Could the local population of the Lower Rhine delta supply the Roman army?

Part 2: Modelling the carrying capacity using archaeological, palaeo-ecological and geomorphological data

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Abstract

In this part two of a diptych of articles, we modelled and quantified the carrying capacity of the landscape and the demand and supply of the Roman army in the western Lower Rhine delta with wood and food in the period A.D. 40 – 140. The absolute volumes of the wood and food were calculated (in m^3 and kCal) and converted into surfaces needed (in km^2). In addition, the acreage of available land in the area was quantified (in km^2). A comparison of these various values reveals that the carrying capacity of the landscape was larger than hitherto assumed. Initially, the landscape was not limiting for the total demand. However, the pressure on the landscape increased due to a growing population, and because of this the upper limits on the possibilities of production set by the landscape may have been reached in the second century A.D. Furthermore, our calculations show that wood and food, especially cereals, could be procured from agrarian settlements in the immediate surroundings. Therefore, the local population was probably much more involved in the provisioning of the Roman army in the Lower Rhine delta. It seems likely that the Roman army combined local provisioning with extra-regional supply and long-distance transport.

Keywords: conceptual model, demand and supply, food and wood provisioning, limes, quantitative model, Roman army, Roman farming

1. Introduction

As a result of a number of recent studies on Roman forts and other military structures in the Rhine delta, the development of the Roman frontier is once again at the centre of attention after a period of relative silence (e.g. Blom & Vos, 2008; Graafstal, in press; Luksen-IJtsma, 2010; Polak *et al.* 2004; Polak, 2009; Van der Kamp, 2007; idem 2009). The series of small military forts which were built from the 40s A.D. onwards between Vechten and the North Sea was in use well into the third century (fig. 1). The original wooden forts were rebuilt in wood several times, for instance after the Batavian revolt (A.D. 69). It was not until the mid-second century that they were replaced by (partly) stone forts (e.g. Bechert 1983, 94; Blom & Vos 2008, 416; Glasbergen 1972; Haalebos 1977; Ozinga *et al.* 1989; Polak *et al.* 2004). It is not only unusual that the forts were rebuilt at the same locations; they were also given a different function at the end of the first century. Initially, they served to protect shipping, but when the Rhine became the northwestern frontier of the Roman Empire, the so-called *Limes*, the function changed to border defence (Graafstal in press; Polak *et al.* 2004, 249-250; Van Dinter 2013).

As has already been mentioned in the first part of this diptych, good logistics and supply are key to the success of military operations (e.g. Groenman-Van Waateringen 1989). These aspects probably also formed the basis of the sustainable stay of the Roman army in the Dutch Rhine-Meuse delta, which lasted several centuries. Of course, the Rhine as a transport river by itself was enough to guarantee the successful presence of the Roman army. However, the question is to what extent the *limes* landscape and the rural population contributed to the success by supplying the army with food and wood.

In the previous century, based on the then still limited set of (bio)archaeological data, researchers believed that the food for the army in the Rhine-Meuse delta was imported: cereals from Gallia and the meat from Barbaricum (Bloemers 1983; Groenman-Van Wateringe 1977; Van Es 1981, 166-173; Willems 1986; Whittaker 1994). At that moment little was known about the origin of the timber for forts and other military structures and the fire wood (Groenman-Van Wateringe 1988; Stuijts 1988; Van Enckevort 1987; Van Rijn 1990).

Part 1 of this diptych of articles gives a descriptive overview of the results of archaeological, palaeo-environmental and geomorphological research that has since been carried out in the Rhine-Meuse delta (Kooistra *et al.* 2013). This overview reveals that the local population of the central Dutch River Area to the south of the Rhine was completely integrated in the Roman empire as early as the first century. From the end of the first century, this population was certainly capable of producing a surplus of crops, mainly emmer wheat and barley, and livestock, mainly cattle (e.g. Groot 2008; Groot *et al.* 2009; Heeren 2009; Roymans 2004; Vos 2009). Although not as well researched, this also appears to have been the case for the western Rhine-Meuse delta (Bloemers 1978; Flamman & Goossens 2006; Siemons & Lanzing 2009; Van der Velde 2008). Timber for military constructions was mainly provisioned from the surroundings of the forts (Van Rijn 2004; Lange 2007), except in the case of the large construction campaigns in AD 99/100 and 123/125 during which the road and river infrastructure along the Rhine were drastically renewed (Luksen-IJtsma 2010, 95). Import products were also found in the forts. For example, the cereals spelt wheat and bread wheat were imported, and it cannot be excluded that meat was also imported. The amphorae present in the forts make clear that more products were imported, such as wine, olive oil and fish sauce.

The extent of the local production of food for the army, however, cannot be analysed through descriptive, qualitative research. Therefore, in part 2 of the diptych an attempt will be made to establish the extent of the possible local supplies of food and wood to the army in the western Lower Rhine delta. To this end, a conceptual model was developed in which the landscape and its use are central (fig. 2). This conceptual model is based on a existing landscape model (Kooistra 1996, 63-80; 92-113), with the addition of more recent site models (Groot *et al.* 2009; Groot & Kooistra 2009; Vos 2009). In the models of these authors, the landscape and its use by the agrarian population were central. The conceptual model presented here is more extensive because it also contains the requirements of the Roman army for food and wood.

Subsequently, this conceptual model is applied to the western Lower Rhine delta for the first one hundred years following the arrival of the Roman army to estimate the demands and supplies of wood and food. Accordingly, these quantities are converted into areas of land necessary to produce the quantities needed. Based on these estimated amounts the following questions will be answered: 1. Could the provisioning theoretically have been sustained by the local environment? And if so, 2. Could the local rural population hypothetically have produced enough surplus to fulfil the demand of the army? The results of the calculations are also compared to the archaeological evidence described in part one of this diptych.

In this way, the calculations will give an indication whether the carrying capacity of the area was significant or not and contribute to the discussion on the role of the local population in the provisioning of the Roman army and its associates. Therefore, the research offers a unique opportunity to gain further insight into both the carrying capacity of the landscape and the local supply and demand of wood and food in the Lower Rhine delta after the arrival of the Roman army.

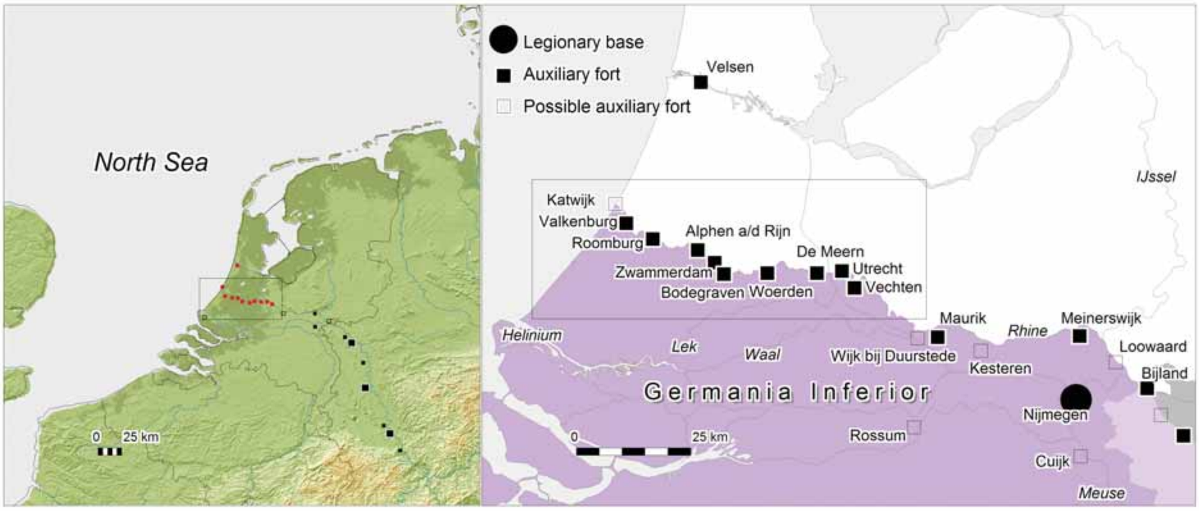

Figure 1. Research area in the Netherlands with Rhine delta forts projected on modern topography (after Polak, 2009). Box indicates research area and in purple the Roman province Germania Inferior at the end of the first century A.D.

2. Methods

2.1 Model concept

For this research we developed a conceptual model to determine the potential of the Lower Rhine landscape in provisioning the Roman army with food and wood (fig. 2). This model is based on three main components: (i) the landscape, (ii) the rural population and (iii) the Roman army and its associates. The area of land available for obtaining wood for timber and fuel, and food production in an area forms the central component of the model. A landscape is a defined area within which the geomorphology, hydrology and (natural) vegetation determine the suitability for human activities, by providing wood, and allowing for arable farming and animal husbandry. This landscape thus poses an upper limit on the *availability* of local resources.

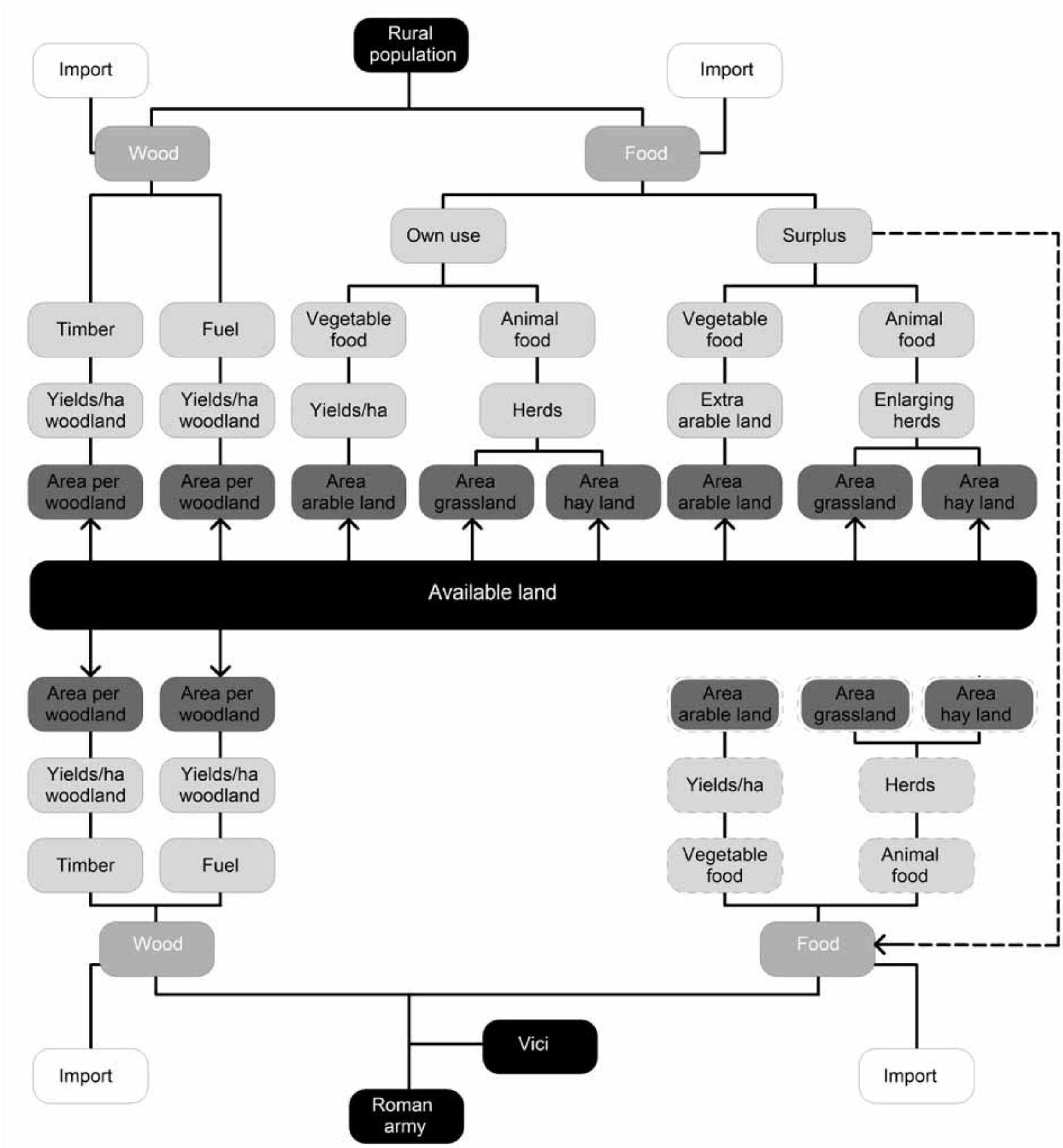

Figure 2. Conceptual model of the landscape services in provisioning wood and food, and the demands of the rural population and the Roman army and its associates in the Rhine-Meuse delta.

The rural population forms the second component in the model. The rural settlements in the delta are *producers* with an agrarian system based on mixed farming. The rural settlements need wood for timber as well as for fuel. This wood was predominantly locally acquired and probably retrieved from different types of woodland that were present in the surroundings. These various woodlands provided different yields, thereby determining the required area of woodlands. The food production consisted of a mixture of vegetable and animal food. The yields of the fields determine the area of arable land needed, and the animal species and herd size determine the areas of grassland and meadows needed for grazing and fodder. If a surplus of both manpower and suitable land is available, the rural population is to a certain extent able to produce extra food for consumers, like the Roman army.

The Roman army and its associates, such as relatives of the soldiers, craftsmen and merchants, living in the *vici*, form the third component in the model. They only produce food on a limited level, e.g. in gardens, and are therefore considered as *consumers* of food. Their food is mainly provided by the surplus produced by the rural population, complemented by food imported from outside the area. When considering wood, they are not just consumers: in our model the Roman army collects wood required for building and fuel by itself in the area. Still, some wood might have been imported from elsewhere. Locally derived wood would have put an extra claim on the woodlands in the area.

2.2 Model implementation

We applied the model to the *limes* zone in the Lower Rhine delta in the period A.D. 40 - 140. Settlements were located on the alluvial ridges of the Lower Rhine, while the gathering of wood and production of cereals and animal food in the research area is assumed to be basically restricted to a c.10 km wide zone distributed evenly on both sides of the river (fig. 3; Vos 2009, 230). The eastern border is positioned halfway between the Roman fort at Vechten and the fort at Wijk bij Duurstede, e.g. about eight kilometres east of Vechten, and the North Sea forms the western border. The study period is limited chronologically to the period from AD 40 to 140, the time by which a highly complex defence system had been established in the Lower Rhine delta. As the population size distinctly changes around 70 AD, we distinguish an early Roman period (AD 40 – 69) and a middle Roman period (AD 70 – 140).

