Chapter 7
Modelling Agricultural Strategies in the Dutch Roman *Limes* via Agent-Based Modelling (ROMFARMS)

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Abstract This chapter presents an agent-based model developed to investigate the impact on land and labour costs of different agricultural strategies that could have been undertaken in the Early and Middle Roman periods (12 BCE to 270 CE) in the Lower Rhine delta. A short description of the sub-processes in ROMFARMS to simulate settlement population dynamics, arable farming, animal husbandry and wood acquisition is provided. The results show that settlements in the Dutch *limes* zone during the Roman period were mostly limited by the relatively small labour pool available. Whilst not prevented outright by the availability of labour, the results show that only a small proportion of the total quantity of grain demanded by to military settlements, towns and *vici* can be supplied by local settlements. Two different possible scales of supply were envisaged with the results indicating that a macro-regional supply network was more feasible in which all settlements in the Lower Rhine delta were involved in the supply of consumer-only settlements. Whilst several methodological issues were noted, ROMFARMS is presented as an innovative tool for Dutch Roman archaeology with good potential for further development.

Keywords Agent-based modelling · Agriculture · Roman archaeology · Dutch *limes* · Surplus production

7.1 Introduction

ROMFARMS is an agent-based model developed in NetLogo (v. 6.0.2; Wilensky 1999) to investigate different possible agricultural strategies undertaken during the Early and Middle Roman periods (12 BCE to 270 CE) in the Lower Rhine region. ROMFARMS produces results on the land and labour costs of agriculture under the conditions of different scenarios. These have been used to assess the relative limiting impact of these factors of production on agricultural productivity to better understand the impact of different agricultural behaviours and the feasibility of

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different strategies of subsistence-based and surplus arable farming and animal husbandry.

7.1.1 The Surplus Debate in Dutch Roman Archaeology

Whether rural agrarian settlements in the Dutch Roman *limes* zone were capable of supplying *castella*, *castra*, *vici* and towns that developed from the Early Roman period (12 BCE onwards) has been the subject of significant debate within Dutch archaeology. Initial assessments of the agricultural economy of the Lower Rhine delta before and during the Roman period cited literary sources, the limitations of the natural landscape and the local spectra of cereals cultivated locally as evidence against local supply of grain or animal products (Van Es 1981; Bloemers 1983; Willems 1986; Whittaker 2004). In contrast, archaeobotanical, zooarchaeological and other archaeological evidence points to the strong likelihood of at least partial supply by native agrarian settlements in the Lower Rhine region (see Kooistra et al. 2013, 5–7).

Recent research undertaken by Van Dinter et al. (2014) and De Kleijn et al. (2016, 2018) have used detailed landscape capacity models to develop further theories regarding the extent of possible supply by local agrarian settlements. Neither study excluded local supply of either grain or meat outright. Rather, they both calculated that the full quantity demanded by military settlements, towns and *vici* could not be fulfilled by local supply. Both landscape capacity approaches assume agricultural extensification as the mechanism undertaken for surplus production of grain and animal products. In contrast, previous studies have also posited arable intensification and different herd management strategies aimed to exploit cattle or sheep for different products (e.g. Groot 2008; see Sect. 7.2.3). This paper adds further results to the surplus production debate in Dutch Roman archaeology. It uses spatial dynamic modelling techniques to simulate the various processes of the agricultural economy as well as fundamental underlying processes such as settlement population dynamics.

7.2 Overview of Sub-models and Processes

7.2.1 Initialization

ROMFARMS is a discrete patch model comprising of cells each representing 1 hectare. Distances between cells are calculated from the centre of each cell. Both randomly generated and reconstructed landscapes are used in the simulation depending on the tested scenario. Each cell possesses a value for the variable *landscape-type* which determines whether a cell contains flood-basin, levee or neither.

Settlements are located on levee cells which are also used for arable land. Flood-basin is used for animal husbandry by settlements. These land-use assumptions are derived from Groot and Kooistra's (2009) assessment of land use at Tiel-Passewaaij. In randomly generated landscapes, areas of flood-basin and levee are generated with the number of cells for each landscape element determined by the value for parameters *area-levee* and *area-floodbasin*. In reconstructed landscapes, the GIS extension is used to provide values to cells from 32 rasters which cover the majority of the inhabited Lower Rhine delta during the end of the pre-Roman Iron Age and Roman period. Whilst all cells are coloured in reconstructed landscapes according to the landscape element they contain, only raster values corresponding to levees or flood-basin update the value for *landscape-type*. Levees or flood-basins remain the only landscape element used by settlements for arable farming or animal husbandry.

