Quantifying land use for grazing cattle in Europe: estimations of pasture per capita in Holocene Europe

Koen Pronk

Research project Environmental Change and Ecosystems, Sustainable Development, Utrecht University

Supervisor: Kees Klein Goldewijk

Keywords:

Land use

Cattle grazing

Pasture

Neolithic

Europe

Subsistence strategies

Anthropocene

ABSTRACT

Anthropogenic land cover change (ALCC) has impacted the environment throughout the Holocene. The onset of agriculture on the European continent catalyzed ALCC as early Neolithic farmers converted natural areas for crop cultivation and animal husbandry. Quantifying historical land-use data is an important input for climate and carbon models that are designed to make projections about future climate- and environmental change, therefore more accurate estimates of prehistoric land use directly improve the accuracy of climate and carbon models. Especially the use of permanent pastures in early farming communities is uncertain, and novel approaches to quantification could prove beneficial to historical land-use databases. This study explores methods to quantify the use of cattle-pastures per capita. A robust formula that converts cattle heads per person to pasture (ha) per capita is identified. Subsequently, two methods to determine cattle heads per person in prehistoric settlements are identified: 1) relating the number of cattle individuals to the number of houses in archaeological sites based on bone excavations, and 2) relating individual dairy consumption to the daily milk production of prehistoric cows. The results indicate that pasture per capita gradually increased over the course of the Neolithic and Bronze Age until a plateau is reached around 100 BCE. Although the presented estimates come with a high degree of uncertainty, the quantification methods provide an indication of the order of magnitude of minimum pasture per capita. However, more research is needed to draw conclusions about the degree in which grazing land consisted of converted agricultural areas, instead of natural areas.

Word count: 5903

Table of Contents

1 Introduction

Throughout the Holocene – starting from twelve millennia prior to the industrial revolution - human activities have affected the shaping of landscapes (Morrison *et al.,* 2021). The conversion of land for human activities has accumulated through the ages, and 37% of the world's ice-free land is currently being used for agriculture (Klein Goldewijk *et al.,* 2017a). An important consequence of agricultural expansion - and subsequent landcover change - are increasing greenhouse gas concentrations in the atmosphere (i.e. Pielke, 2005). However, the total contribution of land-use related carbon emissions to the global carbon budget is unclear. There are large uncertainties related to the carbon densities of converted lands and rates of deforestation (Houghton *et al.,* 2012). Another compromising factor is the historical component of mapping land use and an effective analysis of land-use emissions (Giguet-Covex *et al.,* 2014).

Projections of future environmental scenarios are provided by earth system models. However, in order to make these projections, models rely on historical land use data (Morrison *et al.,* 2021). Attempts have been made to quantify historical agricultural land conversion, but the unavailability of reliable data, and the variety of methods and models causes data on historic anthropogenic land cover change (ALCC) to remain inaccurate (Klein Goldewijk *et al.,* 2017a). An especially ambiguous component of ALCC is pastoralism (Klein Goldewijk *et al.,* 2017a). Identifying the extent of agricultural land used for grazing livestock therefore directly contributes to the accuracy of earth system models. This study aims to formulate estimates on pasture per capita throughout the Holocene in Europe. In particular, the number of hectares of converted land used to let cattle graze will be analyzed, starting from the Neolithic transition until the Bronze Age, resulting in the following research question: *How did pasture per capita develop during the Holocene throughout Europe?*

Agriculture was slowly introduced in Europe from the Near East, across the Mediterranean and Danube river, and eventually to Western and Northern Europe. (Ammerman & Cavalli-Sforza, 1971; Barker, 1985; Gregg, 1988). With the farmers came dietary shifts related to agricultural subsistence strategies replacing Mesolithic hunter-gathering strategies, introducing domesticated livestock and subsequent land conversion. The onset of agriculture resulted in forest clearing and permanent settlement becoming prevalent across Europe from roughly 4500BCE onwards (Williams, 2000). Ruddiman (2003, 2007) notes that in the early days of farming, ALCC per person was substantially higher compared to contemporary land use due to inefficient practices and technology, and deforestation. Early land conversion lead to alterations in global biogeochemical cycles: 'early deforestation by humans reversed a naturally decreasing CO_2 trend 7000 years ago and drove subsequent values upward, while early rice irrigation and livestock tending had the same effect on the methane trend beginning 5000 years ago' (Ruddiman & Ellis, 2009). This 'early anthropogenic hypothesis' thereby presumes that a relatively small human population was able to significantly influence the environment (Ruddiman & Ellis, 2009).

