Farming along the limes

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Summary

Chapter 1

Chapter 1 provides a brief overview of the "Finding the limits of the *limes*" project (NWO Project number: 276-61-005) conducted at the Vrije Universiteit, Amsterdam between 2012 and 2017. The project aimed to analyse and reconstruct the cultural landscape of the Dutch *limes* zone between 12 BCE and 270 CE. It presents the key methodological and theoretical research questions of the project, and how the role that the research presented in this thesis has within the wider project.

This study aimed to implement a new tool for Dutch Roman archaeology by developing a spatial dynamic model to simulate the agricultural economy of the region and using the Dutch Roman *limes* as a testing ground for this type of methodology. How extensive archaeological and palaeo-environmental data-sets could be incorporated into such a model and the challenges of translating "expert judgement" models into formal simulation models were tackled. A key archaeological question at the core of the project was the potential for surplus agricultural production in the Dutch Roman *limes* zone. This study has generated new hypotheses about how surplus agricultural production for the Roman army in the region could have been organised and its impact on land-use.

Chapter 2

The current state of knowledge regarding the Dutch Roman *limes* is given in chapter 2. This is not an exhaustive overview of decades of archaeological research in the region, the current state of knowledge has focused on the types of information needed to inform and develop the behaviours and assumptions that the simulation model created for the research use. However, despite extensive research, there remain uncertainties, as highlighted in chapter 1, which need addressing.

The foci of this chapter were the settlement history of the region, both rural, military and urban, in order to introduce the nature of supply and demand for agricultural production between 12 BCE and 270 CE. The natural landscape of the Dutch *limes* zone is described, including some of the limitations and opportunities that different parts of the landscape offered. The floral and faunal record were also provided, with a focus on the main elements of the agricultural economy: cereals and main livestock. What the archaeobotanical and zooarchaeological record can reveal about different agricultural practices is also discussed. The current evidence for surplus production of grain and animal products is also given, as well as recent modelling approaches that have sought to address the surplus production debate in Dutch Roman archaeology.

Chapter 3

Chapter 3 presents the research aims and objectives of this study. These have been formulated as a response to the missing knowledge from an evaluation of the current state of knowledge. The theoretical objectives were formulated to answer some of the key questions of the "Finding the limits of the *limes*" project and to contribute new knowledge to the understanding of agriculture and its limits in the Lower Rhine delta between 12BC and 270AD:

i. To produce new results for the consumption demands and labour supply from rural agricultural settlements with differently-sized, dynamic populations,
ii. To produce estimate land and labour costs for subsistence-based agriculture as assumed for the Late Iron Age before the development of the *limes* in the Lower Rhine delta,
iii. To identify and gauge the impact of different limiting factors affecting the different elements within the agricultural economy,

iv. To provide new estimated outputs from subsistence-based agricultural activities including grain production and the production of meat, milk, wool and manure from livestock,
v. To produce land and labour estimates for different agricultural tasks when different surplus-based agricultural strategies are undertaken,
vi. Assess whether changes in the agricultural economy were necessary for surplus production
vii. To gauge the relative impact of different limiting factors between surplus-based and subsistence-based agriculture,
viii. To assess the impact of land availability in reconstructed landscapes on agricultural productivity,
ix. To generate new results related to the way local rural settlements could supply military and urban settlements that developed in the Dutch Roman *limes* zone.

Chapter 4

In chapter 4, the model developed for this research, ROMFARMS, is presented. The model developed is an example of an agent-based model. Agent-based models are useful tools when observing how complex systems emerge from micro-level behaviour. Agents are autonomous entities (in the case of this research; settlements) that make decisions based on their current situation according to pre-defined behavioural rules. Often agent-based models are distinguished between detailed, descriptive models and simplistic models. Given that this research aimed to explore the agricultural economy by simulating several possible agricultural strategies inferred from the archaeological evidence presented in chapter 2, a descriptive, exploratory model was chosen. The current state of the art for agent-based modelling in studying ancient agriculture highlights how agent-based modelling can be useful in tackling various questions regarding agricultural economies in the past.