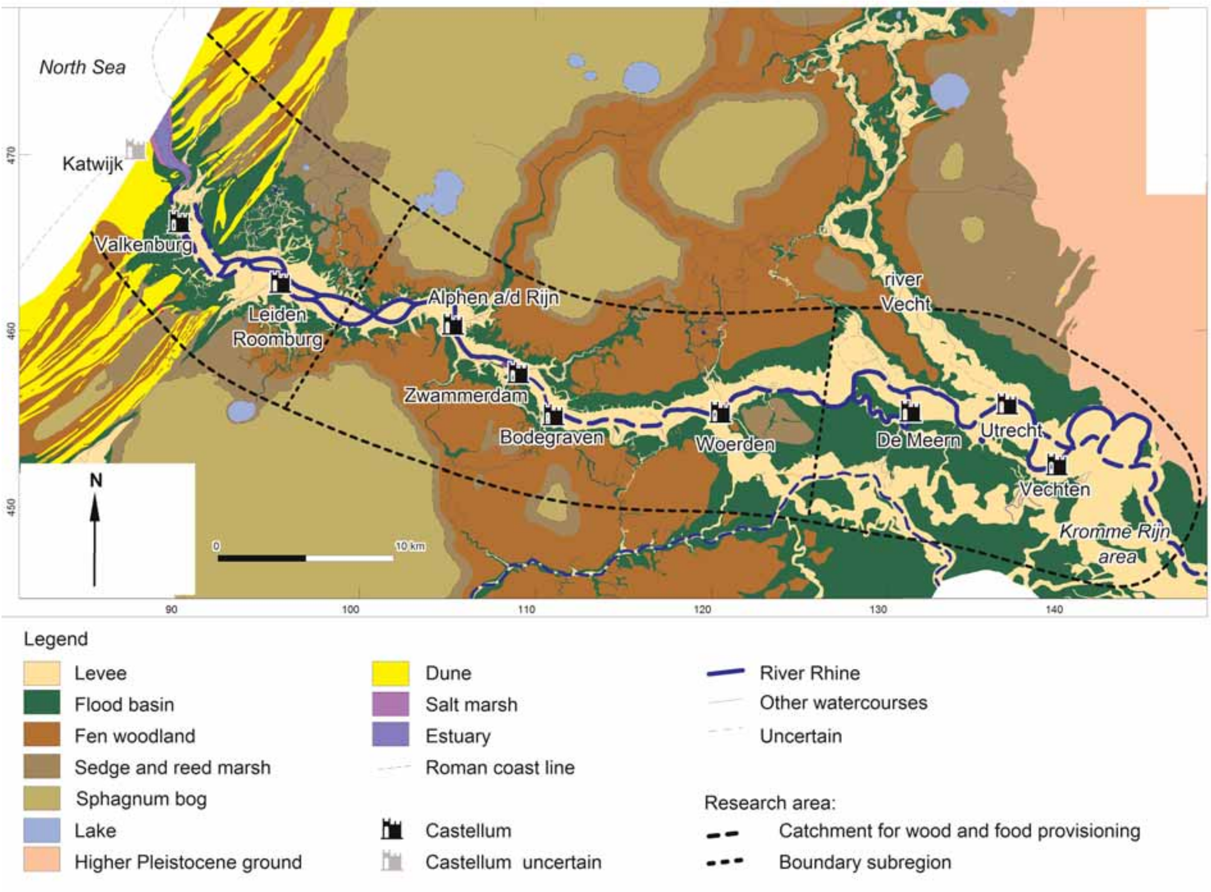

Figure 3. Palaeogeographical map of the western Lower Rhine delta during the Roman period (after Van Dinter 2013).

To quantify the carrying capacity of the landscape, and the demand and supply of wood and food in the research area we formulated four modules, i) a landscape module to determine the area of land that was available, ii) a population module to reconstruct the population size, iii) a military module to determine the demand of the Roman army and its associates and iv) a rural module to calculate both the demand and the surplus production capacity of the rural settlements. The data required for these modules are based on a geomorphological landscape reconstruction of the research area (fig. 3) combined with (bio)archaeological data from excavations of military sites and rural settlements. Information concerning the required amount of food for the soldiers, other males, women and children, arable systems, viable herds, yields etc. are obtained from historical sources, ethnographical studies or experiments. The complete list of parameter values and underlying assumptions used in our model is given in Appendix 1.

2.2.1 Landscape module

The Roman defence system was erected along the south bank of the Lower Rhine (fig. 3). The research area was divided into three different regions, each with their own specific type of landscape (Kooistra *et al.* 2013). The river region in the east with several alluvial ridges with broad levees that enclosed clayey flood basins; the central peat region with large peat areas behind the relatively narrow levees and flood basins of the Rhine; and the western coastal region with the freshwater tidal district, the estuary of the Rhine and the dune area. The various geomorphological units have distinct characteristics in terms of elevation and composition of the subsoil and thereby determined the suitability of the area for settlement, woodland growth, agrarian use and animal husbandry (table 1). The areas of land (in km^2) that were potentially available in each region for local wood and food supply were determined on the basis of a newly constructed, detailed palaeogeomorphological map (Van Dinter 2013; digitally available at *http://www.persistent-identifier.nl/?identifier=urn:nbn:nl:ui:13-08qf-sf*). In this detailed map the legend units 'levee' and 'flood basin' are subdivided into sub-classes according to their height. The subdivision between 'high' and 'low' in table 1 are based on this subdivision. The distribution of the levees and flood basins east of fort Vechten, the Kromme Rijn area, are based on Berendsen (1982) and the subdivisions into 'high' and 'low' are set at 2/3 respectively 1/3 of the total unit 'levee' and conversely for the 'flood basin'.

*Table 1. The different landscape units and their potential for human use (colour = possible suitable; partially coloured means only parts of the landscape unit are suitable); * = only in use as hay land, ** = only in use as grassland, *** = only areas directly bordering a flood basin are in use as hay land.*

2.2.2 Population module

The population module estimates the size of both the military and rural populations. The military component in the model focuses on the supply of a *standing* army and includes soldiers stationed in the forts as well as the related inhabitants of the civil settlements, the *vici*, that over time were erected around the forts. Although the forts downstream of Vechten were built to house one cohort, about 480 - 500 soldiers, writing-tablets excavated in the Roman fort Vindolanda in England show that a fort is often not fully manned (Bowman 2003, tablet Vindolanda II 154; also http://vindolanda.csad.ox.ac.uk). It appears that several of the western Dutch forts did not contain complete cohorts either. Glasbergen & Groenman-van Waateringe (1974) assume that cavalry was also stationed in fort Valkenburg in the pre-Flavian period (AD 40 – 69; phase 1 two *turmae* and in phase 1b and 2/3 both eight *turmae,* half *ala quingenaria*). As a result, only 384 respectively 256 men could reside in the fort. Indications for the presence of cavalry are also established for the forts in Vechten and in Utrecht (Zandstra & Polak 2012; Chorus in press). As this evidence is only recently revealed and the other forts do not show evidence for the presence of cavalry, it is not included in our model. But in paragraph 4.3 we shortly discuss the amount of food needed for the cavalry horses for these three forts and the possibility for local production.

In our calculations we therefore use a number of 350 permanent inhabitants per fort, and assume a double garrison in the larger fort of Vechten (Appendix 1). The extra pressure brought by the provisioning of marching armies, like the gathering of soldiers preceding the British invasion, is not included in our model as these demands are short-termed (Groenman-van Waateringe 1989). Neither taken into account is the presence of the Roman fleet, because there is no firm evidence (yet) for the presence of large scale military harbours, like in Velsen (Morel 1988; Bosman 1997), in this part of the delta during the research period.

Estimates of the rural population size were derived from the reconstructed number of rural settlements in the research area. We attempted to derive a minimum population size, in order to determine to what extent the surplus production by the rural population could meet the needs of the Roman army.

2.2.3 Military demand module

The military demand of wood and food was estimated in terms of wood volumes and kCal food. We assume that the army was involved in the felling of woodlands to obtain timber for construction of the various military structures and for fuel. The wood demand comprises the necessary volumes of both timber needed for the military structures (forts, watch towers, roads, waterfront installations, and granaries, all including renovation and repair) and fire wood. The presence of bathhouses in the research area has not been established before AD 150. Therefore, the wood consumption regarding their construction and fuel consumption has not been taken into account (Vollgraff & Van Hoorn 1941; Haalebos 1977, 65; Polak *et al.* 2004, 20). Fire wood was needed for various activities, such as domestic use (cooking, baking and heating), craft activities and for cremations. Part of this firewood was branch wood or picked up, but most likely this was not enough to cover the demand.

Wood for timber has requirements with regard to tree species and size, but is only needed in large quantities during building campaigns or for large-scale maintenance activities. Fuel wood requires a constant supply, but has less demands in terms of tree species and size. These differences have been considered in the model, as well as the rate at which the forests regenerated after cutting (Appendix 1).

We assume that the soldiers and vicus inhabitants were only food consumers and not producers (Kooistra *et al.* 2013). Estimates of the necessary amount of food of both soldiers and vici inhabitants are based on the diet (in kCal), and the ratio in their diets between plant and animal food. Based on palaeo-ecological and archaeological data it is assumed that the Roman soldiers and their associates acquired most of their energetic requirements from cereals and beef (Kooistra *et al.* 2013). In this publication, therefore, the calculations are limited to the demand and supply of cereals that could be grown and supplied locally. We assume that the cereals that could not be grown in the rural settlements in the delta due to specific ecological requirements were imported and these are not incorporated in the model (Appendix 1). For meat and meat products, we have accordingly assumed the sole use of cattle in our model.

The next step consisted of the translation of the required m^3 and kCal into areas of woodland, arable fields and grazing grounds (km^2). According to the range of wood taxa in the archaeological record, the wood would have come from various types of woodlands that grew on the different landscape units. The yields of these various woodlands will have differed. The calculations of the areas of woodland are based on estimated wood yields of the woodlands that were used in the Roman period, natural as well as managed ones, that were present in the various landscape units, and divided over the most likely landscape units.

It was not possible to use the yields of modern natural woodlands in the Netherlands for the estimation of the yields of the natural woodlands (Clerckx *et al.* 1994; Jansen *et al.* 1996; Wolf 1995). First of all because that kind of woodland no longer exists today, and secondly because modern woodlands are relatively young, the substrate is generally moderately nutrient-rich and the hydrological situation is not natural in most cases. Estimates for the yield of the Roman woodlands have therefore been based on research on the remnants of a Roman woodland near Zwolle (M.J. Kooistra *et al.* 2006; Sass-Klaassen & Hanraets 2006), and the trunk diameters in combination with the number of year rings of construction wood used in the Roman forts of Valkenburg and Alphen aan den Rijn.

The calculations for the areas of arable fields are based on the energy yield in kCal per kg cereals, the amount of sowing seed, the yields per ha, the rotation system and any reserves. The calculations for meat, however, cannot be based directly on the number of kCal and their equivalent in terms of numbers of animals. The reason is that the slaughtered animals, in our case cattle, are part of a herd. These herds are not slaughtered all at once, but should provide a long-term, steady supply of meat, with other words, the herds have to be large enough to be and stay viable. Therefore, we have chosen an approach in which the number and size of the herds are central, and in which the yield in kCal per herd per year is estimated. Based on the requirement for meat, expressed in kCal, the number of herds necessary is calculated. The number of ha required for pasture and meadows is calculated per herd. The fact that the age composition of the herd and thus its food intake changes throughout the year as a result of births, growth, deaths and slaughter is taken into account. The yield of pasture and meadows is estimated. Through a combination of these data, it was eventually possible to calculate the total amount of pasture and meadows required. We have used optimum and constant yields to estimate the minimum of land needed to sustain the total population in the research area with wood and food.

2.2.4 Rural production module

The demand for wood and food by the rural population is likewise estimated in terms of m^3 wood and kCal food and calculated in a similar way to the military demand. From the archaeological record it is clear that the import of both wood, for example wine barrels, and food was very limited and therefore this is not taken into consideration in our calculations. With regard to wood, estimates were made of the required volumes of construction wood for rural farm houses and fire wood (in terms of m^3), and with the estimated yields of the woodlands (paragraph 2.2.3; m^3/ha) the volumes have been translated into the required areas (km^2).

On the basis of the palaeo-ecological and archaeological data it is assumed that the rural population, just like the military population, obtained most of their energetic needs from cereals and beef (Kooistra *et al.* 2013). The estimates for the required amount of food (in terms of kCal) have then been calculated in the same way as in the military module.

Furthermore, the potential surplus production capacity of the arable farming and the animal husbandry was calculated based on surplus labour capacity of the rural population. Subsequently, the total rural demand and supply of food are converted into areas of land (km^2) necessary to produce these amounts.

2.3 Local provisioning? Comparisons between carrying capacity, demand and supply

Finally, we compared the area of land that was *available* with the amount of land that was *required* to provide the total population, e.g. the local farmers as well as the Roman army and its associates, with wood and food. Furthermore, we also considered to what extent the local labour capacity was sufficient to carry out the work involved to produce the amount of food that was needed to provision the Roman army with local products.

3. Results

3.1 Land availability

The landscape of the research area contained a variety of units suitable for different uses (fig. 3 and table 1). The distribution and dimension of these units differs per region (table 2). Table 2 shows the size of the various geomorphological units in the three distinguished regions in the research area. The area of high grounds, such as levees and dunes, as well as the area of wet flood basin roughly decreases from east to west. Furthermore, vast fen woodlands were present behind the flood basin in the central and western part of the research area. In the eastern river region, fen woodlands were only present north of the Rhine, downstream along the river Vecht (fig. 3).

	West		*Central*		*East*	
	Total	South	Total	South	Total	South
Levee, high	17	11	39	22	105	73
Levee, low	16	9	18	10	27	19
Flood basin, high	22	12	18	10	34	24
Flood basin, low	43	17	50	27	75	45
Fen woodland (*)	44 (17*)	22 (5*)	140	77	8	0
Sedge and reed marsh (**)	40 (30)	15 (7)	20 (6)	15 (6)	8 (8)	0
Sphagnum bog	11	4	39	25	0	0
Dune	> 36	> 18	0	0	0	0
Salt marsh	> 2	> 1	0	0	0	0
Total	> 231	> 109	324	186	257	161

*Table 2. Size of geomorphological units in the western Lower Rhine delta in the Roman period (in km^2); * = on barrier plain, ** = bordering flood basin.*

3.2 Population size

3.2.1 Military population

Based on the assumptions listed in Appendix 1, the ten forts were populated by a total number of 3,850 soldiers in both periods (table 3; appendix 1). The minimum number of reconstructed vici inhabitants changed from only 700 *vici* inhabitants in the early Roman period (around the fort at Vechten) to 3,850 in the middle Roman period (table 3). This means that the lowest estimate of the total military population in the research area is 4,550 persons in the early Roman period and 7,700 in the middle Roman period (table 3).

	West	*Central*	*East*	*Total*
Early Roman Period (AD 40 - 69)				
Forts (N)	3	4	3	10
Vici (N)	0	0	1	1
Number of soldiers	1050	1400	1400	3850
Number of vici inhabitants	0	0	700	700
Total population	*1050*	*1400*	*2100*	**4550**
Middle Roman Period (AD 70 - 140)				
Forts (N)	3	4	3	10
Vici (N)	3	4	3	10
Number of soldiers	1050	1400	1400	3850
Number of vici inhabitants	1050	1400	1400	3850
Total population	*2100*	*2800*	*2800*	**7700**

Table 3. The estimated number of soldiers and vici inhabitants per period per region.

3.2.2 Rural population

Based on the archaeological reports in the national archaeological database ARCHIS, 210 settlements were reconstructed on the levees and the dunes in the research area (Kooistra *et al.* 2013; table A1 in Appendix 1). Figure 4 shows the location of reconstructed settlements. The distribution of the rural settlements over the research area is not uniform. The eastern and western regions seem to have been more densely populated than the central peat region. In these two regions, there were on average almost two settlements per km^2 high levee. According to Vos (2009, 214) such high settlement densities were only reached in the most densely inhabited regions of the Rhine-Meuse delta.

These settlements were not all inhabited contemporaneously; several were only inhabited during the early or middle Roman period. The number of settlements in the Rhine-Meuse delta increased during the first two centuries A.D. (Kooistra *et al.* 2013). To account for the differentiation in settlement sizes, we use an average number of farmsteads per settlement, the so-called settlement-unit with 1.5 farmsteads, which were inhabited by c. 10 people for each rural settlement (Appendix 1). The amount of land that was occupied by the settlement-units themselves is not taken into account in the model, because this turned out to be less than 5% on the levees and dunes in the Early and Middle Roman period (Appendix 1).