Pasture is an important component of historical land use (Klein Goldewijk *et al.,*2017a/b), and in order to provide the best possible estimates on pasture per capita in Holocene Europe, this study integrates studies from a variety of disciplines. Different methods provide indications of the prevalence of grazing cattle. Some detailed contributions to mapping prehistoric subsistence have been made by DNA sampling, pollen analysis and carbon dating (i.e. Roberts, 2013; Giguet-Covex *et al.,* 2014). Using the knowledge provided in these historical sources, the results presented here give insight in the role of animal husbandry in environmental change in Europe, while simultaneously exploring different approaches to quantifying historical land use.

2 Research questions

The main aim of the study is to provide insight in historical land use by quantifying ha cap^{-1} of pastures in Holocene Europe. Considering the quantifiable information that is available, the research question particularly focuses on exploitation of cattle for dairy and meat. The first sub-question is related to the geographical and cultural component of the main research question. In order to create a scenario for ha cap^{-1}, mapping the onset and spread of agriculture in Europe is essential. The second sub-question aims to identify the prevalence of cattle exploitation in agricultural subsistence strategies. Together these questions are linked to pasturing, and the ecological impact that is implied by converting natural ecosystems to permanent pastures. Pasture use for meat and dairy production will be the focal point of this study, and will be explained in more detail in the next sections.

Research question: How did per capita pasture for meat and dairy exploitation of cattle develop during the Holocene throughout Europe?

First sub-question: How, when and where did agricultural activities spread through Europe throughout the Holocene?

Second sub-question: How did the prevalence of cattle exploitation (compared to other forms of subsistence) develop in Europe throughout this same period?

3 Background

3.1 Historical land use: pastures

Historical anthropogenic land use is defined by agriculture. Land conversion for agricultural practices has a larger environmental impact compared to subsistence strategies dependent on natural areas, like hunting and gathering. In the case of grazing cattle, permanent pastures have a much larger environmental impact compared to browsing, temporary meadows or natural grazing areas (Klein Goldewijk *et al.,* 2017b). The conversion of natural ecosystems into lands of food production is introduced in Europe during the Neolithic revolution: the transition from Mesolithic hunter-gatherers to Neolithic agriculturalists (Childe, 1951; Gregg, 1988). Agriculture spread out through Europe from the Near East in a few millennia, starting around 7000 BCE (figure 1, section 2.4). These early farming communities gave the most substantial contribution to ALCC during this period, as arable land was cultivated. During the early Neolithic, the use of converted pasture as (part of) a subsistence strategy has been documented. For example, Giguet-Covex *et al.* (2014) show that permanent pastures were present in Switzerland around 4800 BCE, based on lake sediment DNA.