The choice of tool (agent-based modelling) enabled an explicit analysis of the cause and effect chains of agricultural decisions made by settlements. Scenarios of agricultural production, the implications of different strategies in arable farming, animal husbandry and fuel and timber collection could be analysed by the results generated from agent-based modelling. In turn, these can generate new hypotheses about the feasibility or sustainability of these strategies as well as reject some hypotheses. Agent-based modelling also allowed the simulation of the agricultural economy with the conditions that settlements were presenting changing every year not only as a result of decisions made in previous years but also by random events (such as deaths of settlement inhabitants or livestock) and random fluctuations in yields and outputs.

The key features of ROMFARMS are:

- Developed using multiple data-sets,
- Simulates the agricultural economy as a whole; integrating different agricultural tasks into a single model,
- Incorporates stochasticity, or randomness, into sub-processes to better reflect agriculture as a dynamic task,
- Key outputs are the results of land and labour use under different scenarios of agricultural production

ROMFARMS comprises several sub-models that simulate the various elements of the agricultural economy assumed from the current state of knowledge collected in chapter 2. Initially, the landscape is either randomly-generated or reconstructed from palaeogeographic data. Settlements and woodland are placed randomly in the landscape. Each step of the simulation, which represents one year, settlement populations can expand or decrease. This is determined by a population dynamics model that simulates births, marriages, and deaths within a household in a settlement. Settlements subsequently undertake arable farming, animal husbandry, and fuel and timber collecting. Different arable farming strategies are available to settlements: subsistence-based, where settlements produce only enough grain for the requirements of their inhabitants; extensification, where settlements expand farms to produce surplus-grain; and intensification, where settlements incorporate manure into the same area of land that they would cultivate when undertaking subsistence-based farming. Animal husbandry is simulated through a dynamic model of herd dynamics, with each settlement able to manage one herd of sheep and/or cattle. Sheep and cattle reproduce and die as a result of natural causes, but further mortality can be caused by slaughtering. When animals are slaughtered meat is available. From living animals, wool (from sheep), milk (from both) and manure (from cattle) is available. The yields of these products depend on the animal husbandry strategy settlements employ. Settlements must also collect fuel each year and timber less frequently. ROMFARMS uses specific rules regarding how settlements select an area in the wider landscape to forage for fuel and timber.

At the end of each year, ROMFARMS records various outputs including yields of grain and animal products, the area of land used, and the labour expended for each task. Some of the conditions that are created by the decisions made by settlements in the previous year become starting conditions for settlements in the next year.

ROMFARMS is scenario-based. The inputs for different user-defined parameters combine to simulate different agricultural strategies. Chapter 4 details the values for different parameters to enable the replication of experiments.

Chapter 5

Before the potential for surplus production can be analysed, the subsistence-based economy must be simulated to identify the underlying limiting factors. In chapter 5, the results from simulating the subsistence-based economy in randomly-generated landscapes are presented.

Firstly, the results from simulating settlement population dynamics are provided. Settlement populations are the sole source of labour in ROMFARMS, and therefore population dynamics underpins the other processes simulated by ROMFARMS. The results show, inevitably, that as settlement populations expand, the demand for food, fuel, and timber, as well as the land to produce these products, expands as well as the labour pool available. High mortality rates mean that women in ROMFARMS must produce a large number of children in their lifetime to prevent population extinction which corroborates what is known about populations in the Roman world.

The results from simulating subsistence-based arable farming show that even when no surplus grain is needed, fluctuations in yield each year can mean that a surplus is inadvertently produced. Experimenting with different subsistence-based arable farming strategies have produced new results relating to the area of land needed by settlements of different sizes and the quantity of surplus grain they can produce. Chapter 5 also explores the impact of different limiting factors on the ability for settlements to produce enough food. These limiting factors were identified as the availability of labour, land and sowing seed. The results showed that it was the availability of sowing seed that most impacted the ability for settlements to produce enough food. This highlighted the need for settlements to produce small buffers of extra grain, not only to protect against exogenous forces such as climate fluctuations or disease, but also to ensure that population increases in settlements that they could not predict did not result in sowing seed needed for the following year did not needed to be used to feed the inhabitants. The results also showed that the total labour available to settlements was superfluous to their needs i.e. settlements could cultivate more land than they needed with their available labour pool.