Settlements in ROMFARMS vary from small settlements comprising one household to larger settlements comprising two, three or five households. A household in ROMFARMS is considered one couple with any dependent children, elderly or unmarried adults. Within one step of the simulation, settlements undertake arable farming, animal husbandry and fuel acquisition. One step of the simulation represents one calendar year. Timber collection for construction wood is undertaken by the settlement's inhabitants once per 20 years. The number of households each settlement comprises is the maximum number of households. During a simulation, the number of married couples with dependents in each settlement may drop below the maximum number of households but cannot exceed it (see Sect. 7.2.2). At the start of each simulation, settlements are inhabited by one adult male and female per household and four individuals between 0 and 15 per household, with ages of children generated randomly. Settlements are provided with herds of livestock at the beginning of each simulation. Settlements start each simulation with 1 herd of sheep, cattle or horse containing 30 adult animals. In addition, each settlement is provided with a catchment area containing all cells within a 10 km round trip from the settlement. A settlement's catchment area contains all arable land and woodland on levees that a settlement has access to. Whether the arable land and woodland remains available for use depends on whether other agents have already made use of it.

ROMFARMS is described in more detail in Joyce (2019) and can be accessed from http://modelingcommons.org/browse/one_model/5687#model_tabs_browse_info.

7.2.2   *Population Dynamics*

The agricultural production unit in ROMFARMS is the settlement. Each settlement is comprised of one or multiple households. A system dynamics model of settlement demography was combined with a further sub-model which simulated marriage, establishment of new settlements and migration. Mortality was determined by probability values for death per age of individual which are derived from Coal and Demeny's Model West Level 3 Female life table (1966). Fertility rates were taken

from Coale and Trussell's (1978) estimates. This sub-model simulates changes in settlement populations each step from which settlements derive their individual labour supply. Labour supply is divided into "weak" and "strong" forces (after Danielisová and Štekerová 2015). The latter can undertake all agricultural tasks; the former can only undertake fuel collection. Children under 10 years have no labour value. Unmarried or widowed individuals will remarry provided there is another individual of the opposite sex between 16 and 49. Marriages are patrilocal unless the number of households in the male spouse' settlement has reached the maximum. If the female spouse' settlement has also reached the maximum number of permitted households, a new settlement is established. If the maximum settlement density of the landscape has been reached, the settlement is established outside of the simulation and the new couple is removed.

In each step, the population of each settlement is calculated, and the total calories required by the inhabitants are estimated using demands from Gregg (1988) and FAO (2004). The quantity of fuel required is also calculated.

7.2.3   Arable Farming

A sub-model simulating arable farming was included in ROMFARMS. In this sub-model, settlements cultivate grain using different behaviours based on three agricultural strategies: subsistence-based, extensification and intensification. Under subsistence-based arable farming, settlements seek to cultivate only enough land to produce grain for their own consumption needs and sowing seed for the following year. Harvests fluctuate each year, with grain yields per hectare of cultivated land fluctuating ±20% around a mean 1000 kg/ha. In addition, settlements can cultivate a small surplus each year to serve as a buffer against exogenous forces such as disease, adverse weather, pests and socio-political factors. Settlements undertaking arable extensification seek to cultivate extra land provided there is sufficient labour, arable land and sowing seed to do so. Settlements undertaking arable intensification cultivate no more land than they would under subsistence-based farming. However, they will incorporate manure into arable land to boost grain yields and remove the need for fallowing each year. ROMFARMS does not simulate nutrient cycles in the soil but settlements undertaking either subsistence-based arable farming or arable extensification must leave land cultivated 1 year, fallow in subsequent years.

In each step, the land costs and labour expenditure for the various tasks associated with arable farming are calculated for each settlement. Arable tasks that require labour expenditure are sowing, ploughing, harvesting and manuring. The yield of grain is also calculated. Any grain not required by settlements for their own consumption or for sowing seed is considered surplus.

Arable extensification and intensification are the two strategies of surplus arable production simulated in ROMFARMS. The two strategies are distinguished by the land use and resource input (Ellis 1993, 206). The two strategies simulated in ROMFARMS follow the two proposed by De Hingh (2000, 43). Extensification

increases the area of land used, but the labour input per unit of land does not increase from subsistence-based farming. Intensification increases the labour input per unit of land but does not increase the overall area of land that is cultivated. Although the investment of labour and capital has defined the concept of agricultural intensification (Bieleman 2010), manure as a valuable commodity can be seen as a form of capital (Ellis 1993; De Hingh 2000).

7.2.4   Animal Husbandry

To simulate animal husbandry, a system dynamics model of herd population dynamics was included in ROMFARMS. This sub-model simulates the herd dynamics of three major livestock species: cattle, sheep and horse. Each year, livestock reproduce, die of natural causes and are slaughtered. Death due to natural causes of livestock is simulated using the method developed by Galic (2014). Slaughter rates are expressed as the probability of an individual animal dying. They were developed from an earlier study of animal husbandry for the "Finding the limits of the *limes*" project (Joyce and Verhagen 2016). Horse herds are simulated differently, as settlements in ROMFARMS exploit these animals to maximise the number of immature animals that can be removed as a surplus commodity. Horses are therefore not slaughtered but are removed from the herd.

