
<td>5</td>
<td>Moderate levees are very suitable for pasture (Van Dinter et al., 2014)</td>
</tr>
<tr>
<td>low levee</td>
<td>5</td>
<td>Moderate levees are very suitable for pasture (Van Dinter et al., 2014)</td>
</tr>
<tr>
<td>river dunes</td>
<td>5</td>
<td>Based on the soil this palaeogeographical entity is considered to be rich in nutrients making it very suitable for pasture (expert judgement Gouw-Bouman).</td>
</tr>
<tr>
<td>fluvial terrace</td>
<td>5</td>
<td>Based on the soil this palaeogeographical entity is considered to be rich in nutrients making it very suitable for pasture (expert judgement Gouw-Bouman).</td>
</tr>
<tr>
<td>covered alluvial ridge</td>
<td>5</td>
<td>Covered alluvial ridges are very suitable for pasture (Van Dinter et al., 2014)</td>
</tr>
<tr>
<td>high floodplain</td>
<td>5</td>
<td>High floodplains are very suitable for pasture (Van Dinter et al., 2014)</td>
</tr>
<tr>
<td>low floodplain</td>
<td>2</td>
<td>Low floodplains are only limited suitable. (Van Dinter et al., 2014)</td>
</tr>
<tr>
<td>eutrophic peat</td>
<td>0</td>
<td>Eutrophic peat is not suitable for pasture (Van Dinter et al., 2014)</td>
</tr>
<tr>
<td>mesotrophic peat</td>
<td>0 / 3</td>
<td>Mesotrophic peat is only suitable as grassland (Van Dinter et al., 2014: 10)</td>
</tr>
<tr>
<td>oligotrophic peat</td>
<td>1 / 0</td>
<td>Oligotrophic peat is only suitable as hay land and bordering floodplain (Van Dinter et al., 2014)</td>
</tr>
<tr>
<td>high pleistocene sands</td>
<td>5</td>
<td>The soil map shows that high pleistocene sands are relatively nutrient; this nutrient level makes these relatively high suitable for pasture.</td>
</tr>
<tr>
<td>cover sand</td>
<td>5</td>
<td>Cover sands - sandy aeolian deposits form the last Ice age - are considered as very suitable for pasture</td>
</tr>
<tr>
<td>post-Roman erosion</td>
<td>0</td>
<td>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.</td>
</tr>
</tbody>
</table>
### Table A3. Relative demand factors for land-use types

<table>
<thead>
<tr>
<th>Land-use type</th>
<th>description</th>
<th>Start situation</th>
<th>Physical suitability</th>
<th>Distance relationships</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential*</td>
<td>exogenous</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Military*</td>
<td>exogenous</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Water</td>
<td>exogenous</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Arable Farming</td>
<td>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.</td>
<td>20</td>
<td>0 - 10</td>
<td>-20</td>
</tr>
<tr>
<td>Pasture</td>
<td>For AD 70 and AD 140 the land use from the previous time slice has been reused. A value of 20 had been given</td>
<td>20</td>
<td>0 - 10</td>
<td>-20</td>
</tr>
<tr>
<td>Meadow</td>
<td>see pasture</td>
<td>20</td>
<td>0 - 10</td>
<td>-20</td>
</tr>
<tr>
<td>Woodland</td>
<td>endogenous</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Unused land</td>
<td>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</td>
<td>-1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>exogenous</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Appendix B. Demand for land use types

Table B1. Overview of the assumptions to calculate the demand for land use for rural settlements 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**

\[
\frac{(67.5\% \text{ (percentage of diet)} \times 2,200 \text{ kCal (daily need per person)} \times 10 \text{ (number of persons per settlement)} \times 365 \text{ (number of days per year)})}{(800 \text{ kg (yearly weight of cereals)} \times 3,100 \text{ kCal (amount of kCal per kilo cereals)}) \times 1.5 \text{ (surplus production)} \times 2 \text{ (to take fallow lands into account)}} = \frac{6.6 \text{ ha of arable farming needed per settlement}}{}
\]

### 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 herd 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**

\[
\frac{(22.5\% \text{ (percentage of diet)} \times 2,200 \text{ kCal (daily need per person)} \times 10 \text{ (number of persons per settlement)} \times 365 \text{ (number of days per year)})}{3,800,000 \text{ kCal (maximum production meat of a herd of 50 animals)}} = \frac{12.7 \text{ ha pasture needed per settlement}}{}
\]

\[
16 \text{ (ha needed for pasture for a herd of 50 cows)} - 3.3 \text{ (fallow land)} = 10.1 \text{ ha meadow needed per settlement}
\]
Table B2. Overview of the assumptions to calculate the demand for land use for military structures AD 70 and AD 140 based on Van Dinter et al. (2014)

<table>
<thead>
<tr>
<th>Demand for land</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal forts accommodated 350 soldiers, larger forts 700</td>
</tr>
<tr>
<td>an average soldier needs 3,000 kCal per day, a vicus inhabitant 2,200</td>
</tr>
<tr>
<td>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</td>
</tr>
<tr>
<td>A normal vicus would have had approximately 350 inhabitants a large vicus 700</td>
</tr>
</tbody>
</table>

For calculating the demand of arable land that is needed to sustain the Roman military in AD 70 and AD 140 the following calculation is applied per sub region:

\[
\begin{align*}
((a \text{ (Number of normal forts)} \times 350 \text{ (number of soldiers)} + b \text{ (Number of large forts)} \times 700 \text{ (number of soldiers)}) \times 3,000 \text{ (kCal per day needed for a soldier)} \times 365 \text{ (days in a year)} \times 0.675 \text{ (% of diet existing of cereal)} + (c \text{ (Number of normal vici)} \times 350 \text{ (number of inhabitants)} + d \text{ (Number of large vici)} \times 700 \text{ (number of inhabitants)}) \times 2,200 \text{ (kCal per day needed for a normal person)} \times 365 \text{ (days in a year)} \times 0.675 \text{ (% of diet existing of cereal)}) / (3,100 \text{ (kCal per kg)} \times 800 \text{ kg (the useful amount of kilos that 1 ha produces)} \times 2 \text{ (to include fallow lands)} = \text{the number of ha of additional arable land required.)}
\end{align*}
\]

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

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

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.
Appendix C. Supplementary data

The software, modelling configuration including a set of scripts to run the model, and modelling results are available at:
password: HERCULES

Please note, that this is a temporary solution. At the moment that the article would be be published we will make it available through a sustainable link in a long-term repository (e.g. DANS https://dans.knaw.nl/nl, HERCULES’S Knowledge HUB http://www.hercules-landscapes.eu/knowledge_hub.php or differently when requested by the journal’s publishers)