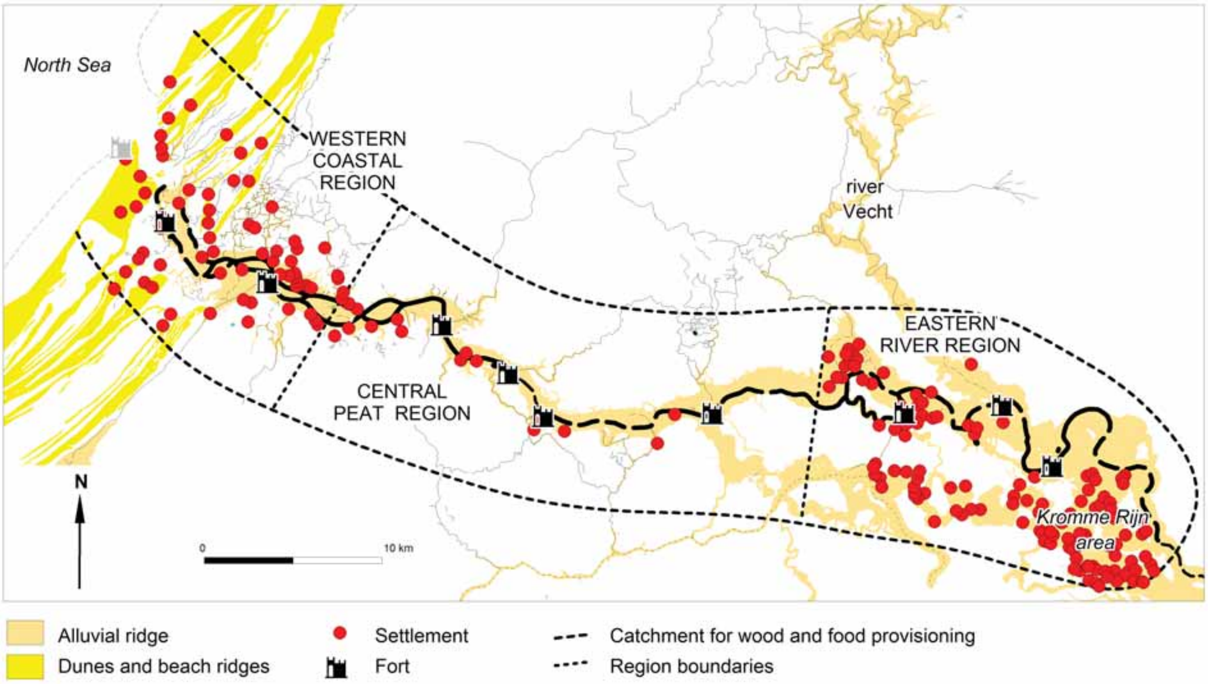

Figure 4. Reconstructed settlements in the western Lower Rhine limes zone based on ARCHIS database (2009; after Kooistra et al. *2013).*

These estimates and associated assumptions (table A2 in Appendix 1) lead to a reconstruction of 105 settlement-units in the early Roman period and 177 in the middle Roman period (table A2 in Appendix 1). When considering that there were settlements that disappeared (e.g. by natural river erosion or excavation of sand or clay by human for raw material during later centuries) or so far have remained undiscovered, a correction was applied that leads to a minimum reconstructed number of settlements of about 120 in the early Roman period and about 200 in the middle Roman period (table 4; table A3 in Appendix 1). In both periods 38 of these settlement-units were located north of the Rhine. This leads to a reconstruction of 1,200 people in the early Roman period, a figure that nearly doubles to 2,000 in the middle Roman period. This implies that the military population largely outnumbered the rural population in both time periods, roughly by a factor 3.5 (table 3 and 4).

	West	*Central*	*East*	*Total*
Early Roman period (AD 40 – 69)				
Northern dunes	10	-	-	10
Northern levees	9	9	10	28
Southern dunes	4	-	-	4
Southern levees	5	11	63	79
Total	28	20	73	**121**
Middle Roman period (AD 70 – 140)				
Northern dunes	10	-	-	10
Northern levees	9	9	10	28
Southern dunes	8	-	-	8
Southern levees	10	21	127	158
Total	37	30	137	**204**

Table 4. The minimum number of reconstructed rural settlement-units per region and location north and south of the river Rhine.

3.3 Military demand

3.3.1 Wood demand

Wood research has shown that most timber was acquired locally (Kooistra *et al.* 2013). This wood was acquired in various forests which differed in composition and structure from modern woodlands. As the yields from modern woodlands differed largely from those in Roman times, they could not be used for calculations. Therefore the yields of the Roman woodlands had to be estimated.

Tree taxon	*Growth category**	*Age (from year of germination)*		*Trunk diameter (at breast height in cm)*		*Yields (in m3/ha)*	
		Modern	*Roman*	*Modern*	*Roman*	*Modern*	*Roman "Natural"*
Oak	3 - 4	80 - 120	82 - 122	15.8 - 23.3	10 - 20	105 - 171 a	100 - 125
Oak	5	80 - 120	123 - 244	38.2	34 - 40	247 a	
Oak	-	-	-	-	-	-	50 - 75 b
Alder/Oak/Birch	4	90	-	26.5	30 - 40	139 a	100
Alder	8	10 - 25	-	4.6 - 13.8	6 - 15	13 - 136 a	13 - 100
Ash/elm	4	90	58 – 217	22.5	25.5	195 a	175
Ash/elm	4	Up to 55		16.2	9 - 16.5	135 a	100
						Alder coppice	
Alder	-	30 - 40	-	-		80 - 230 c	200
Alder/Ash	-	8**	12***	8 - 10	7 - 15	200 - 250**** d	

*Table 5. Estimates of the yields of Roman trees (in grey), on the basis of the differences between present-day and Roman woodlands, in ages and trunk diameters of the various taxa. Except for the reference of Casparie all references relate to modern data. The Roman data are distilled from archaeological and dendrochronological research carried out in the research area; * = an indication for the variations of wood accretion (in the production levels of wood volume), depending on factors such as soil types, hydrological regime, etc., ** = for fuel, *** = for timber (this number of rings is based on c. 40 counts of archaeological samples of alder).*
References: a. Jansen et al. *1996, b. yields of the 'bog fringing forest' are deduced from Casparie 1982, 155, c. Clerckx* et al. *1994, d. Ter Keurs pers. com.*

Geomorphological unit	*Estimated wood yield (in m3/ha)*	*Main taxa*
Levee, high	100	Oak, maple, ash, elm
Levee, low	125	Alder, ash
Flood basin, high	125	Alder, willow
Coppice on low levees or high flood basin	200	Alder
Fen woodland	75	Oak, ash, alder
Barrier plains	100	Alder, willow

Table 6. Estimated yields of Roman woodlands (with the main taxa found in the archaeological record and wood remains) on the different geomorphological units in the Lower Rhine delta.

The yields from the Roman woodlands were estimated based on age and (estimated) diameters of (real or reconstructed) Roman tree remains (Staring 1983; Jansma 1995; Fokma 1998; M.J. Kooistra *et al.* 2006; Sass-Klaassen & Hanraets 2006). Table 5 shows a comparison of these values with those of various taxa of modern trees. The differences are remarkable: remains of Roman tree trunks with diameters similar to modern trees usually contain many more year rings than modern trees. In other words, trees from Roman natural woodlands grew slower than present trees and were thinner than modern trees of the same age. Hence, the yields of

Roman woodlands were lower than those of modern woodlands (table 5). Based on these estimates, the wood yields were calculated for the various forest types present on the different geomorphological units in Roman times (table 6). The resulting yields vary strongly among different woodland types. The lowest yields were obtained for the woodlands on the fens, while the highest yields would have come from alder coppices located on the lowest parts of the levees and the high parts of the flood basin.

According to the assumptions indicated in Appendix 1, the total minimum estimated wood demand of the military population was 7.3 x 10^5 m^3 in the early Roman period and rose to 28.7 x 10^5 m^3 in the middle Roman period (table 7; table A5 in Appendix 1). The woodlands that most likely provided these quantities are shown in table 7. These forests cover 37.6 km^2 in total in the early Roman period and 45.2 km^2 in the middle Roman period. Both the actual and the relative amounts of exploited woodlands differ per region and time period, depending on the population size and presence of different woodlands. It is assumed that in the early Roman period only the high levees in the central peat region still carried substantial areas of natural mixed woodlands. The natural woodlands on the levees in the eastern river region and western coastal region were most probably already largely deforested, as these areas were relatively densely populated in pre-Roman times (Kooista *et al.* 2013). Therefore, it is assumed that the Roman army stationed in the eastern region mainly exploited the flood basins and the fens downstream along the river Vecht. The forts in the western coastal region most likely retrieved part of their timber from the natural mixed woodlands on the levees in the peat area, only a few kilometres upstream.[1] By AD 70, these woodlands had been felled almost completely (Van Rijn 2004). To cope with the disappearance of these resources, the Roman army probably found a permanent solution through the development of alder copses on the edge of the levees and in the flood basins. These copses could provide both timber and firewood.

	West		*Central*		*East*		*Total*	
	Timber	*Fuel*	*Timber*	*Fuel*	*Timber*	*Fuel*	*Timber*	*Fuel*
Early Roman period (AD 40 – 69)								
Demand (in m^3 x 10^5)	0.3	1.4	0.4	1.8	0.6	2.8	1.4	6.0
	km^2	km^2	km^2	km^2	km^2	km^2	km^2	km^2
Levee, high	1.1 *	-	1.9	4.6	3.1	-	6.2	4.6
Levee, low	0.9	-	0.8	3.7	1.3	3.7	2.9	7.4
Flood basin, high	0.8	1.8	0.8	3.7	1.3	3.7	2.8	9.2
Fen woodland	0.2	-	-	2.0	-	-	0.2	2.0
Barrier plains	-	2.3	-	-	-	-	0.0	2.3
Total	3.0	4.1	3.4	14.0	5.7	7.4	12.1	25.5
Middle Roman period (AD 70 – 140)								
Demand (in m^3 x 10^5)	1.6	6.4	1.6	8.6	1.9	8.6	5.1	23.6
	km^2	km^2	km^2	km^2	km^2	km^2	km^2	km^2
Levee, high	-	-	-	-	-	-	-	-
Levee, low	-	-	-	2.5	0.9	-	0.9	2.5
Flood basin, high	-	-	-	2.5	0.9	-	0.9	2.5
Coppice on low levees or high flood basin	0.9	1.8	1.3	2.5	1.0	4.9	3.1	9.2
Fen woodland	11.1 **	-	8.6 **	-	1.8 **	-	21.6	0.0
Barrier plains	-	4.6	-	-	-	-	0.0	4.6
Total	12.0	6.4	9.8	7.4	4.6	4.9	26.5	18.7

*Table 7. Estimate of wood demand (m^3) for military population per region in the period between AD 40 and 140, converted into km^2 and divided over the woodlands on the most likely used different geomorphological units. Difference in total values are due to rounding; * partially retrieved in central peat area, ** (partially) retrieved north of the river Rhine.*

3.3.2 Demand of vegetable food

Cereals were the most important food for the Roman soldiers (Kooistra 2009; idem 2012; Kooistra *et al.* 2013). Therefore, the calculations for the demand and supply of vegetable food are only based on the consumption of cereals. Although part of the cereals for the Roman army was imported from elsewhere, it is likely that a substantial part was obtained from local farmers and thus produced within the study area (Kooistra *et al.* 2013). In our calculations we therefore assumed that 50% of the total military demand for cereals was derived from cereals that could be produced in the local surroundings. Based on the assumptions for the vegetable food demand (Appendix 1), the estimated total energy requirement of locally produced cereals per year for the army and its associates in the research area was 16.1 x 10^8 kCal in the early Roman period and 24.9 x 10^8 kCal in the middle Roman period (table 8). The total area of cultivated arable fields needed to feed the army and its entourage with emmer and barley was 6.6 km^2. In the middle Roman period, when *vici* appeared around all forts, 10.2 km^2 of arable fields would have been required for cereal production. As the model is based on a two-course rotation, this means that the abovementioned areas need to be multiplied by two, resulting in a total of about 13 km^2 in the early Roman period and about 20 km^2 in the middle Roman period (table 8).

	West	*Central*	*East*	*Total*
Early Roman period (AD 40 – 69)				
Energy needed for soldiers (kCal)	3.9 x 10^8	5.1 x 10^8	5.1 x 10^8	14.1 x 10^8
Energy needed for vici inhabitants (kCal)	0	0	2 x 10^8	2 x 10^8
Total energy needed for soldiers and vici (kCal)	3.9 x 10^8	5.1 x 10^8	7.1 x 10^8	16.1 x 10^8
Arable land needed for soldiers (km^2)	1.6	2.1	2.1	5.8
Fallow land needed for soldiers (km^2)	1.6	2.1	2.1	5.8
Arable land needed for vici inhabitants (km^2)	0	0	0.8	0.8
Fallow land needed for vici inhabitants (km^2)	0	0	0.8	0.8
Total arable + fallow land needed (km^2)	**3.2**	**4.2**	**5.8**	**13.2**
Middle Roman period (AD 70 – 140)				
Energy needed for soldiers (kCal)	3.9 x 10^8	5.1 x 10^8	5.1 x 10^8	14.1 x 10^8
Energy needed for vici inhabitants (kCal)	3.0 x 10^8	3.9 x 10^8	3.9 x 10^8	10.8 x 10^8
Total energy needed for soldiers and vici (kCal)	6.9 x 10^8	9.0 x 10^8	9.0 x 10^8	24.9 x 10^8
Arable land needed for soldiers (km^2)	1.6	2.1	2.1	5.8
Fallow land needed for soldiers (km^2)	1.6	2.1	2.1	5.8
Arable land needed for vici inhabitants (km^2)	1.2	1.6	1.6	4.4
Fallow land needed for vici inhabitants (km^2)	1.2	1.6	1.6	4.4
Total arable + fallow land needed (km^2)	**5.6**	**7.4**	**7.4**	**20.4**

Table 8. Cereal demand for locally produced cereals, e.g. emmer and barley, (kCal) necessary to feed the Roman army and the vicus inhabitants per region in the period between AD 40 and 140, converted into areas of cultivated arable land with cereals and fallow land (km^2).

3.3.3 Demand of animal food

Because cattle was the main meat provider of the army, the calculations for the demand and supply of domestic meat and meat products are only based on the consumption of beef (Kooistra *et al.* 2013). As no data are available on the size and calorific value of cattle herds kept by the farmers in the Roman period in the Rhine-Meuse delta and the amount of land needed for pasture, these parameters are estimated by combining data on herd size, composition, slaughter patterns, and calorific values from several studies (Gregg 1988; Lauwerier 1988; IJzereef 1981; Meffert 1998). According to Gregg (1988), the minimum size of a viable herd is at least 30 heads in winter time. Based on our assumptions, such a herd will annually yield a total of 2.3 x 10^6 kCal (table A6 in Appendix 1). As a settlement-unit needs 1.8 x 10^6 kCal of meat products yearly (Appendix 1, ad 3.4.3), this would leave 0.5 x 10^6 kCal - equivalent to almost one cow a year - to the settlement as surplus for exchange or storage, feasting, ritual etc. As this herd size does not yield a significant surplus of meat for the Roman army, a herd size of 50 heads in winter time was taken as the basis for further calculations. A herd of this size has a different composition and size structure than one with 30 heads. The increase results in a proportionally different slaughter pattern. A herd of 50 heads will annually yield 3.8 x 10^6 kCal (table A7 in Appendix 1). This means that a herd of 50 heads may produce a yearly surplus of c. 2.0 x 10^6 kCal, an equivalent of c. 4 mature cows.

We assume that the herds grazed on the pastures and fallow land. After harvesting, they could also feed on the stubble left on the arable fields. During the winter period, lasting four months, they were fed with hay. Yet, the herd size is not stable throughout the year. Calving, natural deaths and slaughter influence the herd size. Therefore, different numbers were used to calculate the hay and grass consumption. Table 9 shows the size and relative food intake of each age group during the year. During the winter months an equivalent of 45.6 mature cows were used for calculations on hay consumption and during the grazing season an equivalent of 47.9 cows for pasture.

Based on three bovines per ha, the areas needed for pasture of a herd of 50 heads amounts to 16 ha (section 3.4.3 in Appendix 1). In addition, hay meadows were needed to produce fodder for the winter period. As a herd of 50 heads would consume hay to the equivalent of 45.6 mature cows and assuming a high annual yield of 3400 kg hay per ha, at least an extra 10.1 ha of meadow was needed to sustain the herd's needs during the winter months (section 3.4.2 in Appendix 1). Hence, an area of at least 26.1 ha of pasture and meadow was needed to sustain a viable herd of 50 heads. Assuming a fallow system was used for crop cultivation (section 3.3.2), the additionally required land for pasture and meadows by a settlement-unit to sustain a herd was reduced by the amount of fallow land, which is 3.3 ha per settlement-unit (section 3.4.2 in Appendix 1).