Settlements can exploit sheep and cattle for different products resulting in different slaughter rates per age cohort of animals. Accordingly, settlements can exploit cattle for meat, milk or manure/traction, and they can exploit sheep for meat, milk or wool. Exploitation strategies reflect behaviour of settlements to maximise the potential output of a particular product from a herd but simultaneously maintaining the viability of the herd and preventing its extinction.

In each step, the yields of potential products are estimated from cattle and sheep herds as is the potential number of immature horses that can be removed from the horse herd kept by a settlement as a surplus commodity. In addition, the area of land needed to pasture animals and the area of grassland needed to produce hay for winter fodder for 4 months are calculated. The labour expenditure required to produce this fodder is also estimated.

7.2.5   Wood Collection

The collection of fuel and timber from the local environment was probably a major task of the agricultural economy in the past. ROMFARMS simulates this task by combining a patch choice and central place foraging model (after Shaw 2008). Settlements collect wood from the landscape with the resource spread heterogeneously. Settlements will seek a patch containing wood that is the nearest patch containing more wood than the average per patch in that year. Settlements will stay

in a patch until either sufficient wood has been collected or the quantity of wood falls below the average per patch. In the case of the latter, settlements will look for a new patch to collect wood from. Once sufficient wood has been collected, or the maximum quantity of wood that can be collected by the foraging party has been reached or there is no more wood left in the landscape, collected wood is returned to the settlement. This approach avoided using the Principle of Least Effort as the sole behavioural rule for wood acquisition (see Shackleton and Prins 1992; Shaw 2008; see also Brouwer et al. 1997). Unless a patch is used as arable land, wood regenerates in the patch.

Settlements will collect wood for fuel multiple times in a year. The number of times is determined by the user-defined parameter collection-frequency. To minimise the number of foragers required per collection, the "strong" workforce (see Sect. 7.2.2) is used primarily with the "weak" workforce only used when the quantity of wood that can be collected by the "strong" workforce is less than the quantity required by all the settlement's inhabitants.

In each step, the combined time required to travel by the foraging party from the settlement to each patch foraged from and back to the settlement is calculated. In addition, the time spent in each patch to process wood to be returned to the settlement is calculated. The combined time is the labour expenditure per settlement for wood acquisition.

7.2.6   Description of Experiments

Whilst ROMFARMS has been used to simulate a large number of scenarios, they cannot all be discussed here. The experiments included in this study concern surplus production in randomly generated and reconstructed landscapes. The values for user-defined parameters for these scenarios are provided in Appendix Table 7.4. Scenarios were simulated using NetLogo's inbuilt BehaviourSpace function. This allowed for a model to be run multiple times, automatically recording outputs and iterating over different parameter values.

The experiments discussed in this chapter concern only surplus arable farming and animal husbandry. Firstly, surplus strategies of arable farming and different exploitation strategies of livestock were simulated in randomly generated landscapes to identify their key limiting factors and to identify cause and effect chains of agricultural decisions in optimum conditions. Subsequently, the same strategies were simulated in reconstructed landscapes of the 32 sub-regions to gauge the relative impact of the natural landscape as well as generate new results related to supply and demand of food in each sub-region.

7.3   Discussion

7.3.1   *Arable Extensification and Intensification*

7.3.1.1   Limiting Factors for Arable Intensification and Extensification

Experiments with subsistence-based arable farming identified a number of limiting factors that impact settlements' abilities to undertake arable farming successfully. The availability of land, labour and sowing seed were identified as possible limiting factors. These same factors also have a limiting impact on the ability for settlements to undertake arable intensification and extensification. For the former, a further limiting factor was expected. Without access to manure, settlements would be unable to boost yields. The differences in the two strategies of surplus arable farming resulted in differences in the relative impact of the limiting factors.

Settlements undertaking extensification require larger quantities of sowing seed than required under subsistence-based arable farming or arable intensification. Without extra sowing seed, the area of land that can be cultivated cannot increase. In randomly generated landscapes, the principal limiting factor for settlements undertaking arable extensification was the availability of labour. Provided that the proportion of grain removed as surplus for external consumers did not exceed 70%, settlements had access to more sowing seed than needed. The availability of labour placed a maximum limit on the area of land that could be cultivated that was lower than the area that could be sown or the area that settlements had access to in randomly generated landscapes (see Table 7.1).

The ability for settlements to produce surplus grain when undertaking arable intensification is dependent on the availability of manure. Settlements must manage cattle herds to undertake arable intensification and therefore are limited by the number of cattle that can be managed. The workforce available to settlements enabled enough cattle to be managed to supply sufficient manure for an optimal application on the arable land to be cultivated. The availability of manure is therefore limited by the cattle exploitation strategy employed by settlements.