The results from experimenting with different animal husbandry management practices showed the impact on the yields of different products. Furthermore, new results for the land and labour costs to manage these herds were produced. The results showed that for larger settlements, the number of cattle and sheep available in the single herds that settlements own in ROMFARMS was not sufficient to meet the energy requirements of the inhabitants. These larger settlements needed to keep more animals, however, the labour pool available to settlements did not prevent them from doing so. Rather, settlements were restricted by the fertility of animals and the trade-off between maximising outputs and preventing either the extinction of the herd (when animals were exploited for meat) or the expansion of a herd that could not be managed by the labour pool available to settlements.

Experimenting with different fuel strategies highlighted the strong limiting impact that labour availability had on this element of the agricultural economy. The results showed that settlements, regardless of their size, would need to collect fuel regularly to ensure enough firewood was foraged each year from the landscape. An optimum strategy of daily collection was necessary to prevent settlements experiencing fuel deficits. Furthermore, it was shown that labour limited the feasible daily per capita consumption rate of settlements. Labour costs each year for fuel collection were high. Fuel collection was the largest labour expenditure of all tasks undertaken each year by settlements.

By analysing the whole labour expenditure each year, seasonal underemployment in the agricultural calendar was confirmed. In many periods, apart from the constant need to collect fuel, there was little other labour expenditure. In labour-intensive periods, although the majority of labour hours available to settlements was used, there was sufficient labour each year.

Chapter 6

In chapter 6, experiments with surplus based agriculture were analysed. The quantity of surplus grain produced under subsistence-based arable farming and the fact that any surplus was a result of random fluctuations on grain yield each year meant that a shift to surplus-based arable production was necessary if native rural settlements were required to supply military and urban settlements in the region. Arable extensification, where settlements seek to expand farms through the use of extra sowing seed, was shown to result in a significant increase in labour costs as well as land use. The principle limiting factor was identified as labour availability. The amount of labour available to each settlement capped the maximum area of land that settlements could cultivate and the total amount of extra sowing seed that was produced each year could not be used. A trade-off was also identified between maximising the amount of surplus grain and ensuring enough grain remained to expand farms. When settlements undertake intensification, they incorporate manure into arable land but do not expand their farms. This resulted in an increase in labour expenditure. Labour availability was not identified as the principle limiting factor, however. Instead, settlements were limited mostly by the availability of manure. Without the incorporation of manure, by not expanding their farms, the quantity of surplus available would not differ from that produce when settlements undertake subsistence-based arable farming. A cost-benefit analysis of arable extensification and intensification highlighted possible scenarios in which one strategy was more favourable than the other. Extensification resulted in higher land costs per ton of surplus grain and intensification required greater investment in labour per ton of surplus grain.

The adoption of arable extensification and intensification was not observed as an either-or decision. The results showed settlements were able, with the labour pools available to them, of undertaking both, whereby settlements would incorporate manure into expanded farms. Although this has yet to be implemented in ROMFARMS, it generated a new hypothesis regarding how settlements could produce surplus grain.

Surplus production of animal products was possible for all settlements. However, the number of sheep that was needed before surplus milk or meat was available did not reflect the zooarchaeological record. If sheep were indeed exploited in surplus-based animal husbandry, it would likely have been for their wool. The results suggested that surplus production of meat and milk from cattle was more plausible. In addition, it highlighted the potential importance of dairy products in surplus production of animal products, as the surplus of milk available from large cattle herds was unexpectedly large. In this chapter, the results from simulating horse herds were also presented. The breeding of surplus horses was a trade-off between preventing the extinction of the herd and removing the greatest number of immature horses. The number available from each herd, when compared with the possible number required by the Roman army in the region showed that not all settlements needed to engage in horse breeding. The ubiquity of horse bones in rural settlements suggested a distinction between ad hoc breeders and intensive breeders.