Herd composition	*Number in winter when fed hay*	*Food intake (% of mature cow)*	*Total intake herd for hay (as number of mature cow)*	*Number in grazing period*	*Food intake (% of mature cow)*	*Total intake herd for pasture (as number of mature cow)*
Calf	0	0	0	15	15	2.25
Up to 1 year	12	80	9.6	0	0	0
Heifer	10	80	8	22	80	17.6
Oxen	7	100	7	7	100	7
Cow	19	100	19	19	100	19
Bull	2	100	2	2	100	2
Total	50	-	45.60	65	-	47.85

Table 9. Calculations of pasture needed for a herd composition of 50 heads in winter. Food intake is calculated to the equivalent of mature cows (1 mature cow taken as 100%; see also Gregg 1988, 107).

Based on the assumptions for the demand of meat (Appendix 1), the total energy requirement of meat per year for the army and its associates in the research area is reconstructed at 10.7 x 10^8 kCal in the early Roman period and 16.5 x 10^8 kCal in the middle Roman period (table 10). As one herd of 50 heads produced a yearly surplus of 2.0 x 10^6 kCal, the reconstructed settlement-units would have been able to produce 2.4 x 10^8 kCal in the early Roman period and 3.3 x 10^8 kCal in the middle Roman period (table 10). This, however, is only 20-25 % of the meat required for the army; none of the regions would have been able to produce enough animal food for the army in both periods. This apparent deficit means that the number of herds needed was larger. An extra herd of 50 heads would yield a surplus of 3.8 x 10^6 kCal, as the demands of the rural settlement-units in the area were already fulfilled. Thus, 219 extra herds of 50 heads would be needed in the early Roman period, roughly corresponding to two additional herds per settlement-unit when distributed evenly (table 10). These extra herds would by themselves require an extra land-use for the Roman army and the *vici* inhabitants of 57.1 km², distributed over 35 km² of pasture and 22.1 km² of meadows.(table 10). Together with the land in use by the settlement-units (table 13 and 15a), the total area needed for animal husbandry in the early Roman period would be 84.7 km², of which 50.4 km² needed for pasturage and 34.3 km² as meadow.

For the middle Roman period, with a reconstructed number of 166 settlements south of the river Rhine and an increased number of *vici* inhabitants, the need for extra herds increased to 348, adding up to a total of 514 herds of 50 heads (table 10). So again, when distributed evenly, each settlement-unit had to take care of approximately three or even four herds. These extra herds would require an extra 90.8 km². This figure would, together with the land used by the local population (table 13 and 15b) add up to a total of 128.7 km², distributed over 76.8 km² of pasture and 51.9 km² of meadow. This would be the absolute minimum of land needed for animal husbandry to sustain the Roman army and its associates in the research area in this period with meat (table 10).

	West	*Central*	*East*	*Total*
Early Roman period (AD 40 – 69)				
Energy needed for soldiers (kCal)	2.6×10^8	3.4×10^8	3.4×10^8	9.4×10^8
Energy needed for vici inhabitants (kCal)	-	-	1.3×10^8	1.3×10^8
Total energy needed for soldiers and vici (kCal)	2.6×10^8	3.4×10^8	4.7×10^8	10.7×10^8
Rural settlements (keeping one herd of 50 heads) (N)	28	20	73	121
Surplus production of rural settlements (kCal)	0.6×10^8	0.4×10^8	1.4×10^8	2.4×10^8
Extra herds needed to feed Roman army and vici (N; excl. domestic need)	53	80	86	219
Pasture needed for extra herds (km²)	*8.5*	*12.8*	*13.8*	*35.0*
Meadows needed for extra herds (km²)	*5.4*	*8.1*	*8.7*	*22.1*
Total of herds needed to feed Roman army, vici and domestic need of settlement-units (N)	**81**	**100**	**159**	**340**
Middle Roman period (AD 70 – 140)				
Energy needed for soldiers (kCal)	2.6×10^8	3.4×10^8	3.4×10^8	9.4×10^8
Energy needed for vici inhabitants (kCal)	1.9×10^8	2.6×10^8	2.6×10^8	7.1×10^8
Total energy needed for soldiers and vici (kCal)	4.5×10^8	6.0×10^8	6.0×10^8	16.5×10^8
Rural settlements (keeping one herd of 50 heads) (N)	18	21	127	166
Surplus production of rural settlements (kCal)	0.4×10^8	0.4×10^8	2.5×10^8	3.3×10^8
Extra herds needed to feed Roman army and vici (N; excl. domestic need)	109	147	92	348
Pasture needed for extra herds (km²)	*17.4*	*23.5*	*14.7*	*55.7*
Meadows needed for extra herds (km²)	*11.0*	*14.8*	*9.3*	*35.1*
Total of herds needed to feed Roman army, vici and domestic need of settlement-units (N)	**127**	**168**	**219**	**514**

Table 10. Demand of meat (kCal) necessary to feed the Roman army and the vicus inhabitants per region in the period between AD 40 and 140, converted into numbers of herds and areas of pasturage and meadow needed for extra herds (based on surplus production of herds of 50 heads in wintertime).

3.4 Rural demand and supply

3.4.1 Wood demand

There is little information on the wood used for farms and barns in the rural settlements in the research area in the first and second centuries A.D. (Lange 2009). Rural settlements in other areas provide information that mostly alder, ash and oak had been used for construction (Van

Rijn 1995; idem 2003; Vorst & Hanninen 2005) and that is most likely the case here too. The quantity of timber and firewood is estimated per settlement-unit (table A8 in Appendix 1). Based on these assumptions the total wood demand of the rural settlements is calculated at c. 1.2 x10^5 m^3 in the early Roman period and rises to 5.1 x10^5 m^3 in the middle Roman period (table 11 and table A8 in Appendix 1). The forests that most likely provided these quantities cover 4 km^2 in total in the early Roman period and 2.3 km^2 south of the river in the middle Roman period. The quantities needed are very small and almost negligible compared to those used by the army and the *vici* in both periods (table 7). The rural settlements in both periods were in all probability supplied by alder retrieved from woodlands nearby. In the early Roman period, the wood is assumed to be derived from the various natural woodlands on the levees and in the flood basin, the fen woodlands and the barrier plains. In the middle Roman period, natural woodlands on the levees and flood basin had become scarce. There are strong indications that a system of wood management was introduced and that most wood was acquired from alder coppices established on the high flood basins. With the development of these alder coppice it is likely that the rural population became involved in the management. The appearance of farm buildings of native character in the 2nd century, for example on the site of Valkenburg-Marktveld (Hallewas *et al.* 1993, 37-42) in former military territory could be interpreted in this view.

	West		*Central*		*East*		*Total*	
	N	*S*	*N*	*S*	*N*	*S*	*N*	*S*
Early Roman period (AD 40 – 69)								
demand (in m3 x 10*5)	0.1	0.7	0.1	0.1	0.1	0.1	0.3	0.9
	km²		km²		km²		km²	
Levee, high	0.05	-	-	-	-	-	0.05	0.00
Levee, low	0.04	-	-	-	0.16	0.99	0.20	0.99
Flood basin, high	0.04	0.02	0.01	-	0.16	0.99	0.21	1.01
Fen wood land	-	-	0.46	0.58	-	-	0.46	0.58
Barrier plains	0.32	0.18	-	-	-	-	0.32	0.18
Total	**0.45**	**0.20**	**0.47**	**0.58**	**0.32**	**1.99**	**1.23**	**2.76**
Middle Roman period (AD 70 – 140)								
demand (in m3 x 10*5)	0.3	0.3	0.2	0.6	0.3	3.5	0.8	4.3
	km²		km²		km²		km²	
Levee, low		0.02		0.17		-		-
Flood basin, high		0.02		0.17		-		-
Barrier plains		0.18		-		-		-
Coppice on low levees or high flood basin		0.09		0.17		2.05		2.31
Total		**0.3**		**0.51**		**2.05**		**2.31**

Table 11. Minimum wood consumption for timber and fuel (m^3) for agrarian settlements per region in the period between AD 40 and 140, converted into km² and divided over the woodlands on the most likely used different geomorphological units. Difference in total values are due to rounding.

3.4.2 Arable farming

The rural population was autarchic in food supply; cereals were the primary vegetable food component (Kooistra *et al.* 2013). Based on the assumptions of vegetable food demand, one settlement-unit needed 3.3 ha to satisfy its own needs for cereal food (Appendix 1). The minimum amount of land necessary to feed the total rural population in the early Roman period amounts to 8.0 km², distributed over 2.6 km² north of the river and 5.4 km² south of the river Rhine (table 12). In the middle Roman period, the number of settlements south of the river doubled and therefore 13.6 km² was needed of which 11 km² was located south of the river

Rhine. These areas were smaller than those required to fulfil the demand of the military population, but less than the ratio of the population sizes because we assumed that the military population imported part of the consumed cereals, e.g. spelt wheat and bread wheat (Appendix 1; 50%).

	West		*Central*		*East*		*Total*	
	N	*S*	*N*	*S*	*N*	*S*	*N*	*S*
Early Roman period (AD 40 – 69)								
Settlements (N)	19	9	9	11	10	63	38	83
Arable land for own use (km²)	0.6	0.3	0.3	0.4	0.3	2.1	1.3	2.7
Fallow land for own use (km²)	0.6	0.3	0.3	0.4	0.3	2.1	1.3	2.7
Total land needed for own use (km²)	1.2	0.6	0.6	0.8	0.6	4.2	2.6	5.4
Middle Roman period (AD 70 – 140)								
Settlements (N)	19	18	9	21	10	127	38	166
Arable land for own use (km²)	0.6	0.6	0.3	0.7	0.3	4.2	1.3	5.5
Fallow land for own use (km²)	0.6	0.6	0.3	0.7	0.3	4.2	1.3	5.5
Total land needed for own use (km²)	1.2	1.2	0.6	1.4	0.6	8.4	2.6	11

Table 12. Areas of arable and fallow land (in km²) needed to feed the rural population per region and period; N = north of the river Rhine; S = south of the river Rhine.

3.4.3 Animal husbandry

Cattle was the main meat provider in agrarian settlements during the entire Roman period (Kooistra *et al.* 2013). In our model, meat products consumed by the rural population were entirely obtained from their own cattle. A settlement-unit needed c. 1.8 x 10^6 kCal per year (Appendix 1). With one herd of 50 heads per settlement-unit and each herd requiring at least 16 ha of pasture and 10.1 ha of hay meadow (Appendix 1). As seen above (section 3.4.2) a fallow system was used for crop cultivation; the additionally required land for pasture by a settlement-unit to sustain a herd was reduced by the amount of fallow land, which is 3.3 ha per settlement-unit (section 3.4.2 in Appendix 1). The minimum area necessary to feed the total rural population in the early Roman period amounts to 8.7 km² north of the river and 18.9 km² south of the river Rhine (table 13). In the middle Roman period, when the number of settlements south of the river had doubled, accordingly requiring 37.8 km² of pasture and meadow land south of the river Rhine.

	West		*Central*		*East*		*Total*	
	N	*S*	*N*	*S*	*N*	*S*	*N*	*S*
Early Roman period (AD 40 – 69)								
Settlements = herds (N)	19	9	9	11	10	63	38	83
Land needed for husbandry (km²)	4.3	2.1	2.1	2.5	2.3	14.4	8.7	18.9
Pasture (km²)	2.4	1.1	1.1	1.4	1.3	8.0	4.8	10.5
Meadow (km²)	1.9	0.9	0.9	1.1	1.0	6.4	3.8	8.4
Middle Roman period (AD 70 – 140)								
Settlements = herds (N)	19	18	9	21	10	127	38	166
Land needed for husbandry (km²)	4.3	4.1	2.1	4.8	2.3	29.0	8.7	37.8
Pasture (km²)	2.4	2.3	1.1	2.7	1.3	16.1	4.8	21.1
Meadow (km²)	1.9	1.8	0.9	2.1	1.0	12.8	3.8	16.8

Table 13. Areas of pasturage and hay land needed (in km²) for animal husbandry to feed rural population per region and period (based on one herd of 50 heads in wintertime per settlement-unit). Difference in total values are due to rounding; N = north of the river Rhine; S = south of the river Rhine.

3.4.4 Rural surplus production

Arable farming

We assumed that the agrarian population had to produce cereals for the army, in addition to the production of their own consumption, and that the soldiers and the *vicani* did not contribute to the production process. As manpower is essential for the cultivation of cereals, this implies that the rural labour potentially forms a constraint for the surplus production for the Roman army. In the process of grain production, the labour exertion during harvest is a potential bottleneck. Ploughing, sowing, and working the soil can be accomplished by a small number of people over a longer period of time. Harvest time, on the other hand, is limited, because if the grain remains in the field too long after ripening, the ears fall apart before they can be harvested. In addition, the chance that the ripe grain will be eaten by, for example, birds or mice, increases the longer it remains in the field. Therefore, the harvest had to be completed within two weeks (Gregg 1988).

	West		*Central*		*East*		*Total*	
	N	*S*	*N*	*S*	*N*	*S*	*N*	*S*
Early Roman period (AD 40 – 69)								
Settlements (N)	19	9	9	11	10	63	38	83
Potential arable land available for surplus production (km2)	1.8	0.9	0.9	1.0	1.0	6.0	3.7	7.9
A. Sum arable fields (km2)	2.7		1.9		7.0		11.6	
B. Arable land needed for demand of military population (km2)	1.6		2.1		2.9		6.6	
Net result (A-B), surplus (+) or deficit (-) of arable land (km2)	**1.1**		**- 0.2**		**4.1**		**5.0**	
Extra settlements needed to compensate deficit (N)	-		**2**		-		-	
Middle Roman period (AD 70 – 140)								
Settlements south of the Rhine (N)	-	18	-	21	-	127	-	166
A. Potential arable land available for surplus production (km2)	-	1.7	-	2.0	-	12.1	-	15.8
B. Arable land needed for demand of military population (km2)	-	2.8	-	3.7	-	3.7	-	10.2
Net result (A-B), surplus (+) or deficit (-) of arable land (km2)	-	**-1.1**	-	**-1.7**	-	**8.4**	-	**5.6**
Extra settlements needed to compensate deficit (N)	-	**9**	-	**14**	-	-	-	-

Table 14. Number of settlements and estimated areas of arable land (in km^2) available for surplus production based on labour capacity (A), the demand of the military population (B) and the net result (A-B) per time period and per region; N = north of the river Rhine; S = south of the river Rhine.

The potential cereal surplus production capacity per region per time period based on the availability of extra labour provided by the rural settlements is shown in table 14. In the early Roman period, the maximum amount of available labour for surplus production allows cultivation of 7.4 km^2 north of the river and 15.8 km^2 south of the river, or 23.2 km^2 in total. In the middle Roman period, when we assume that only the settlements south of the river delivered surplus production, the available labour capacity allowed cultivation of 31.6 km^2 of land. When this surplus production capacity is compared to the demand of the Roman army and its associates, it turns out that in both the early and middle Roman period the total number of reconstructed settlement-units was large enough to provide extra labour for surplus production. However, the amounts of the surplus production differed per region. In the early Roman Period, the rural settlements south of the river Rhine in the eastern river region alone could have provided sufficient surplus for that region, while the forts in the central peat region and in the western coastal region could only have been supplied with enough emmer and barley if the settlements on the northern side of the Rhine helped in providing it. In the middle Roman period, when we assume that only settlements south of the river produced surplus for the Roman army, shortages must have occurred in the central peat region and in the western coastal region. However, the agrarian population of the eastern river region would have been able to produce enough emmer and barley not only for the military and *vici* inhabitants stationed in the region, but also to supplement the production deficiencies in the central peat and western coastal regions.

Cereal transport

The imported cereals for the Roman army, e.g. spelt wheat and bread wheat, were most likely transported by ship, either over the North Sea and up the river, or by navigating downstream on the rivers Rhine or Meuse (Haalebos 1997). Cereals that were produced by the local rural population were probably also preferably transported by ship, along the rivers and many smaller tributaries in the *limes* zone. Because not all cereal-producing farms were positioned along waterways, the cereals must have been transported over land over short distances. It is likely that cattle belonging to the local herds were used for this. Therefore, our model does not account for extra draught cattle in the rural population.