Table 7.1 Maximum area of land (ha) that can be cultivated by settlements per limiting factor when surplus takeoff is 70%

No. of households	Availability of labour	Availability of sowing seed
1	6.83	24.08
2	9.03	34.54
3	12.27	49.22
5	18.99	78.15

7.3.1.2 Cost-Effectiveness of Strategies

A calculation of the cost-effectiveness of intensification and extensification was made to compare the increased labour and land costs for surplus grain produce. Costs for extensification incorporated only the area of extra land cultivated and labour to cultivate this extra land. Costs for intensification incorporated the labour costs to produce the manure required in addition to the labour costs for sowing, ploughing, harvesting and the incorporation of manure into cultivated land.

The results showed that the two surplus arable strategies provided different advantages to settlements depending on the availability of land and labour (see Table 7.2). Under intensification, the land cost per ton of surplus grain is lower than under extensification. This indicates that intensification is a more advantageous strategy when the availability of arable land is reduced. For per ton of surplus grain, extensification uses less labour than intensification. Accordingly, despite overall higher absolute labour costs under extensification, it would be a more beneficial strategy should the availability of labour be restricted.

7.3.2 Surplus Animal Husbandry in Randomly Generated Landscapes

In ROMFARMS, the available workforce for each settlement permits the management of herds larger than the herd sizes that emerge via the system dynamics sub-model of animal husbandry. A small surplus of meat and milk is already available from the cattle herds simulated in ROMFARMS, with more meat and milk available from smaller settlements as their consumption requirements are smaller. If settlements managed larger herds, the quantity of surplus meat and milk would increase although more pasture and meadow land would be required as well as a greater expenditure of labour. Settlements can manage more cattle than required for their own needs with the labour available to them.

The availability of surplus meat and milk is dependent on the exploitation strategy employed. Cattle exploited for meat and milk produce larger quantities of meat and milk each year than herds exploited for manure (see Table 7.3). Slaughter rates for cattle exploited for manure result in fewer adult animals slaughtered, reducing meat yields. Furthermore, the size of herds exploited for manure is smaller, which also reduces the quantity of milk available. The likelihood of sheep husbandry being a viable mechanism for surplus production of meat and milk is slim. The number of sheep needed to be kept by settlements is not reflected in the zooarchaeological evi-

Table 7.2 Extra land and labour costs per ton of surplus grain under different arable farming strategies

Strategy	Hours per ton surplus grain	Hectares per ton surplus grain
Extensification	74.68	1.34
Intensification	127.74	0.00

Table 7.3 Mean annual yield output per herd of cattle and sheep as simulated in ROMFARMS

Species	Strategy	Milk (l)	Meat (kg)	Wool (kg)	Manure (kg)
Cattle	Milk	5313.28	632.13	–	81078.76
Cattle	Meat	3488.94	688.27	–	62329.22
Cattle	Manure/traction	1966.92	459.58	–	30972.12
Sheep	Meat	160.51	19.38	51.40	–
Sheep	Milk	300.80	14.88	59.89	–
Sheep	Wool	242.97	31.02	66.86	–

dence available from the study region. If sheep husbandry did play a role in surplus farming in the Lower Rhine delta, it is likely it was small-scale or even specialised, such as the surplus production of wool (see Groot 2008; Van Dijk & Groot 2013).

The results from ROMFARMS show that the possible yield of milk from cattle herds regardless of the exploitation strategy employed outstrips the possible yield of meat. The supply of raw milk from rural agrarian settlements to military settlements, towns or *vici* in the region is unlikely. Instead, a small-scale and specialised way of market participation in the Roman period could have been through the production of cheese (van Driel-Murray 2003, 2008).

Specialised horse-breeding in the region to supply surplus horses, primarily to the army, has been argued in many studies of the ancient economy in the Dutch *limes* zone (see Kooistra 1996; Nicolay 2008; Vossen and Groot 2009). Horse bones in rural zooarchaeological assemblages are almost ubiquitous with some assemblages containing up to 30% horse remains (see Lauwerier and Robeerst 2001, Table 1). Vossen and Groot (2009) calculated an annual demand of 373 horses from military settlements in the Early Roman period and 413 in the Middle Roman period for the eastern part of the Dutch *limes* zone alone. Potentially seven immature horses can be removed from horse herds simulated by ROMFARMS without causing the extinction of the herd. To fulfil the total demand of horses for the Roman army in the Lower Rhine delta, not every rural settlement would need to specialise in horse-breeding therefore. The near ubiquity of horse bones in rural settlements indicates there was a distinction between specialised horse-breeders who managed herds like those simulated in ROMFARMS and small-scale breeders who supplied an animal on an ad hoc basis.

7.3.3 Surplus Production in Reconstructed Landscapes

Simulating agriculture using landscapes reconstructed from palaeogeographic data enabled an analysis of land as a limiting factor. Owing to restrictions in computer processing power, the whole Lower Rhine delta was divided into 32 equal sized sub-regions of 100 km² (see Fig. 7.1). The natural landscape of each of these sub-regions presented different possibilities and challenges (see Kooistra et al. 2013).