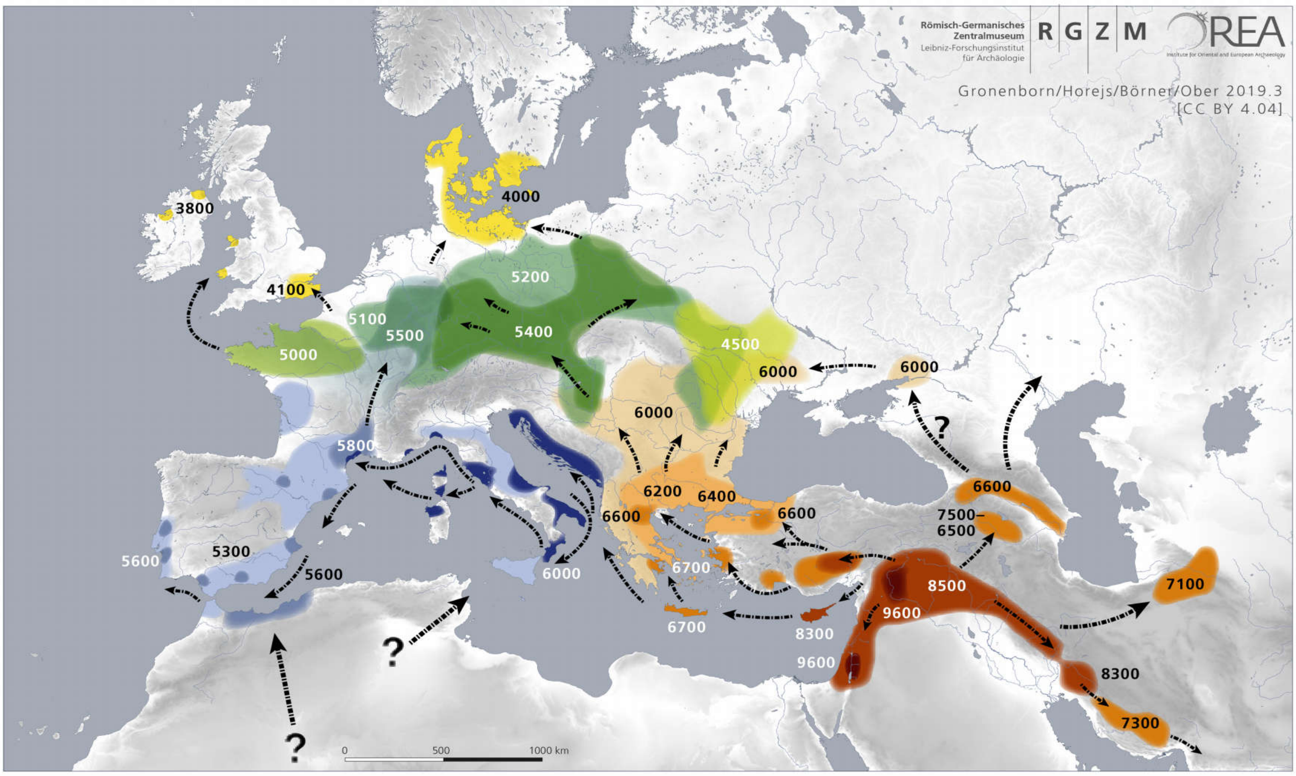

Figure 1. The spread of agriculture adopted from Gronenborn, Horejs, Börner and Ober (RGZM/OREA, 2019). The depicted episodes and direction of movement resemble both migration and diffusion (the spread of ideas rather than physical movement). Dates are in years calibrated BCE.

3.2 Early Anthropocene hypothesis

An important addition to the notion that agricultural activities catalyzed an increase in ALCC, is the idea that the contribution per person to the carbon budget was relatively high due to ineffective agricultural methods and unrestricted land availability (Ruddiman, 2007). In successive periods, agricultural intensification meant more efficient land use and food production. But in the early days of farming in Europe, a small human population impacted the environment substantially (figure 2). Ruddiman & Ellis show that a decreasing trend in atmospheric CO2 was reversed in the early Holocene (2009). The main cause that is identified is forest clearing, as substantial areas of carbon sink were destroyed. They subsequently put forward the premise that the Anthropocene actually started at around 5000 BCE rather than at the start of the industrial revolution, using the term 'early Anthropocene hypothesis' to describe this phenomenon (Ruddiman, 2003; 2007).