Animal husbandry

In order to calculate the surplus production of animal food, initially the surplus of the herds of the settlement-units is assumed to be used for the army's demand for meat. In section 3.3.3, we have seen that when taking one herd of 50 heads per settlement-unit, in both periods c. three-quarters of the yearly demand for meat from the army cannot be met (table 10). Therefore, the number of extra herds required to meet this demand was calculated in that paragraph. Since the needs of the local population were already satisfied by the yield of their own herd, the total yield of these extra herds can be supplied to the Roman army as surplus. It has already been established earlier that in both the early and middle Roman periods each settlement-unit had to keep at least two to three extra herds on average to meet the total demand from the army. However, the settlements are not evenly spread over the landscape in the research area. This picture becomes even stronger in the middle Roman period when only the settlements on south of the river Rhine are supposed to produce for the Roman army and its associates. When we look at the individual regions, it becomes clear that due to the limited number of reconstructed settlements in the central peat and western coastal region even more herds per settlement-unit would have been necessary there, while in the eastern river region only c. one herd extra was needed per settlement-unit (table 10).

Draught cattle

To satisfy the demands of the Roman army, our model assumes that the local farmers bred more cattle. Some of these would have been used temporarily as draught animals. Therefore, it was not necessary to breed even more cattle to supply sufficient draught power for the ploughing of a larger number of fields. After being used as draught animals, the cattle could still be supplied to the army as food. Archaeozoological research on the fortress Alchester where relatively older animals were present than in the contemporary sites from the region (Thomas 2008), suggests that the army was indeed supplied with cattle that had first been used as draught animals.

4. Discussion

<table>
<tr><th>a.</th><th>Salt marsh

(km2)</th><th>Sedge and reed marsh*
(km2)</th><th>Dune

(km2)</th><th>Levee, high

(km2)</th><th>Levee, low

(km2)</th><th>Flood basin, high
(km2)</th><th>Flood basin, low
(km2)</th><th>Fen woodland
(km2)</th><th>Barrier plain with fen woodland
(km2)</th></tr>
<tr><td>Western coastal region</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Available land</td><td>2</td><td>30</td><td>36</td><td>17</td><td>16</td><td>22</td><td>43</td><td>27</td><td>17</td></tr>
<tr><td>Woodland</td><td>-</td><td>-</td><td>-</td><td>1.2 **</td><td>0.9</td><td>2.7</td><td>-</td><td>0.2</td><td>2.8</td></tr>
<tr><td>Arable land</td><td>-</td><td>-</td><td colspan="2">5.6</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Grassland ***</td><td></td><td>-</td><td colspan="4">12.0</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Hay land</td><td></td><td colspan="6">8.1</td><td>-</td><td>-</td></tr>
<tr><td>Central peat region</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Available land</td><td>-</td><td>6</td><td>-</td><td>39</td><td>18</td><td>18</td><td>50</td><td>140</td><td>-</td></tr>
<tr><td>Woodland</td><td>-</td><td>-</td><td>-</td><td>6.5</td><td>4.4</td><td>4.5</td><td>-</td><td>3.1</td><td>-</td></tr>
<tr><td>Arable land</td><td>-</td><td>-</td><td>-</td><td>5.6</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Grassland ***</td><td>-</td><td>-</td><td>-</td><td colspan="3">15.3</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Hay land</td><td>-</td><td></td><td>-</td><td colspan="4">10.1</td><td>-</td><td>-</td></tr>
<tr><td>Eastern river region</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Available land</td><td>-</td><td>8</td><td>-</td><td>105</td><td>27</td><td>34</td><td>75</td><td>8</td><td>-</td></tr>
<tr><td>Woodland</td><td>-</td><td>-</td><td>-</td><td>3.1</td><td>6.1</td><td>6.1</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Arable land</td><td>-</td><td>-</td><td>-</td><td>10.6</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Grassland ***</td><td>-</td><td>-</td><td>-</td><td colspan="3">23.0</td><td>-</td><td>-</td><td></td></tr>
<tr><td>Hay land</td><td>-</td><td></td><td>-</td><td colspan="4">16.1</td><td>-</td><td>-</td></tr>
<tr><td>Total</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Available land</td><td>2</td><td>44</td><td>36</td><td>161</td><td>61</td><td>74</td><td>168</td><td>175</td><td>17</td></tr>
<tr><td>Woodland</td><td>-</td><td>-</td><td>-</td><td>10.8</td><td>11.5</td><td>13.2</td><td>-</td><td>3.3</td><td>2.8</td></tr>
<tr><td>Arable land</td><td>-</td><td>-</td><td colspan="2">21.8</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Grassland ***</td><td></td><td>-</td><td colspan="4">50.4</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Hay land</td><td>-</td><td colspan="6">34.3</td><td>-</td><td>-</td></tr>
<tr><td>b.</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Western coastal region</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Available land</td><td>1</td><td>7</td><td>18</td><td>11</td><td>9</td><td>12</td><td>17</td><td>17</td><td>5</td></tr>
<tr><td>Woodland</td><td>-</td><td>-</td><td>-</td><td>-</td><td colspan="2">2.8</td><td>-</td><td>11.1 ****</td><td>4.8</td></tr>
<tr><td>Arable land</td><td>-</td><td>-</td><td colspan="2">6.8</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Grassland ***</td><td></td><td>-</td><td colspan="4">19.7</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Hay land</td><td>-</td><td colspan="6">12.8</td><td>-</td><td>-</td></tr>
<tr><td>Central peat region</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Available land</td><td>-</td><td>6</td><td>-</td><td>22</td><td>10</td><td>10</td><td>27</td><td>77</td><td>-</td></tr>
<tr><td>Woodland</td><td>-</td><td>-</td><td>-</td><td>-</td><td colspan="2">9.1</td><td>-</td><td>8.6 ****</td><td>-</td></tr>
<tr><td>Arable land</td><td>-</td><td>-</td><td>-</td><td>8.8</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Grassland ***</td><td>-</td><td>-</td><td>-</td><td colspan="3">26.2</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Hay land</td><td>-</td><td></td><td>-</td><td colspan="4">17.0</td><td>-</td><td>-</td></tr>
<tr><td>Eastern river region</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Available land</td><td>-</td><td>-</td><td>-</td><td>73</td><td>19</td><td>24</td><td>45</td><td>-</td><td>-</td></tr>
<tr><td>Woodland</td><td>-</td><td>-</td><td>-</td><td>-</td><td colspan="2">9.8</td><td>-</td><td>1.8 ****</td><td>-</td></tr>
<tr><td>Arable land</td><td>-</td><td>-</td><td>-</td><td>15.8</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Grassland ***</td><td>-</td><td>-</td><td>-</td><td colspan="3">30.8</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Hay land</td><td>-</td><td>-</td><td>-</td><td colspan="4">22.1</td><td>-</td><td>-</td></tr>
<tr><td>Total</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Available land</td><td>1</td><td>13</td><td>18</td><td>106</td><td>38</td><td>46</td><td>89</td><td>94</td><td>5</td></tr>
<tr><td>Woodland</td><td>-</td><td>-</td><td>-</td><td>-</td><td colspan="2">21.7</td><td>-</td><td>21.6 ****</td><td>4.8</td></tr>
<tr><td>Arable land</td><td>-</td><td>-</td><td colspan="2">31.4</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Grassland ***</td><td></td><td>-</td><td colspan="4">76.8</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Hay land</td><td>-</td><td colspan="6">51.9</td><td>-</td><td>-</td></tr>
</table>

Table 15. Area of land available (in km²) versus the minimum amount of land (in km²) needed to provide the rural and military population with wood (brown), cereals (yellow) and meat (green) per region and time period and distributed over the potential suitable landscape units. In the middle Roman period, the supply for the military

*population was no longer derived from land located north of the river Rhine (Kooistra 2009; Appendix 3.3.2); * = bordering flood basin, **= partially retrieved in central peat area, *** = corrected for use of fallow land for grazing, **** (partially) retrieved north of river.*

4.1 Land availability and suitability

Table 15 shows the total area of land that is available and the amount of land which is minimally necessary to provision the entire population, i.e. the rural settlements plus the Roman army and *vici*, with wood and locally produced plant and animal food. The comparison indicates that the landscape in the research area did not form a limiting factor for supplying the necessary amount of wood, cereals and animal products to the rural settlements as well as to the Roman army and its associates during the early and middle Roman periods (table 15). Timber, cereals and fodder could largely be retrieved from different landscape units, thereby avoiding conflicting spatial demands (Kooistra *et al.* 2013).

Timber could be collected from the various types of woodland that grew on the levees and in the flood basin as well as the vast fen woodlands further away. This is in agreement with the wood remains of Roman military constructions, which show that most of the timber used in military constructions came from local woodlands. In the early Roman period, the natural old woodlands on the levees and the natural alder wetland woodlands on the higher parts of the flood basins were felled. Later on, timber wood was mainly obtained from the alder copses established on the low levees and flood basins, but also from woodlands on the peat situated more inland (table 15b).

Cereals could only have been cultivated on the higher parts of the levees and the dunes. Table 15 shows that enough potentially suitable land was present for this purpose, assuming that only 50% of the cereals consumed by the soldiers and vici inhabitants consisted of locally produced cereals, even if only fields were utilized that were located on the levees and dunes south of the river Rhine. Thus, the landscape was not necessarily a limiting factor in the supply of locally produced cereals, e.g. emmer and barley, to the Roman army and the *vici*.

Livestock probably grazed on the low parts of the levees and in the fertile flood basin (table 15). Furthermore, both the fallow land and the stubble fields provided supplementary food for the animals. Finally, animal fodder could be harvested on the low parts of the levee and in the high parts of the flood basin. And although we assume that only the settlements on the south bank provided supplies in the middle Roman period, grazing may have taken place on both sides of the river Rhine in the flood basin, only needing a few extra guards against cattle thieves. The landscape was thus not a limiting factor for the grazing area of the herds needed to provide enough meat for the total population in the research area.

According to our estimates, roughly 20% of the levees, flood basins and dunes were required for wood and food provisioning during the early Roman period, rising to c. 55% in the middle Roman period. These figures are minimum estimates as our calculations are based on estimates of minimum population sizes, maximum surplus labour capacity per rural settlement and constant and optimal harvest yields. For the early Roman period this minimum required area is only a quarter of the available landscape; and even if the real requirement would have been twice as large, this area was still available. Therefore, we are confident that in the early Roman period the landscape did not limit local supply. However, if the results are indeed under-estimates of the real numbers, this implies that in the middle Roman period the landscape may have limited a completely local supply.

4.2 Labour availability

The size of the rural population did form a limiting factor for the provisioning of the army and its associates with locally produced food. The largest problem arose for the meat supply. The rural settlements had to increase the amount of livestock and on average take care of c. three herds of 50 heads per settlement-unit both in the early and middle Roman period. This would amount to 150 animals in wintertime. We think this is implausible, especially as no archaeological data are available that point to keeping larger herds, such as an increased number of stable boxes in the byre-houses, or the construction of extra sheds where animals could be housed. We think that even when the herds were kept outside all year long, which is most likely as the winters are fairly mild in the Netherlands and the cattle was much sturdier than nowadays, some stable capacity would have been necessary, especially for cattle used for extra labour and providing milk. But more importantly, the amount of extra (herding) labour was probably strongly limited in the early Roman period because of incomplete households as local farmers were recruited as Roman soldiers (Tacitus, Germ. 29; Hist. 4.12, 17). It is assumed that this recruitment was replaced by taxing in the middle Roman period (Groot *et al.* 2009). Although it is often supposed that herding was a children's task, it seems impossible for the children of one settlement-unit to herd c. 150 animals and even more in summer. Another aspect to take into account is the distribution of the settlements throughout the landscape: in densely populated areas, the herdsmen would have to take their animals to fields at considerable distances from their homes. So, it is likely that the majority of the meat products was imported, probably extra-regionally, for instance from the densely occupied central Dutch river area (Vossen 2003; Heeren 2009, 191) or additional supply came from other sources such as pork, sheep and goat, or fishing and fowling (see also section 4.3). The way transport of (live or dead) animals or meat products was organised and the problems it posed will not be discussed in this article.

The reconstructed number of settlements in the peat region during the early Roman period, and in the peat and coastal region during the middle Roman period was too low to provide enough labour power during harvest time of the locally grown cereals, e.g. emmer wheat and barley. However, the rural labour capacity and the carrying capacity of the landscape for surplus production of cereals in the river area were sufficiently large to overcome this problem. Again, incompleteness of households may also have limited the labour availability for cereal production. Thus, the actual surplus production might have been smaller in the early Roman period than calculated. The total storage capacity in the settlements, indicated by the number and size of the granaries, increased from the 40s AD onwards and in the second century the storage capacity exceeded the demand for the local community (Groot *et al.* 2009; Heeren 2009). This suggests that rural settlements in the middle Roman period were indeed capable of substantial surplus production, and that the associated extra labour capacity was available.

We assume that the tree felling and management of the woodlands were governed by the Roman army or its associates, and that the soldiers themselves were involved in wood cutting. It is unknown whether the rural population was also (structurally) employed for this task. If so, the rural labour capacity for felling trees was probably enough to fulfil the daily needs of wood, but prior to intensive building campaigns of the Roman army their capacity was probably too low. Furthermore, employment of local farmers would not have been possible during periods of harvest and slaughter.

Periods and intensity of the different provisioning activities varied throughout the year (fig. 5). During certain time periods several activities coincided, for example during late autumn with the slaughtering of cattle, ploughing of the fields and wood felling. To avoid this leading to labour shortage, activities might have been shifted in time. For example, wood cutting might have been postponed from autumn to the winter period. To overcome temporary labour shortages during periods of peak activities external labour force may also have been attracted, consisting either of military personnel, seasonal workers from elsewhere or a combination of both. It is likely that the soldiers were at least employed during the building of the military structures like forts, watchtowers and roads. During summertime the soldiers had their military duties and therefore it is assumed that they were not involved in cereal harvesting. If besides the rural population extra assistance was indeed called upon, the logistics were probably so complex that only a tight organisation, like the Roman army, could have directed such authority. If these workmen were already inhabitants of the *vici*, their provisioning is included in the calculations; if not, extra supplies were needed temporarily.

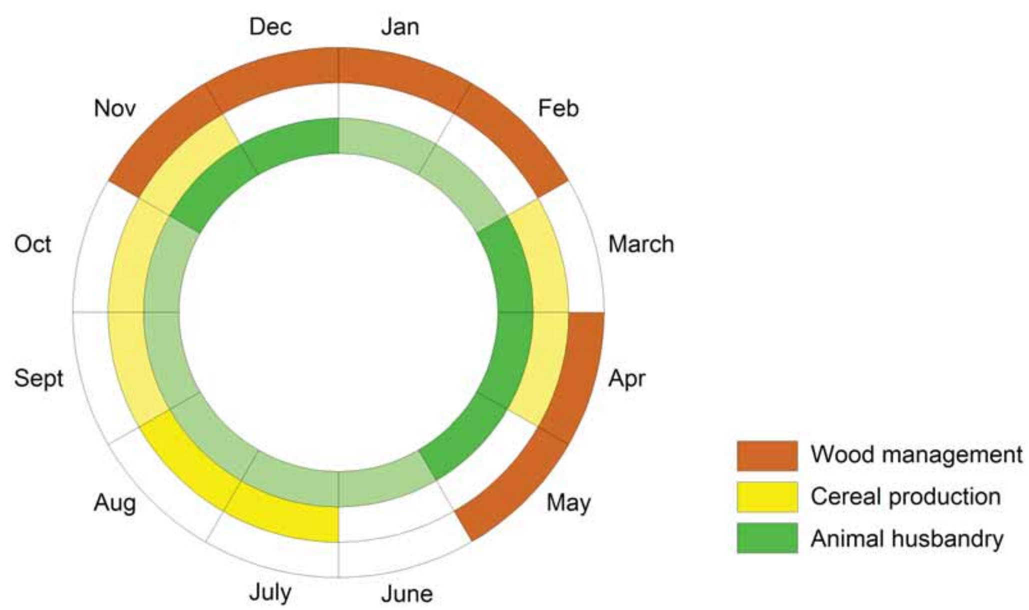

Figure 5. Employment of workmen needed for harvesting of wood, production of cereals and animal food production during the year (intensity of colour reflect labour intensity).