In addition to reconstructing the natural landscape, settlement densities for each sub-region were calculated from a data-set of find-spots. A data-set of military settlements, towns and *vici* was also compiled from available evidence to estimate
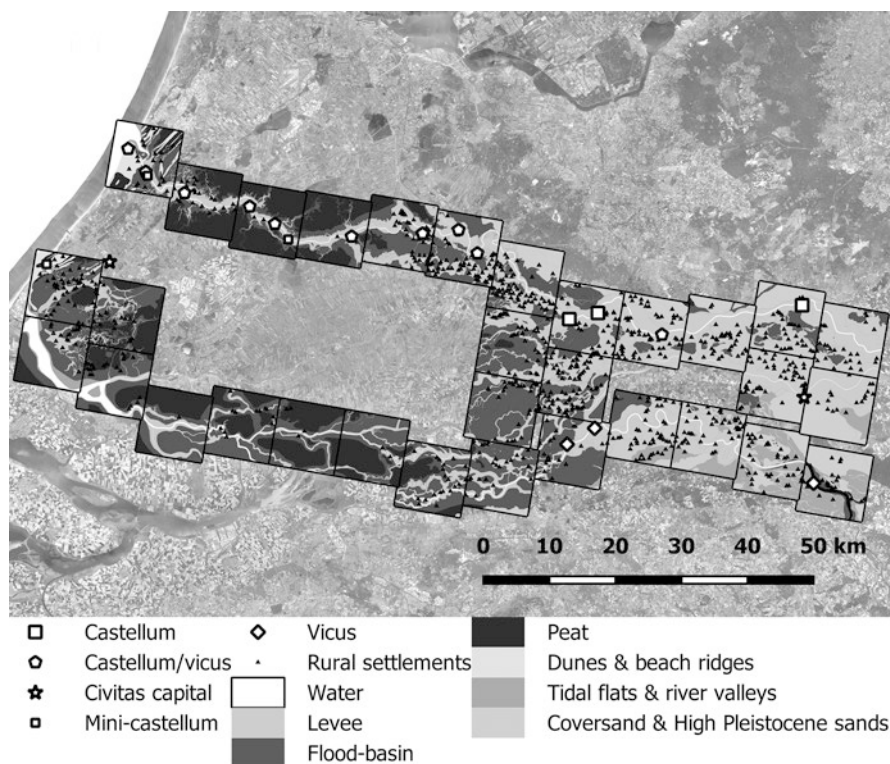
Fig. 7.1 Palaeogeographic reconstruction of the Lower Rhine delta showing the location of 32 sub-regions used in ROMFARMS. Base map = PDOK Luchtfoto Beeldmateriaal 25 cm

possible demand in each of the sub-regions in the Early and Middle Roman periods. This is one of only a few formal estimates of demand in the study region for this period and uses data-sets produced from new methods developed by Verhagen et al. (2016a, b). As such it is subject to significant uncertainties. Nevertheless, this formal estimate of demand has helped to identify the data necessary to establish more accurate and robust estimates.

7.3.4   Land Use in Reconstructed Landscapes

Despite uncertainties in the data-set of rural settlements and reconstructed settlement densities for each sub-region, an analysis of potential land use for arable farming and animal husbandry was undertaken. Although scenarios were simulated using settlement sizes ranging from one to five households, archaeological evidence from the Lower Rhine delta indicates that large settlements were rare (see Sect. 7.3.5). The majority of settlements comprised just one or two households. Arable land use by small settlements in each sub-region was low enough for both surplus

strategies that the availability of land was not a limiting factor (see Fig. 7.2). Only in those sub-regions with very little arable land, such as those in the peat areas of the central Lower Rhine delta, that were occupied homogenously by large settlements with five households did the availability of arable land restrict the settlements' ability to undertake arable extensification.

Comparisons were also made between the area of pasture and meadow land needed for different cattle herds managed by settlements in each sub-region. Settlements undertaking arable intensification need very few cattle resulting in only a relatively small proportion of the total area of pasture and meadow land being used in each sub-region each year. Conversely, settlements undertaking an extensive animal husbandry strategy by managing herds much larger than those simulated by ROMFARMS could potentially use almost all pasture and meadow land available. In landscapes with smaller settlements, the total number of animals that could be managed was limited most by the availability of labour. When landscapes were occupied by large settlements with three or five households, the availability of land did become more limiting in many sub-regions. Settlements in these scenarios had workforces that could manage more animals than could be supported by the natural landscape.

Only a few instances were recorded when the use of land for one agricultural task could limit the availability of land. In some sub-regions occupied by large settlements comprising three or five households, the use of arable land for pasturing animals can increase the total number of animals that can be managed. In these scenarios, the area of land available for animal husbandry is reduced because settlements undertake arable farming.