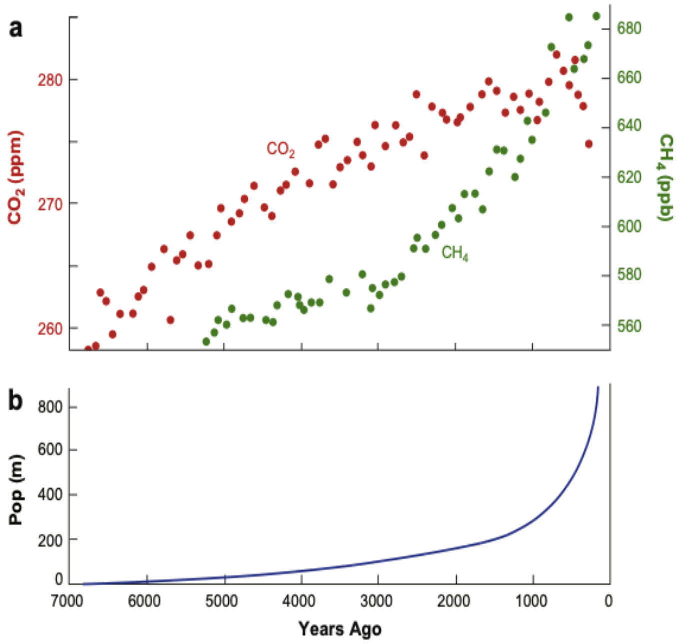

Figure 2. Figure depicting CO2 and methane measurements from Antarctic ice-sheet cores (a) and population growth (b), covering the period from 7000 to 200 years ago, adopted from Ruddiman & Ellis (2009). The CO2 and methane trends are depicted in (a). CO2 values show an increase that coincides with the onset of agriculture, where the global trend before this period was a decrease in CO2 concentration. The increase in CO2 prevalence rapidly increases before 2000 years ago and then flattens off. Indicating human influence on CO2 levels in the atmosphere in the time interval BCE (7000-2000 years ago). CH4 is more closely correlated to population growth.

3.3 Quantifying pastures: culture and agricultural intensification

Quantification of prehistoric pasturing is part of a general dedication to map subsistence, agricultural technology and related land use. The prevalence of pastures is variable through time, but also dependent on spatial contexts. Differences in subsistence have been identified even on relatively small geographic areas (Siebke *et al.,* 2020). Siebke *et al.* (2020) base their findings on dietary composition derived from stable isotope analysis at various archaeological sites in Switzerland. The inhabitants of Neolithic settlements show differences in diets, varying in the amount of plant-based food and animal protein, indicating different agricultural practices. These differences are likely related to variation in ecological properties of a given region, but are also related to cultural differences (Fowler, 2015; Siebke *et al.,* 2020). In other words, cultural dynamics that give substance to subsistence strategies can be an indicator of land use.

Another weighing indicator of pasture quantification is the efficiency of agricultural production, as productivity is directly linked to more efficient land use. Agricultural practices generally intensify over the course of the Holocene. This intensification is supported by a set of factors, like cultural development, climate impact, technological innovation, population growth and social dynamics (Barker, 1985). The yield of converted grasslands influences the land area that is needed to sustain a given cattle herd. Mapping and quantifying agricultural intensification are therefore key components of prehistoric pasture per capita quantification.

However, the main challenge in quantifying pastures lies in the extent of land conversion versus the use of natural grazing areas. It is rather difficult to determine how much land was cleared for livestock keeping and how much natural land was simply *used.* Various different forms of cattle grazing compromise the task of quantifying pasture use, 'such as meadows (for hay), fallow land, rotational pastures (summer and winter, low lying and seasonal high-altitude pastures), temporarily abandoned land and shifting cultivation' (Klein Goldewijk, 2017b: p.325). Each of these methods of cattle feeding come with specific properties and different climate impact.

4 Technical design

4.1 Methods: robust equation to quantify pasturing

In order to quantify historical ha cap^{-1} of pastureland used for grazing cattle, a set of methods is created and adopted. ALCC is substantially larger for converted agricultural lands than for exploitation of natural areas. Hence, the focus in this study is on pastures as defined by the FAO (Klein Goldewijk *et al.,* 2017a): *'Permanent meadows and pastures; the land used permanently (five years or more) to grow herbaceous forage crops, either cultivated or growing wild (wild prairie or grazing land)'* (p. 314-315).

First, desk research was conducted in order to find both qualitative and quantitative indications of ha cap^{-1}. The gathered material (section 3.2), was then analyzed to formulate estimations. In the discussion section, these results will be compared to the HYDE database (Klein Goldewijk, 2010; 2017). Various databases on historical land use have attempted to quantify pasturing using different methods (Houghton *et al.,* 1983; Klein Goldewijk *et al.*, 2010; 2017a; Kaplan *et al.,* 2011). The HYDE database consists of estimations of land-use change, population dynamics and agricultural activities, and is primarily used for carbon and climate models. Pasturing forms an uncertainty within the database, and this study aims to contribute to the accuracy of estimations.