4.3 Parameter uncertainties

The model consists of many parameter values that influence the model outcome. The assigned parameter values are based on a large number of assumptions, inevitably leading to considerable uncertainties. While it was impossible to estimate all uncertainties and to undertake a full uncertainty assessment we will address here the main sources of uncertainty and the potential implications for the obtained results.

The landscape reconstruction, which forms the template for the provisioning of wood and food, is based on high-resolution data (Van Dinter, 2013). Errors in the size of different landscape units within the research area are less than a few km² per unit, implying no significant change in the interpretation of land availability in Roman times.

Our main concern is the reconstruction of the rural population size. The calculations are based on a minimum number of reconstructed settlement-units (table 4). However, it is possible that the number of undiscovered settlements is underestimated, especially in the central peat region and in the dune area. Therefore, we performed a *maximum* calculation in which we assumed a uniform, maximum density on the high levees and dunes of one settlement-units/km² both north and south of the river in the early Roman period, and one settlement-unit/km² north of the river Rhine and two settlement-unit/km² south of the river in the middle Roman period (table 16). These estimates led to a reconstruction of 200 settlement-units in the early Roman period and over 300 in the middle Roman period. This is almost a doubling of the total numbers when compared to our minimum estimate of settlement-units.

	West	*Central*	*East*	*Total*
Early Roman period (AD 40 – 69)				
Northern dunes	18	-	-	18
Northern levees	7	18	32	57
Southern dunes	18	-	-	18
Southern levees	11	22	73	106
Total	54	40	105	**199**
Middle Roman period (AD 70 – 140)				
Northern dunes	18	-	-	18
Northern levees	7	18	32	78
Southern dunes	36	-	-	18
Southern levees	22	44	146	158
Total	83	62	178	**323**

Table 16. The maximum number of reconstructed rural settlements-units per region and location north and south of the river Rhine.

If the rural population did indeed reach these maxima, wood consumption would have increased, but the demand of the local population was relatively smaller when compared to the demand of the military population. The vast fen woodlands north and south of the Rhine formed an almost inexhaustible source of wood. Neither would the area of land needed to supply the total population in the area with food have posed a problem. Moreover, the rural population would have had a larger surplus of labour capacity and therefore have been able to produce more cereal surplus. This would imply that every region would have been able to produce enough to provision the army stationed in that region (table 16 vs table 14). However, each settlement still would have had to guard implausibly large herds, i.e. 100 heads. It is unlikely that this maximum settlement density was reached in the whole research area, especially not in the peat region. The true population size probably lies somewhere in between these minimum and maximum reconstructions.

Another significant uncertainty in the model is the number of soldiers stationed in the research area and the associated number of *vicus* inhabitants. If the maximum number of soldiers was reached, c. 5,500 soldiers would have been present and accordingly c. 5,500 *vici* inhabitants (table 17; Kooistra *et al.* 2013). Sommer (1984; 1991) even suggests that the number of people living in the *vicus* might have been twice the number of soldiers. Although only small sections of the *vici* in the Lower Rhine delta have been excavated these mainly uncovered extensively used areas, often interpreted as gardens, thus leaving only a few hectares per *vicus* for dwellings (e.g. Hazenberg 2000; Ploegaert 2006; Vos *et al.* 2012). Therefore, we think that each *vicus* only consisted of a few dozen houses. Such a small number of dwellings does not match very large garrisons and presumably implies that our assumption of 350 soldiers per fort and an equal number of people living in the surrounding *vicus* is rather a maximum estimate than an under-estimate. Still, if indeed 5,500 soldiers were (temporarily) present in both periods, the military food demand would have increased by a factor 1.5 in both periods. In that case, the landscape could probably still provide sufficient supply of wood and food in the early Roman period, but the rural population would have been too small to feed this population, both in terms of cereals and meat. In the middle Roman period both the landscape and the labour force provided by the rural population would probably have become restricting.

	West	*Central*	*East*	*Total*
Early Roman period (AD 40 – 69)				
Forts (N)	3	4	3	10
Vici (N)	0	0	1	1
Number of soldiers	1500	2000	2000	5500
Number of vici inhabitants	0	0	1000	1000
Total population	1500	2000	3000	**6500**
Middle Roman period (AD 70 – 140)				
Forts (N)	3	4	3	10
Vici (N)	3	4	3	10
Number of soldiers	1500	2000	2000	5500
Number of vici inhabitants	1500	2000	2000	5500
Total population	3000	4000	4000	**11000**

Table 17. The maximum number of soldiers and vici inhabitants per period per region.

Another uncertainty is the ratio in the consumption of cereal/plant food and animal food, and the species consumed. The rural and military population may have relied on a larger portion of other plant-based categories or on animal products obtained through hunting or fishing than assumed in our model. For example, the fish traps, tanks and fish remains unearthed at or near military sites in the research area show that fish was caught and eaten by the soldiers (Beunder 1990; Esser *et al.* 2007; Lange 2012; Van Regteren Altena & Sarfatij 1994a; idem b; Van Rijn 1993; idem 2013). Clearly, fish was a source of protein. However, fish can never have been responsible for more than a small portion in the daily needs of the Roman soldiers. And contemporary rural settlements, even when located near rivers, brooks or the sea, do often not yield any indication for fish-consumption, a phenomenon that cannot be explained by excavation methods (e.g. Groot 2009). Also, hunting in the Roman army was severely restricted. The consumption of sheep/goat, chicken and pig has been attested in both rural settlements and military installations in our research area but never in large quantities (Cavallo *et al.* 2008a; Groot 2008; Groot *et al.* 2009; Groot & Kooistra 2009). And the ratio of land required for grazing and the calorific output of sheep and goat are negative compared to that of cattle; very large herds and amounts of land would be necessary for the same output of calories.

But even when the meat rations of the soldiers are reduced, the number of extra herds per settlement-unit would on average have been too large in terms of labour availability. F.e. if only c. 10% of the diet consisted of meat and meat products from cattle only, so almost half the amount used in our model, the number of extra herds per settlement-unit would have been about one extra herd of 50 heads in the early Roman period and c. two herds in the middle Roman period (see also paragraph 4.2). This still seems too large to manage for one-settlement-unit.

Also, it is assumed that the yields of the arable fields and grasslands, and the health of the herds were optimal and constant. However, conditions in nature are not constant and optima rarely occur. Hail storms, diseases and pests, periodic flooding and droughts would frequently have caused harvest failure and thereby regularly have reduced the potential local surplus production. In our opinion, soil exhaustion was not likely to have influenced production in the delta as fertile sediment was regularly provided by flooding, even on the high levees (Berendsen & Stouthamer 2001).

Then again, the archaeological record shows the presence of cavalry (Glasbergen & Groenman-van Waateringe, 1974; Chorus, in press) and horses in rural settlements (Cavallo *et al.* 2008b; Goossens 2010; Van Dijk 2008a; idem 2008b; Vos & Lanzing 2000). In addition, pack animals, like mules, may also be assumed to have been present. The extra needs of these nonfood animals in terms of fodder and housing have been left out of our calculations but put an extra pressure on the landscape.

The ration of cereals of a cavalry-soldier with horse and servant(s) obviously differed from the ration of an auxiliary soldier. According to Polybius, who lived in the second century BC, a Roman cavalry-soldier received two Attic *medimni* of wheat a month (equal to c. 2.5 kilo per day; Erdkamp 1998) and seven *medimni* of barley (equal to c. 8.8 kilo per day). Hereby, it is assumed that the wheat was consumed by the soldier and his servant(s) while the barley was consumed by the horse and pack animals. An auxiliary cavalry-soldier received less: 1 1/3 Attic *medimni* per month (c. 1.7 kilo of wheat per day), and 5 attic *medimni* per month (c. 6.3 kilo barley per day; Polybius 6.39).

Evidence for the presence of cavalry-units is only established for the forts in Vechten, Utrecht en Valkenburg (paragraph 2.2.2). Due to the comparable size of the forts in Valkenburg and Utrecht, it it is not plausible that more than an half halve *ala quingenaria* (8 *turmae* , each consisting of 16 horsemen) at the most was stationed in the fort in Utrecht as well. However, the fort in Vechten was larger and might have housed a larger cavalry-unit. To feed the horses and other pack animals of one half *ala quingenaria* c. 600 tons of barley would have been needed per year (8 *turmae* x 16 horses x 6.3 kilo barley x 365 days). To grow this amount of barley, 7.5 km² arable land is necessary per half *ala quingenaria* or 15 km² including fallow land (Appendix 3.3.2). Considering the required space for stables, however, it is likely that fewer soldiers were stationed in the forts with cavalry units than in the forts without cavalry. However, the ration of cereals for a horse is much larger than that for a soldier (Polybius 6.39). Therefore, when it comes to the supply of cereals, soldiers and horses are not interchangeable in a cereal supply-model.

In our model, in the early Roman period there are some rural settlement-units that could potentially cultivate extra arable land, both in the western coastal region and in the eastern river region (i.e. 5.2 km² in total; table 14). In the middle Roman period, this is only the case in the astern region, i.e. 8.4 km² (table 14). Since 7.5 km² was already required to grow barley for one half *ala quingenaria*, there are not enough agrarian settlements in our research area to supply at least three *ala quingenaria* with enough barley for horses and pack animals. Thus, this barley must have been imported. The eastern river region was part of the relatively densely populated and intensively exploited *civitas Batavorum* (Kooistra *et al.* 2013). Research by Vossen and Groot (2009) argued that farmers of the entire *civitas Batavorum* must have been able to supply enough barley for the Roman army in the Dutch delta, including horses.

Altogether, we assume that the numerous parameters will not all have been estimated either too high or all too low; some will be estimated too high and others too low. We believe that the total results of our calculations do not change significantly by various changes in parameters. This means that the order of magnitude of the estimated demand and supply will remained the same, so that the conclusions of section 4.1 and 4.2 will be upheld.

4.4 Provisioning of the Roman army

In the opinion of the authors, the rural population in the Lower Rhine delta may have been much more involved in the provisioning of the Roman army between AD 40 and 140, especially for wood and cereals, than has been assumed until now. For meat supply, the picture is less clear. The rural settlements in the central part of the Rhine-Meuse delta do show changes in settlement structure, storage capacity and animal husbandry, proving that they were already integrated into a larger economical framework in the early phase of military presence (Groot *et al.* 2009; Heeren 2009). Apparently, the arrival of the Roman army influenced the rural settlements to change their economy and intensify their production, perhaps by putting pressure on and taxing the rural population. However, the local provisioning of food had to be combined with import over long(er) distances, just as in other parts and other periods of the Roman Empire, for example Scotland (Hanson 2007), Britain (Thomas 2008), and Central Jordan (Parker 2006).

The provisioning with timber and fuel seems to have been much more a solely military matter that was carried out by the soldiers themselves. Such activities would have posed too much of a logistical problem for the rural population, certainly at periods of heightened activities, for example the transport of large quantities of wood from alder wetlands to the places of construction. For the road and river infrastructure along the river Rhine of AD 123/125 oak was imported. The employment of the rural population in the wood winning did probably not start until the development of alder copses in the middle Roman period.

5. Conclusion

The estimates of the demand and supply of the Roman army in the western Lower Rhine delta with wood and locally produced food during the first one hundred years after the arrival of the army shows that the landscape in the early Roman period (AD 40 – 70) could in theory meet the total demand of the total population in the area and posed no limit. The required space for forestry, arable farming and animal husbandry was available and did not conflict. However, because of a rising population the pressure on the landscape increased in time. From the end of the first century AD onwards, the landscape may have posed an upper limit on the availability of local resources and thereby the local production.

The calculations show that nearly all wood, for both construction and fuel, could be gathered locally during the whole research period. This corresponds to the archaeological record. The employment of the rural population in the wood winning did probably not start until the development of alder copses in the middle Roman period.

In addition, the total rural population, even estimated at a minimum, was also able to produce enough surplus cereals, e.g. emmer and barley, to fulfil the demand of the Roman army and its associates for these cereals (assuming that only 50% of the total military demand for cereals was derived from cereals that could be produced in the local surroundings). Cereal deficits in the central and western region could be supplemented by surplus yields from the eastern region. However, spelt wheat and bread wheat, other components of the military diet, were not cultivated locally and had to be imported.

Meat supply for the Roman army most probably did form a problem. The rural settlements would have to keep implausibly large cattle herds for which manpower was also lacking. Therefore, it seems likely that the Roman army combined local provisioning with extra-regional supply and long-distance transport.

Overall, the local population was probably much more involved in the provisioning of the Roman army in the Lower Rhine delta between fort Vechten and the North Sea, especially for cereals, than hitherto assumed. Therefore, this study is a step forward in identifying the carrying capacity of the natural landscape and the logistical organisation concerning the provisioning of the Roman army in the Rhine delta.

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Note

1. This is also suggested to Van Giffen in a letter from January 9th 1943 by the palynologist F. Florschűtz, University of Utrecht, who performed the first pollen analysis for fort Valkenburg.

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Appendix 1. Parameter values and underlying assumptions used in the modelling of the carrying capacity of the Lower Rhine delta

Population size

2.2.1 Landscape module

- The areas occupied by the military constructions include 3-4 ha for forts incl. ditches and a construction-free zone, less than 1 ha for watchtowers, 10 ha on average for *vici* and c. 20 – 30 m broad zone for the military road. The total area occupied is relatively small are therefore not accounted for in our calculations for land use.
- The area that the farm yards occupied in the Rhine-Meuse delta varied between 0,5 to 2 ha (Bakels & Stronkhorst 2004; Heeren, 2009; Van der Velde 2008; Van Londen 2006; Vos, 2009) and is not considered in our calculations for land use, because it turned out to be insignificant (less than 1% resp. 5 % in Early and Middle Roman period).

3.2.1 Military population

- With minimum estimates of c. 250 soldiers per fort (Glasbergen & Groenman-van Waateringe 1974) and a maximum of c. 480-500 (one cohort, *cohors quingenaria equitata*), we assume in our calculations that 350 soldiers were stationed in each of the small castella downstream of fort Vechten (best guess). Vechten is counted as a double fort with 700 soldiers.
- The garrisons of the watchtowers are assumed to be derived from the fort garrisons (Van der Kamp 2007).
- The military installations are permanently occupied.
- The size of the army does not change during the research period, A.D. 40 – 140.
- Only fort Vechten had a *vicus* in the early Roman period (AD 40 – 69; Hessing *et al.* 1997).
- In the middle Roman period (AD 70 – 140), all forts had a *vicus* (Blom & Vos 2008; Brandenburgh & Hessing 2005; De Hingh & Vos 2005; Hazenberg 2000; Haalebos 1977; Kok 1999; Langeveld in prep.; Montforts 1995; Ploegaert 2006; Vos 1997; Vos & Lanzing 2000).
- The number of people living in the *vicus* was equal to that of the garrison in the adjacent fort (Sommer 1984; idem 1991), implying 350 *vicus*-inhabitants per fort downstream of fort Vechten in the middle Roman period. In our calculations the *vicus* of Vechten contains 700 inhabitants in both the early and middle Roman period.

3.2.2 Rural population

- It is assumed that the number of settlements south of the river Rhine doubled in the middle Roman period compared to their number in the early Roman period.
- It is assumed that the number of settlements north of the river Rhine was equal in the early and middle Roman period.
- To account for eroded and non-discovered settlements, a correction factor of 15% was applied to the number of reconstructed rural settlements (Vos 2009).
- Excavation data in the research area show that the majority of the settlements comprised one or two farmsteads in both the early and middle Roman period (Bakels & Stronkhorst 2004; Den Hartog 2009; Van der Mark 2001; Van der Velde 2008; Van Dockum 1995; Van Grinsven & Dijkstra 2005; Van Tent 1978; Vos 2009; Vos & Blom 2004). Therefore, an average - referred to as settlement-unit - has been used in the calculations. Large settlements reconstructed in the Kromme Rijn area with a minimum of 3 - 4 farmsteads are counted double (Vos 2009).
- Previous research indicates that one household in prehistoric times consisted of 5 to 8 people (Bloemers 1978, 55; Willems 1986, 236). Hence, one settlement-unit is inhabited by c. 10 people. In our calculations, a figure of 9.75 ((5+8) x 1.5)/2) people is used, equally distribu-

ted over the different age categories, i.e. children, young adults (10-14 year), adults and old adults, being c. 2.5 (2.4375 = 9.75/4).