7.3.5   Mechanisms of Supply: Micro-regional and Macro-regional Supply Networks

Using a data-set of *castella*, *castra*, towns and *vici*, the demand for grain for human consumption, grain for animal fodder and animal products in each sub-region was estimated. In this paper, only grain for human consumption is considered. Two scales of supply network were envisaged. The micro-regional supply network is one where consumer-only settlements were supplied by rural agrarian settlements located in the same micro-region. The macro-regional supply network was denoted as a supply network where all settlements in the Lower Rhine delta were involved in the supply of all military settlements, towns and *vici* located in the Dutch *limes* zone.

The results from these comparisons showed that for grain supply for human consumption, a micro-regional supply network was infeasible in many scenarios. This is especially the case for scenarios with small settlements possessing one to two households whose surplus grain output was relatively low per settlement. The amount of grain that can be supplied is also lower when settlements undertake arable intensification (see Fig. 7.3). In scenarios where settlements comprised three or five households, a majority of the grain required for either human consumption or to be used as fodder could be supplied on a micro-regional scale when settlements undertake arable extensification. Changes in demand and supply were observed
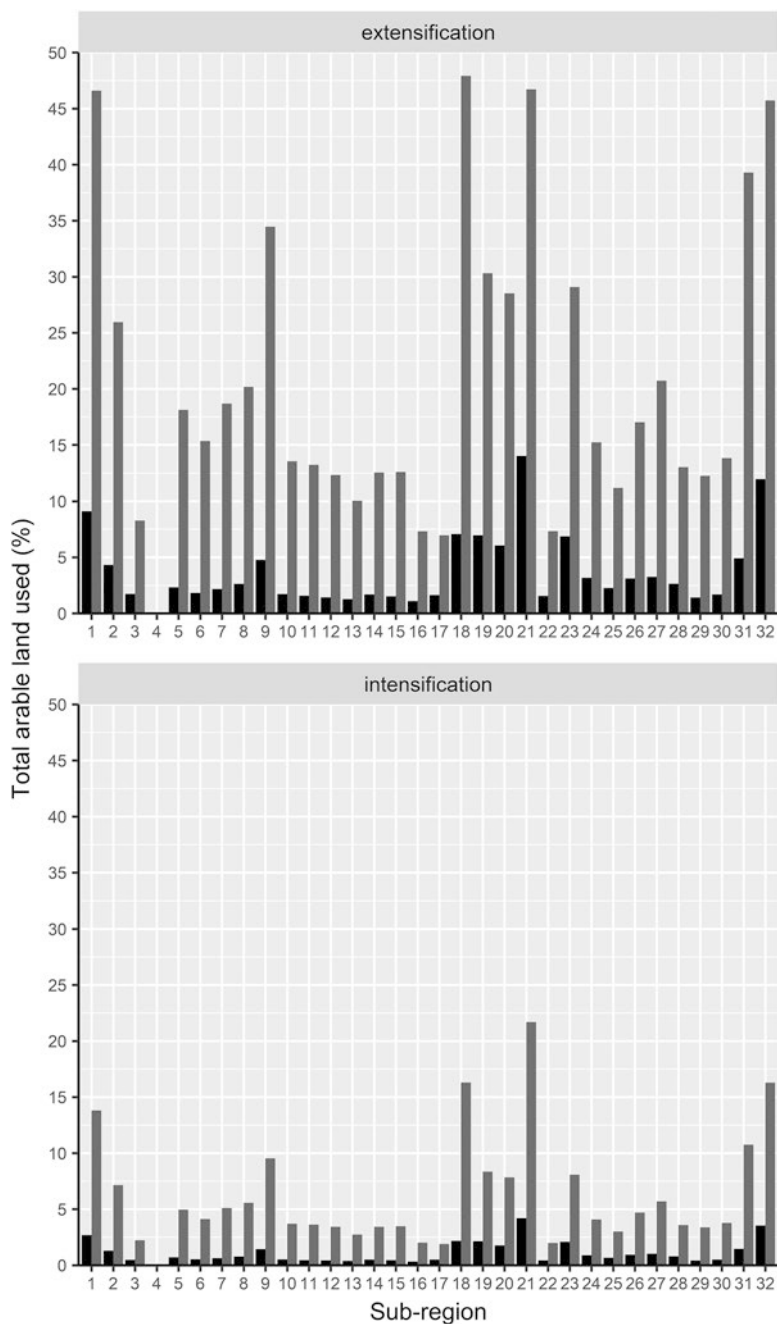
Fig. 7.2 Percentage of total arable land available used per sub-region in scenarios with homogenous occupation by settlements with one (black) or five (grey) households using settlement densities from the Middle Roman Period A
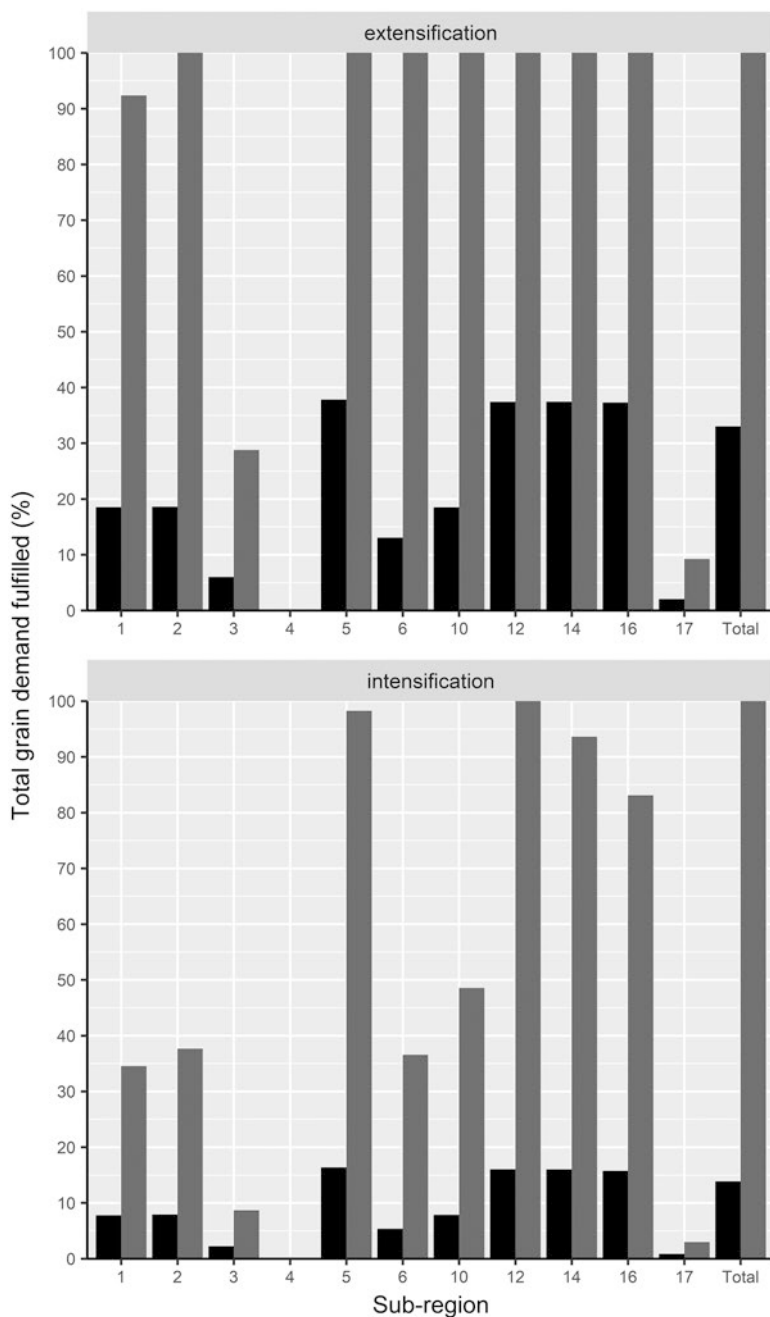
Fig. 7.3 Percentage of grain demand per micro-region and total macro-regional demand that can be fulfilled by supply in each micro-region from settlements with one (black) and five households (grey) during the Middle Roman Period A when demand was highest. Population estimates per *castella* and *vicus* are 350 per settlement (after Van Dinter et al. 2014) with a further 5500 civilians and soldiers in the larger settlements at Nijmegen and 1000 civilians in Forum Hadriani