Chapter 7

In chapters 5 and 6, the results were taken from experiments with randomly-generated landscapes. In chapter 7, agriculture was simulated in reconstructed landscapes form the Dutch *limes* zone. A description of each of the thirty-two delimitated micro-regions was described, highlighting the different opportunities and limitations that the natural landscape presented. In addition, the different settlement densities of each micro-region were provided. By simulating in reconstructed landscapes, the possible impact of land availability on arable farming could be gauged for each micro-region. These results showed that for all micro-regions and throughout the Roman period, the area of suitable arable land required by settlements undertaking subsistence-based and surplus agriculture was more than the area that each settlement could cultivate with the available labour pool. The results confirmed therefore that under subsistence-based agriculture, the availability of sowing seed was most limiting and established the need for settlements to produce a buffer each year. For extensification, labour availability was the most limiting factor. For intensification, settlements remained limited most by the availability of manure and the ability to undertake cattle husbandry.

In each of the sub-regions, the availability of pasture and meadow land, and the availability of labour to each settlement were compared to assess the most limiting factor for extensive surplus animal husbandry i.e. managing the maximum number of animals possible. The results showed that the most limiting factor differed among micro-regions. The results also showed that when settlements also utilised potential arable land for grazing livestock and producing fodder for herds, the maximum number of animals that could be managed per settlement increased in some scenarios and micro-regions. This generated new hypotheses where competition for resources may have occurred.

Comparisons between grain supply and demand were produced. Demand was estimated from the military, urban and equid population in each micro-region. The human and horse populations of *castella, castra,* towns, and *vici* were estimated and the grain they needed each year was calculated, although these estimates were uncertain. Two regional supply mechanisms were proposed: a micro-regional mechanism and a macro-regional mechanism. For the former, only settlements in the vicinity of each military and urban settlement were involved in their supply. For the latter, all rural settlements were involved in the supply of military and urban settlements. The results pointed to a macro-regional supply network being most likely, especially when landscapes were occupied by small settlements. A macro-regional supply would have likely needed a sophisticated supply network which highlighted the scope to incorporate the results from ROMFARMS in models of transport and trade networks for the Dutch Roman *limes* zone.

Chapter 8

In chapter 8, ROMFARMS is compared with the current state of the art in agent-based modelling of agriculture in the past. ROMFARMS is argued to be an important addition to current methods that have been employed so far. Furthermore, because the research questions that ROMFARMS tackles differ, this agent-based model has implemented different elements than other models produced so far.

ROMFARMS is evaluated in chapter 8. The agent-based model produced represents what is likely to be the upper limit of using free, off-the-shelf modelling software. As a result, some processes are simplified in comparison with other agent-based models. Furthermore, simulating on a macro-regional scale has not been possible. Issues with the availability of sources for assumptions is highlighted however the use of formal computation simulation means that ROMFARMS can be easily updated to take into account any new archaeological data. ROMFARMS relies on the economic rationalism of farmers in the past and therefore does not take into account many socio-cultural factors in agriculture. ROMFARMS is a unique addition to Dutch Roman archaeology and has generated new hypotheses for further investigation. In addition, it has reduced the number of possible scenarios of agricultural production by identifying those that are infeasible.

Opportunities for further implementation of ROMFARMS is discussed in chapter 8. Development of the population dynamics sub-model is identified as a priority. This could incorporate recruitment and use different scenarios of population growth and decline, rather than stable populations. Incorporating a continuous patch model, where cells can be used for different tasks would allow simulation of agriculture in more realistic landscapes. Finally, although ROMFARMS has developed new results for the base-line economy from an economic rational perspective, the incorporation of socio-cultural factors is another priority for development of ROMFARMS.