	West	*Central*	*East*	*Total*
Early & Middle Roman Period				
Northern dunes	17	-	-	17
Northern levees	16	15	18	49
Southern dunes	7	-	-	7
Southern levees	9	18	110	137
Total				**210**

Table A1. Reconstructed rural settlements according to original ARCHIS-data (jan 2009).

	West	*Central*	*East*	*Total*
Early Roman Period (AD 40 – 70)				
Northern dunes	8.5	-	-	8.5
Northern levees	8	7.5	9	24.5
Southern dunes	3.5	-	-	3.5
Southern levees	4.5	9	55	68.5
Total				**105**
Middle Roman Period (AD 70 – 140)				
Northern dunes	8.5	-	-	8.5
Northern levees	8	7.5	9	24.5
Southern dunes	7	-	-	7
Southern levees	9	18	110	137
Total				**177**

Table A2. Reconstructed rural settlement-units divided over early Roman and middle Roman period according to first two assumptions in paragraph 3.3.2.

	West	*Central*	*East*	*Total*
Early Roman Period (AD 40 – 70)				
Northern dunes	9.775	-	-	9.775
Northern levees	9.2	8.625	10.35	28.175
Southern dunes	4.025	-	-	4.025
Southern levees	5.175	10.35	63.25	78.775
Total				**120.75**
Middle Roman Period (AD 70 – 140)				
Northern dunes	9.775	-	-	9.775
Northern levees	9.2	8.625	10.35	28.175
Southern dunes	8.05	-	-	8.05
Southern levees	10.35	20.7	126.5	157.55
Total				**203.55**

Table A3. Reconstructed rural settlement-units divided over early Roman and middle Roman period corrected for eroded and non-discovered settlements (15%).

3.3 Military module

3.3.1. Wood demand

Assumptions for wood demand:

Forts:

– To reconstruct the timber needed to built the forts, a 3D fort-wood model was constructed (Van Rijn in prep). Firstly, a model was established for the earliest fort of Alphen aan den Rijn because the excavation of this fort provided the most detailed information on lay-out and dimensions of its structures and timber (Van Enckevort 1987; Van Rijn 2000; idem 2004; Chorus in prep.). Missing information on upper structures and roof constructions was provided through reconstructions (e.g. Davison 1989). The total volume of timber used for this earliest fort Alphen - phase 1a - is 1,751 m^3, varying from 513 m^3 for the rampart including gates and towers (1295 m^2 x 0.37 m^3/m^2 + 130 m^2 x 0.27 m^3/m^2), 324 m^3 (= (551 + 130 m^2) x 0.33 m^3/m^2) for principia and praetorium, 408 m^3 (1890 m^2 x 0.22 m^3/m^2) for the barracks, 131 m^3 (608 m^2 x 0.22 m^3/m^2) for the fabrica, 43 m^3 (138 m^2 x 0.31 m^3/m^2) for the granary and for a structure of unknown function 59 m^3 (275 m^2 x 0.22 m^3/m^2). Paving of the open spaces required 273 m^3 (40 m^2 x 0.08 m^3/m^2). Based on the assumption of similar ground plans of the other forts, but with varying perimeters and division of built-up against open space depending on the fort's size, the volumes of timber needed for each of the other forts were calculated. The total volume for one time construction of all forts in the early Roman period came to 27,088 m^3, and in the middle Roman period to 29,533 m^3 for AD 70 (Tabel A4 and A5).

Early Roman period		**Middle Roman period**	
Katwijk*	2229	Katwijk***	2488
(Valkenburg 1-1a)	(2697)	(Valkenburg 4, Flavian)	(2927)
(Valkenburg 2-3)	(2906)	(Valkenburg 5, Trajanic/Hadrianic)	(2971)
Valkenburg average	2802	Valkenburg average	2949
Roomburg	1910	Roomburg***	2488
Alphen 1	1751	Alphen, Flavian	2163
Bodegraven	2020	Bodegraven***	2488
Zwammerdam 1*	2229	Zwammerdam 2, Flavian	2232
Woerden, pre-Flavian	2020	Woerden, Flavian	2020
De Meern	1910	De Meern***	2488
Utrecht 1,2	2618	Utrecht 3,4, Flavian	2618
Vechten 1**	7599	Vechten 2	7599
Total	**27088**	Total	**29533**

* ground plan unknown, m3 = average taken from 7 known forts; ** assumed to be as large as Vechten 2; *** ground plan unknown, m3 = average taken from 6 known forts

Table A4. Reconstructed wood consumption for timber (m^3) for one time construction of the Roman forts in the early and middle Roman period (Numbering of the various phases after Chorus in prep.).

Other military complexes:

– Volumes of timber for these structures are calculated with a 3D-model based on the field drawings and the dimensions of the excavated features.
– Assuming that the river was completely over watched in between the forts, the number of reconstructed watchtower complexes is estimated at 20 (= resp. 6, 8 and 6 for the three regions). A watchtower covers c. 20 m^2 (Langeveld & Luksen-IJtsma 2010; Van der Kamp

2007; Van Dierendonck 2004). When 0.37 m^2/m^3 is used (for similar structures within the forts), c. 7.5 m^3 of wood is assumed to be needed for the one time construction of a watch-tower complex.
- The number of granaries outside each fort is estimated at two (Hallewas *et al.* 1993) and - based on similar structures within the forts (Glasbergen 1972, fig. 51; Groenman-Van Wateringe 1977, 233; Polak *et al.* 2004; 97) - 43 m^3 of wood was needed to built a granary (for one time construction).

Vici:
- Hardly anything is known about the size or number of houses in *vici* in this area. Therefore, these figures are estimated.
- A *vicus* house is estimated to cover an average of 180 m^2 (8 x 20 - 25 m; Langeveld in prep.).
- A *vicus* is assumed to include 60 houses. Using 0.19 m^2/m^3 for simple structures, the total volume of timber needed for a one time construction of one *vicus* is 2,052 m^3.

Infrastructural works:
- For paths in the early and middle Roman period, it is assumed that 8500 trunks/km were used consisting of alder poles with diameter of 0.06 m and a length of 3 m (based on field drawings of Valkenburg-Marktveld 1986; Hallewas *et al.* 1993). The total path length of 33 km is equally divided over the regions (11 km per region), resulting in a total of 2,379 m^3 wood for a one time construction or 793 m^3 per region.
- The first archaeologically traceable Roman road connecting the forts only appeared at the end of the first century AD (Luksen-IJtsma 2010). The track of the road of AD 99/100 mostly consists of a parallel row of posts on either side of the raised roadbed, mainly oak. It is assumed that 6300 trunks were used for 1 km path consisting of poles with diameter of 0.13 m and a length of 3 m, resulting in 250.86 m^3/km. Reconstruction over a total distance of 66 km (Luksen-IJtsma 2010) results in 16,557 m^3 of wood for a one time construction over 66 km or 5,515 m^3 per region (22 km).
- In AD 123/125 the road and river infrastructure was drastically renewed (Luksen-IJtsma 2010). The road of AD 123/125 shows two different types of wood construction, a lighter and a heavier one. Although part of the timber (mainly oak) for this road was imported (Visser & Jansma 2009), local repairs were conducted with alder which was most likely locally retrieved (Luksen-IJtsma 2010, 97). We calculate the total amount of wood needed for a one time construction. Estimates of the lengths of the two differently constructed segments are based on their position in the palaeo landscape, and set at 33 km each and equally divided over the regions. The lighter construction is similar to that of the road from AD 99/100, except that the posts are larger and set closer together. The heavy construction is a dike-like structure of sods and earth within two parallel rows of posts, enforced by tie beams and cladding against the inside of the posts, and wooden reinforcement of the road ditches. In our calculations, 336.8 m^3 wood was needed per km for the lighter construction, resulting in a total of 11,115 m^3 wood for one time construction or 3,705 m^3 per region (11 km), and for the heavier construction 419.2 m^3 was needed per km, resulting in a total of 13,834 m^3 wood for a one time construction or 4,611 m^3 per region (11 km).
- Waterfront installations, such as revetments, are estimated at 33 km length per region. In our calculations, 3,455 poles with a diameter of 0.10 m and 3 m length were used, resulting in 81.41 m^3/m^2 and 2,687 m^3 per region in the early Roman period. These figures are also used for the first 30 years of the middle Roman period. After AD 99/100, the wood needed is included in the road- and river infrastructure of AD 99/100 and 123/125 (both lasting 20 years in our calculations).
- In the western region, the Corbulo canal is included, measuring 10 km in length, with revetments on both sides. Assuming that these revetments were similar as the revetments

along the river Rhine, 81.4 m^3/m^2 wood was used, resulting in a total of 1,628 m^3 wood for a one time construction.

- Furthermore, quays are added per fort each measuring 1,125 m^2. In Valkenburg-Marktveld – northern gully (nr. 164/165) 15.35 m^3 wood was needed for 81 m^2 (based on field drawings). For 1,125 m^2, an equivalent of 231.26 m^3 wood was needed for one time construction (= per fort).

Renovation and repair of all structures:

- Every 10 years the initial amount of timber for first construction of all structures is assumed to have been used for renovation and repair of all structures, due to the necessity of constant repair in view of (i) the use of less robust wood taxa (alder, ash and elm), (ii) the archaeologically attested problems with repeated flooding, (iii) the various adaptations observed in the forts. Therefore, the initial amounts of all structures in the Early Roman period is multiplied by a factor 3 resp. 7 in the Middle Roman period, with the exception of both roads of which the repair has been calculated over 20 years (AD 99/100 till c. AD 120, and AD 123/125 till AD 140).

Total timber:

- According to our calculations, 135,220 m^3 of timber was needed for the military population in the early Roman period and 509,226 m^3 in the middle Roman period (Table A5).

Firewood:

- The watchtower garrisons are assumed to be derived from the fort garrisons (section 3.2.1; Van der Kamp 2007). So, their fuel consumption is not calculated separately.
- The calculations of the consumption of firewood are based on a study of pre-modern agrarian societies relating to Europe's different climatic zones, and is for this region set at 14.000 kCal per person a day (Malanima 2009a and b). As mostly alder is (most likely) used for firewood and 1 kg of alder provides in heat value 7.6 GJ/kg, this amounts to 3,9 kg per person a day. Taking into account small-scale fuel consuming industries such as workshops for the manufacturing and repair of iron ware for the army, and cremation practices, etc, a daily consumption of 6 kg of firewood per person for the people in the forts and *vici* is assumed.
- Alder with a moisture content of 15% has a specific weight of 500kg/m^3.
- The presence of bath houses has not been established in our area till c. AD 15 (Vollgraff & Van Hoorn 1941; Haalebos 1977, 65; Polak *et al.* 2004, 20), so their fuel consumption has not been taken into account.
- According to these assumptions, 597,870 m^3 firewood was needed for the military population in the early Roman period and 2,360,820 m^3 in the middle Roman period (table A5).

Assumptions for wood yields/supply:

- Yields of the Roman woodlands can only be estimated. The estimates are based on certain components that determine the yields of modern woodlands, such as taxon, age and diameter of trunks at breast height. The first two components can relatively easily be determined on unearthed Roman wood remains, whereas the diameter of trunks at breast height can only is estimated.
- The ages of the trees felled in Roman times were provided through dendrochronological research.
- The original diameters of the Roman tree trunks were reconstructed from the dimensions of the timber and the conversion methods employed (Van Rijn in prep.). This made it possible to compare the relation between trunk diameter and age in yield tables of modern wood with those from the Roman remains and to estimate the yields of various types of Roman woodlands.

	West	*Central*	*East*	*Total*
Early Roman Period (AD 40 – 70)				
Forts	6941	8020	12128	27089
Watchtowers	45	60	45	150
Granaries	258	344	344	946
Vici	0	0	4104	4104
Path	793	793	793	2379
Revetments	2687	2687	2687	8061
Quays	640	853	853	2346
Corbulo Canal	1628	0	0	1628
Total timber (for one time construction)	12992	12757	20953	46702
Total timber in 30 years	*34090*	*38270*	*62860*	*135220*
Firewood forts in 30 years	137970	183960	183960	505890
Firewood vici in 30 years	0	0	91980	91980
Total firewood in 30 years	*137970*	*183960*	*275940*	*597870*
Total in 30 years	**172060**	**222230**	**338800**	**733090**
Middle Roman Period (AD 70 – 140)				
Forts	7925	8903	12705	29533
Watchtowers	45	60	45	150
Granaries	258	344	344	946
Vici	6165	8208	8208	22581
Path	793	793	793	2379
Road AD 99/100	5515	5515	5515	16545
Road AD123/125 light construction	3705	3705	3705	11115
Road AD 123/125 heavy construction	4611	4611	4611	13833
Revetments	2687	2687	2687	8061
Quays	640	853	853	2346
Corbulo Canal	1628	0	0	1628
Total timber (for one time construction)	33963	35678	39466	109107
Total timber in 70 years	*157837*	*162438*	*188951*	*509226*
Firewood forts in 70 years	321930	429240	429240	1180410
Firewood vici in 70 years	321930	429240	429240	1180410
Total firewood in 70 years	*643860*	*858480*	*858480*	*2360820*
Total in 70 years	**801697**	**1020918**	**1047431**	**2870046**

Table A5. Reconstructed wood consumption for timber and fuel (m³) for military population per region including reparation and repair, and regeneration of the various forests.

– The estimated yields of the 'bog fringing forest' are deduced from Casparie 1982, 155.
– The total wood volume of the whole tree is 120% of the volume of timber from the tree (Daamen 2010, 5). The surplus comes in the form of branch wood. This wood can be used for fuel, but has also been used to solidify the wet subsoil. Therefore, the surplus is not taken into account in the calculations of woodland area used.
– Regeneration of woodlands has been taken into account (regeneration factor = RF). In early Roman period, the woodland on the high and low levees close to the forts were probably not allowed to regenerate for safety reasons and can only have been felled once. The surrounding terrain will have been used for other purposes, such as cemeteries, roads, paths etc. However, the woodlands on the low levees, the high flood plains and the barrier plains, which were used for fuel both by the Roman army and rural settlements, are assumed to regenerate in 10 years. The system of alder coppicing in the Middle Roman period aimed at a constant production of wood for poles and fuel. The rotation cycles for the production of timber in the coppices were set at 12 years and for firewood at 8 years (based on ring counts of Roman material (Van Rijn 2004; Lange 2010) and information from coppice experts). The woodlands on the low levees and the high flood plains which delivered

timber to the rural settlements are assumed to regenerate in 15 years, while the forest for fuel which were situated on the low levees, the high flood plains and in the barrier plains are assumed to regenerate in 10 years.
- The proportion of the various woodlands most probably supplying the wood was estimated (used ratios: 1/4, 1/3, 1/2, 1).
- We assume that the wood for the Roman army and *vici* was retrieved from areas south as well as north of the river in both the early and the middle Roman period, especially the peat areas with fen woodland.

3.3.2 Demand of vegetable food

Common food assumptions:
- A 30-year-old legionary soldier with a height of 1.70 metres needs 3 x 10^3 kCal of energy a day (Roth 1999).
- The diet of soldiers does not differ substantially from one another's although there may have been a difference in ethnic background (and thereby maybe in initial food preference or taboos) and in the composition of the garrisons (De Weerd 2006; Polak 2009; idem in press).
- The population of the *vici* consisted of men, woman and children. We assume that the composition of the *vicus* population is comparable to those of the rural settlements and therefore the diet and calorie-intake in our calculations are assumed to be equal to that of the rural settlements. As one settlement-unit requires c. 22 x10^3 kCal (section 3.4.2; 9.75 persons; Gregg 1988, 143), the energy requirements for a *vicus* with 350 people equals that for c. 36 settlement-units and is c. 80 x 10^4 kCal per day.