over time with an increasing demand from military settlements, towns and *vici* from the Early to the Middle Roman period as well as increases in settlement density. These changes result in only slight variations in the pattern of surplus and deficits calculated for sub-regions however. Owing to the variation in settlement density in sub-regions, the surpluses produced in the sparsely populated peat regions (sub-regions 2–4, see Fig. 7.1) produce smaller quantities of surplus grain than the more densely occupied regions in the central part of the Lower Rhine delta (e.g. sub-regions 8–11, see Fig. 7.1).

With most sites identified from surface find-spots and few remains of actual buildings, only broad assumptions can be made about the typical size of a settlement in the region. Vossen (2003) argued that large settlements were exceptional in the region. Van Dinter et al. (2014) and De Kleijn et al. (2016, 2018) both assumed 1.5 households as the average size of a rural settlement. Landscapes occupied homogenously by settlements all comprising the same number of households are unrealistic. However, if the occupation of landscapes by small settlements was the norm, the results from scenarios where simulated settlements possess one or two households better reflect the situation in the past. A micro-regional supply network was unlikely to have been able to fulfil the demands of consumer-only settlements in all sub-region.

In contrast, the results show that a macro-regional supply network for grain is more feasible (see Figure 7.3). The sum total of grain produced, including where sub-regions are occupied by small settlements, is sufficient to fulfil a much higher proportion of the grain demanded in the whole region than in the majority of sub-regions. If landscapes were mostly occupied by small settlements in the Roman Dutch *limes* zone, a macro-regional supply network would be better suited to responding to the demands of *castra*, *castella*, towns and *vici* for grain.

7.4   Conclusion and Outlook

The development of ROMFARMS encountered several theoretical and methodological difficulties. Choosing an appropriate time scale to use in simulations as well as reconciling the different frequencies that agricultural activities took place was required. Each step represents 1 year in ROMFARMS and therefore processes that take place more than once per year were simulated multiple times within each step. This increased processing time significantly. In addition, there existed an upper limit to the number of agents that could be simulated in ROMFARMS. The use of sub-regions prevented simulation of the agricultural economy on a macro-regional scale. The economic activities of military settlements, towns and *vici* that could impact on the availability of land were not simulated. Furthermore, ROMFARMS includes only limited provision for agents to adapt. An inconsistent availability of data to generate different assumptions and estimates was noted. Assumptions were not available for many agricultural tasks. There were also significant uncertainties when estimating settlement densities for periods, the chronology of non-agrarian

settlements and populations of *castella*, *vici* and towns. The calculations of supply and demand are based on currently available domain knowledge. As more domain knowledge becomes available, the accuracy of these estimates will improve.

ROMFARMS relies on the economic rationalism of agents. When farmers undertake surplus production in ROMFARMS, they are limited only by economic factors. Agents in ROMFARMS are not affected by exogenous socio-political or cultural factors. Concepts such as land ownership, land choice or Roman macro-economic policies are incorporated either superficially, or not at all. Although it was understood that these concepts would have impacted agricultural behaviour in the past, it was not possible to produce behavioural rules from them to implement in ROMFARMS. Instead, ROMFARMS has been used to simulate the baseline scenario: the first step in simulating agricultural behaviour in the study region in the past. Future approaches using ROMFARMS may wish to develop the model to incorporate social and cultural factors and observe how the results may differ from the null scenario.

As ROMFARMS is reliant on the sub-model of settlement population dynamics, the strength of this part of the simulation has a large impact on the results produced. The sub-model developed for this model uses simplifications of demographic processes. Marriage rules, for example, are simplified with few rules (c.f. Danielisová et al. 2015; Verhagen et al. 2016a). ROMFARMS assumes patrilocal marriage and the relocation of orphans and other dependents to the nearest settlement. Again, these assumptions are based on currently available domain knowledge which are subject to change and, hopefully, improvement. Further research could analyse the effect of recruitment of the local population into the Roman army which could have had a significant impact on the availability of labour and the marriage pool (see Van Dinter et al. 2014; Verhagen et al. 2016a). The use of life tables and fertility estimates provide usable approximations of mortality and birth rates in the past but should be treated with caution (Woods 2007).

Further development of ROMFARMS should focus on implementation of socio-political and cultural factors. In addition, development of the sub-models, particularly settlement population dynamics, will improve how representative the results are. ROMFARMS as a computational tool is a new contribution to the analysis of agriculture in the past, alongside other recent approaches (see, e.g. Cimler et al. 2012; Saqalli et al. 2014; Danielisová et al. 2015; Danielisová and Štekerová 2015; Baum 2016; Baum et al. 2016; Olševičová et al. 2014). The results from simulating multiple scenarios in both randomly generated and reconstructed landscapes have generated new hypotheses regarding the relative impact of land and labour availability on agricultural productivity and the possible ways in which rural agrarian settlements could have supplied military settlements, towns and *vici* that did not produce their own food. It has reduced the full spectrum of possibilities to a limited range of plausible scenarios which further research can be directed to. The results from ROMFARMS confirm that occupation of the Lower Rhine region by small settlements in relatively sparsely populated micro-regions reduced labour availability, thereby possibly limiting the production of surplus grain and animal products.

Appendix

Table 7.4 Parameter values for scenarios discussed in this chapter

Variable	Value	Increment	Notes
Experiment 1			
No-1-household-settlements	0/2	–	
No-2-household-settlements	0/2	–	
No-3-household-settlements	0/2	–	
No-5-households-settlements	0/2	–	
Runtime	100	–	
Region	"Hyp"	–	
Period	N/A	–	
Area-levee	0.5	–	
Area-floodbasin	0.5	–	
Forest-cover	0.1	–	
Fen-cover	0	–	
%-calories-from-crops	0.1–1.0	0.1	
Store-size	1.5	–	
Strategy-arable	"Extensification"/"intensification"	–	
Surplus-takeoff	0.1–1	0.1	For "extensification" (for "intensification" surplus takeoff = 1.0)
Daily-per-capita-fuel-use	6	–	
Coppicing?	Y	–	
Collection-frequency	1	–	
Reconstruction-frequency	20	–	
Cattle?	Y/N	–	
Sheep?	Y/N	–	
Horse?	Y/N	–	
Sheep-strategy	"Meat", "milk", "wool"	–	
Cattle-strategy	"Meat", "milk", "manure/traction"	–	
Experiment 2			
Region	1–32		
Period	"IJZ", "ROMVA", "ROMVB", "ROMMA", "ROMMB"		
	NB. Other values same as experiment 1		

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