Demand:
- It is assumed that 90% of the energy requirements of both the soldiers and the *vici* inhabitants was derived from cereals and products derived from cattle. The remaining 10% was derived from other plant-based categories or other animal products (Kooistra 1996, 67).
- It is assumed that 75% of this 90%, so 67.5 % in total, can be attributed to cereals both for the soldiers and the *vici* inhabitants (Jobse-Van Putten 1995, 48; Kooistra 1996, 70-73).
- Hence, a soldier needed c. 2.0 x10^3 kCal from cereals per day (67.5% of 3 x 10^3 kCal) and a *vicus* with 350 people c. 53.5 x 10^4 kCal.
- It is assumed that 50% of the cereal needs of the military and the population of the *vici* was fulfilled by imported cereals. The other half was fulfilled by emmer and barley, which could be produced locally. Our calculations are only based on the demand of the cereals that could be derived from the immediate surroundings.

Production - arable farming :
- It is assumed that one kg of emmer wheat (*Triticum dicoccon*) and barley (*Hordeum*) produced in the Rhine - Meuse delta in Roman times provided 3.1 x10^3 kCal (Kooistra 1996, 67).
- Botanical research has shown that crop rotation was used in the Roman period (Kooistra 1996, 306-322). In this model calculations are made for a two-course rotation system whereby a field would be cultivated one year and lay fallow the next.
- For sowing seed, 200 kg of cereals per ha is assumed. The yield is estimated at 1,000 kg of grain per ha (see discussion in Kooistra 1996, 67).
- It is assumed that in the early Roman period, cereals for the army came from both sides of the river Rhine. In the middle Roman period, cereals for the army and *vici* were no longer derived from land located north of the river Rhine (Kooistra 2009).

3.3.3 Demand of animal food

Demand:

- It is assumed that 90% of the energy requirements of the military population was derived from cereals and products derived from cattle. It is assumed that 25% of this 90%, so 22.5% of total diet, can be attributed to meat products both for soldiers and *vici* inhabitants (Jobse-Van Putten 1995, 48; Kooistra 1996, 70-73).
- Hence, the needs of calories per soldier, in terms of meat and meat products, are calculated to have been 675kCal per day (22.5% of 3 x 10^3 kCal) and those of a *vicus* with 350 people c. 18 x10^4 kCal per day.

Production – Animal husbandry:

- Bone material in the archaeological record shows that cattle from the Late Iron Age and Roman Period in the research area is relatively small and that its size is comparable with cattle from the Bronze Age (Lauwerier 1988). No data are available on the caloric value of herds kept by the farmers in the Roman period in the Rhine-Meuse delta. Therefore, we use figures from a study on cattle from the Bronze Age (IJzereef 1981).
- In order to assess the herd size needed to sustain one indigenous settlement-unit, calculations were made by combining data on herd size, composition and slaughter patterns (Gregg 1988), and the calorific value of Bronze Age cattle as reconstructed for this area (IJzereef 1981).
- Cattle was kept for both milk and meat production as attested by the bone material in the archaeological record.
- Assumptions from Gregg (1988) on sex ratio by birth (1:1) and on herd size (stable, no growth) are applied.
- Gregg (1988) assumes a loss of 40% of the annual meat production due to disease, loss, predators and inability to recapture the dead animal. Because of deforestation in the study area, presumably fewer predators were present in comparison to Gregg's study. Therefore, the assumed loss in this study is taken to be 30%.
- Figures on calories from slaughtered cattle in various stages of life are taken from IJzereef (1981): an adult cow/oxen/bull weighs 200 kg - equal to c. 48 x 10^4 kCal - and a calf weighs 35 kg - equal to c. 5.5 x 10^4 kCal (IJzereef 1981).
- As IJzereef (1981) gives no data on heifers, we assume for heifers a weight of around 75% of mature cows/bulls, but with the same ratio of meat (30%), fat (20%) and other (10%) as cows. The remaining 40% of weight is bones, skin and other non-edible parts.
- Numbers of heads in this publication always indicates the herd size in winter time when it is at its smallest.
- The size of a viable herd for reproduction would be at least 30 heads in winter time (Gregg 1988).
- A herd with 30 heads in winter yields in total c. 2.3 x 10^6 kCal of meat per year (Table A6) and a herd with 50 heads c. 3.8 x 10^6 kCal (Table A7).

Feeding cattle:

- The food needs for the herds have been calculated for both meadows (hay) and pasture.
- The regular flooding of the river Rhine certainly contributed to a rich vegetation in the flood basins. Nowadays, naturally managed landscapes are able to provide c. one large herbivore per ha expressed in AU (AU = animal unit; 1 AU means a herbivore with an estimated weight of 450 kg; Bokdam 2003, 18; De Vries *et al.* 2011, 13; Kuitert 2004, 76). Cattle in the Late Iron Age and Roman period are assumed to have been smaller than nowadays: c. 1.15 m wither height and c. 200-250 kg in weight (IJzereef 1981; Lauwerier 1988, 168). Therefore, the assumption is made that during the Roman period two to three

bovines could graze on one ha of meadow. In order to calculate the minimum number of ha needed in Roman times, we calculate with three bovines per ha.

- The food needs for the herds have been calculated for both hay and pasture, assuming that a suckling calf eats 15% of mature animals and heifers 80%. Cows, bulls and oxen are assumed to have the same intake of fodder (100%; see also Gregg, 1988, 107).
- A limiting factor for animal husbandry must have been the high groundwater level and the regular flooding of the river Rhine. Due to winter flooding the grazing area would have been severely limited during four months a year. Therefore the assumption is made that cattle were fed with hay during four months a year. This hay might have been stored in the oversized horrea (Heeren 2009, 189). In an early Roman rural settlement near Utrecht a 1,27 m long scythe was unearthed that might have been used to hay in the meadows (Den Hartog 2009, 71).
- A mature Iron Age cow would consume around 189 kg of hay per month (Groenman-Van Waateringe & Van Wijngaarden-Bakker 1987). So, this would amount to 756 kg (= 189 x 4) of hay per mature cow per year.
- It is assumed that the grasses were of the slow-growing natural varieties that would contain more dry matter than the present-day commercial meadows. The weight loss from grass to hay as a result of loss of moisture is assumed to have been 40%.
- The yield of one ha of meadow in the Late Iron Age Rhine basin is assumed to have been 3,000 kg of hay. This assumption is based on the hay yields cited by Kreuz (1995, 81) and those of unmanured meadows in the Netherlands (unpublished data Natuurmonumenten). In order to calculate with optima and thus to arrive at the minimum number of ha needed in Roman times, calculations with an annual yield of 3,400 kg of hay have been carried out.
- Grazing on the stubble left on the fields after harvesting and on fallow land – respectively 3.3 ha per settlement-unit - has been taken into account.

	In winter (N)	*In spring after calving (N)*	*Dead or slaughtered (N)*	*Calorie output per animal (Cal)*	*Total per category (Cal)*
Calves	0	9	2	55580	111160
Yearling	7	0	0	0	0
Heifers	8	15	2	359850	719700
Oxen	2	2	0	0	0
Cows	11	11	3	479800	1439400
Bulls	2	2	2	479800	959600
Total	30	39	9	1375030	3229860
After loss (only 70% usable)					**2260902**

Table A6. Yields of meat (in cal) from a herd with 30 heads in winter.

	In winter (N)	*In spring, after calving (N)*	*Dead or slaughtered (N)*	*Calorie output per animal (Cal)*	*Total per category (Cal)*
Calves	0	15	3	55580	166740
Yearling	12	0	0	0	0
Heifers	10	22	4	359850	1439400
Oxen	7	7	0	0	0
Cows	19	19	4	479800	1919200
Bulls	2	2	4	479800	1919200
Total	50	65	15	1375030	5444540
After loss (only 70% usable)					**3811178**

Table A7. Yields of meat (in cal) from a herd with 50 heads in winter.

3.4 Rural demand and supply

3.4.1 Wood demand

The assumptions for the wood demand of the rural settlements:

- The calculations for timber of the settlements are based on the archaeologically attested surface area (Van der Velde 2008; Bult & Hallewas 1987). In the early Roman period the average surface of farm stead and storage facilities is c. 82 m^2 and in the middle Roman period c. 103 m^2. With 1.5 farms per settlement and 0.21 m^3/m^2 for the buildings, a total of 28.5 m^3 wood is needed per settlement-unit.
- Every 10 years the initial amount of timber for first construction is assumed to have been used for renovation and repair of all the structures in the settlement, due to the use of less robust taxa (alder, ash and elm).
- The calculations of the consumption of firewood are equal to the based on a study of pre-modern agrarian societies relating to Europe's different climatic zones, and is for this region set at 14.000 kCal per person a day (Malanima 2009a and b). As mostly alder is used for firewood, this amounts to 3,9 kg per person a day. For the rural settlements the daily consumption per person, including the local production of pottery, is raised to 5 kgs, taking into account that there is less of industrial activity than in the forts and the *vici* (Personal comment P. Malanima, University of Naples, Italy, 1-5-2010).
- It is assumed that the wood was retrieved in the settlement's surroundings.
- The total rural demand for timber is 9,402 m^3 in early Roman period and 46,267 m^3 in the middle Roman period and for fire wood resp. 114,236 m^3 and 467,833 m^3 (table A8).

	West	*Central*	*East*	*Total*
Early Roman Period (AD 40 – 70)				
Timber rural settlements N	1476	699	777	2953
Timber rural settlements S	699	855	4895	6449
Total timber	*2176*	*1554*	*5672*	*9402*
Firewood rural settlements N	9609	9609	10676	29894
Firewood rural settlements S	5338	11744	67260	84342
Total firewood	*14947*	*21353*	*77937*	*114236*
Total wood	**17122**	**22907**	**83609**	**123638**
Middle Roman Period (AD 70 – 140)				
Timber rural settlements N	4309	2041	2268	8618
Timber rural settlements S	4082	4763	28804	37649
Total timber	*8392*	*6804*	*31072*	*46267*
Firewood rural settlements N	26904	22420	24911	74236
Firewood rural settlements S	24911	52314	316373	393598
Total firewood	*51815*	*74734*	*341284*	*467833*
Total wood	**60207**	**81538**	**372356**	**514100**

Table A8. Reconstructed wood consumption for timber and fuel (m^3) for rural settlements per region including reparation and repair; N = north of the river Rhine; S = south of the river Rhine.

3.4.2 Arable farming

Demand:

- The energy requirement of the inhabitants of one settlement-unit is c. 22 $x10^3$ kCal per day (Gregg 1988,143), which they produced themselves.
- It is assumed that 90% of the energy requirements of the agrarian population was derived from cereals and products derived from cattle. The remaining 10% was derived from other plant-based categories or other animal products (Kooistra 1996, 67).
- It is assumed that 75% of this 90% can be attributed to cereals (Jobse-Van Putten 1995, 48; Kooistra 1996, 70-73).
- Hence, a settlement-unit needed c. 15 $x10^3$ kCal from cereals per day.
- We assume that the agrarian population of the Limes zone mainly cultivated and consumed emmer wheat (*Triticum dicoccon*) and barley (*Hordeum*) (Kooistra 2009).
- Hardly any imported food plants have been found in the agrarian settlements (Kooistra *et al.* in 2013).

Production:

- It is assumed that one kg of cereals produced in the Rhine - Meuse delta in Roman times (emmer wheat (*Triticum dicoccon*) and barley (*Hordeum*) provided 3.1 $x10^3$ kCal (section 3.3.2; Kooistra 1996, 67).
- In this model, calculations are made for a two-course rotation system whereby a field would be cultivated one year and lay fallow the next (section 3.3.2).
- In the Roman period, a field of cereals would have been sown using a method of broad casting by hand (Kooistra 1996, 67). For sowing seed, 200 kg of cereals per ha is assumed. The yield is estimated at 1,000 kg of grain per ha (section 3.3.2).
- It is assumed that farmers kept some cereals in reserve for their own use. In this model, the total amount of cereals needed per settlement (surplus excluded) comprises the amount of food needed annually plus half of that amount kept in reserve (50%) plus the amount of cereals necessary for sowing.
- The harvest period would have lasted 14 days and one man could harvest 0.25 ha per day or 3.5 ha in total in two weeks (Gregg 1988). The rest of the family would have carried out the transport, drying and threshing of the crop.
- Based on these assumptions, a settlement-unit needed 3.3 ha. of cultivated arable land to satisfy their own needs for cereal food = ((kCal settlement-unit from cereals per day / kCal one kilo of cereals) x 365 days) + (half of that amount of cereals which will be kept in reserve) / (yield of cereals per ha – sowing seed) = (($15x10^3$ / $3.1x10^3$) x 365) + (($15x10^3$ / $3.1x10^3$) x 365) / 2) / (1000 – 200). Including fallow land (the same amount), 6.6 ha land would be needed every year for cereal production.
- It is assumed that cereals were cultivated as a summer crop, with sowing in early spring and harvesting at the end of July or beginning of August. Therefore, the fields had to be situated in locations that were dry from March through the summer, e.g. on the high levees and the dunes (Table 1; Kooistra 1996).

3.4.3 Animal husbandry

The assumptions made for production and consumption of meat and meat products are listed below.

- The energy requirement of the inhabitants of one settlement-unit is c. 22 $x10^3$ kCal per day (Gregg 1988,143), which they produced themselves.

- It is assumed that 90% of the energy requirements of the agrarian population was derived from cereals and products derived from cattle. The remaining 10% was derived from other plant-based categories or other animal products (Kooistra 1996, 67).
- It is assumed that 25% of this 90% can be attributed to meat and meat products (Jobse-Van Putten 1995, 48; Kooistra 1996, 70-73).
- Hence, a settlement-unit needed c. 5 $x10^3$ kCal from meat and meat products per day, equivalent to c.1.8 x 10^6 kCal per year (section 3.3.3).
- It is assumed each farmstead kept one herd of 50 heads (section 3.3.3).
- A herd of 50 heads will annually yield a total of 3.8 x 10^6 kCal (Table A7). This is more than sufficient to satisfy the needs of a settlement-unit. It means that a herd of 50 heads will produce a yearly surplus of c. 2.0 x 10^6 kCal, an equivalent of c. 4 mature cows (section 3.3.3).
- An area of at least 26.1 ha of pasture and meadow was needed to sustain an extra viable herd of 50 heads, consisting of at least 16 ha (= 47.85/3) of pasture and at least 10.1 ha (= (45.6 x 756)/3400) of meadow to sustain the herd's needs during the winter months (section 3.3.3). When taking into account 3.3 ha of fallow land, only 12.7 ha (=16 - 3.3) of pasture would be needed for a settlement-unit (section 3.3.3).

3.4.4 Rural surplus production

Arable farming :

- It is assumed that the same men harvested the cereals needed by the agrarian population as that needed by the military. As one settlement-unit consists of c. 3.66 adult men (section 3.2.2: 2,4375 x 1.5), and one man could harvest 3.5 ha in total in two weeks (section 3.4.2), these men can harvest a maximum of 12.8 ha.
- To satisfy their own needs for cereal food a settlement-unit needed 3.3 ha (section 3.4.2). The maximum amount of arable fields that can be harvested for surplus production is therefore 9.5 ha.
- It is assumed that in the early Roman period, cereals for the army could be produced on both sides of the river Rhine. In the middle Roman period, cereals for the army and *vici* were no longer derived from land located north of the river Rhine (Kooistra 2009).

Animal husbandry:

- It is assumed that one herd of 50 heads will produce a yearly surplus of c. 2.0 x 10^6 kCal (= (3.8 – 1.8) x 10^6 kCal), an equivalent of c. 4 mature cows, when the needs of the settlement-units in the area are taken into account (section 3.4.3).
- An extra herd of 50 heads will annually yield a total of 3.8 x 10^6 calories (table A7), an equivalent of c. 8 mature cows, as the needs of the settlement-units are already taken into account.