During the desk research, directly useable data were adopted and two methods to derive estimates from other data were identified, they will be described in the next sections. The data retrieved from both methods were converted into estimates by means of the following formula:

$$\frac{\frac{Cattle\ head\ per\ household}{Average\ household} * Weight\ of\ cattle * Utilization\ rate * Grazing\ days}{Pasture\ yield} = \frac{Pasture\ (ha)}{cap}$$

This is a robust equation calculating the minimum size in hectares of pasture needed per person. The equation integrates cattle heads per person, grazing days per year, average weight, feed requirements and pasture yield, and can therefore be adjusted accordingly to various ecological or social contexts. The value for cattle weight in this example is based on Cummings & Morris (2018) who identify an average weight of 280-300 kg in Neolithic cows in Britain. Manning *et al.* (2015) present a loss in size of Neolithic cows compared to Aurochs – the wild ancestor of cattle – of 33%. This indicates a bigger body mass of around 470 kg. In this study the average, 385kg, is adopted.

The value for feed requirement is a universal rule of thumb for cattle feed, roughly 4% of the animal's bodyweight (Hijink & Meijer, 1987; Sprinkle & Bailey, 2004). In pastures, this figure is in fact the daily utilization rate consisting of the consumption rate (2.5%), trampling loss (0.5%) and a buffer (1%). The exact numbers in this utilization rate are not rigid in reality and can vary across spatial and temporal contexts. However, to simplify the data analysis presented here a utilization rate of 4% will be adopted.

Pasture yield estimates are obtained from Ebersbach (2003, p. 145-146), who identifies three different production systems in prehistoric settlements, two of which will be discussed here. The first are "maximized systems", which are mostly alpine or oasis settlements. These systems are characterized by a short vegetation period and limited arable land and therefore by intense land preparation, high yields (average yields of 2300kg/ha) and low relative land use. On the other end of the spectrum are "closed systems", where the vegetation period is not a limiting factor and almost all land is arable. This means yields are rather low (average yields of 800kg/ha). Pre-industrial Europe is more accurately defined by a "closed system", as a three-field system has been historically prevalent in Europe, with approximately one year of fallow after two years of cultivation (Ebersbach, 2003). Considering the great variety in vegetation and productivity in European landscapes (Trondman *et al.,* 2015) a generalized pasture yield of 1200kg/ha is adopted. This figure is comparable with contemporary countries with low pasture yields (Mengistu, 2004).

4.2 Method one: bone excavations

In the formula described above, the main challenge is to find data for cattle heads per person (or cattle head per household/average household). The first method is based on bone excavations in Neolithic settlements. The proportion of cattle bones can be compared to the number of houses in a given settlement (Ebersbach, 2003). By doing so, a value for cattle heads per person can be obtained. This approach is adopted by Ebersbach (2003), who relates the amount of individual cattle remains in a given archaeological unit to the herd sizes in Neolithic settlements in Switzerland. The total number of individual cattle remains represents 10-20% of the total heard, as 10% is the natural annual loss of the herd, and 20% is the highest sustainable consumption rate (Ebersbach, 2003). With this approach, the size of herds can be reconstructed and put in perspective to the size of the settlement. For this study, it is assumed that the consumption rate is optimal (20%), as this is more likely than completely natural cattle herd loss in a situation of cattle exploitation as a subsistence strategy.

4.3 Method two: dairy consumption

A second method to quantify cattle heads per person is analysis of the development of dairy consumption. When a reconstruction of the consumption of secondary cattle products, like dairy, can be identified and combined with the (daily) production of cows in a given time period (Neoltihic and Bronze Age in this case), a value for cattle heads per person can be formulated. By example, if the established dairy consumption of a prehistoric human is x liters per day, and the established milk production of a prehistoric cow is y liters per day, then $\frac{x}{y} = Cattle\ heads\ per\ person$. This value can subsequently be integrated into the formula for pasture (ha) / cap (section 4.1).

4.4 Materials

56 sources were consulted in the desk research. These sources consist of history books and papers, but also archaeological reports, comprising different research methods based on i.e. DNA research, carbon dating, pollen analysis and stable isotope analysis. These sources were extracted using search engines Google Scholar, Scopus and the library of Utrecht University. Most of the literature included is descriptive and does not provide directly adoptable data. Therefore, after the desk research was finished, 28 sources were used to formulate estimations (appendix II). This selection is a combination of sources with quantified data that could be adopted into the methods described

in previous sections, and of sources that substantiate a narrative based on which data was constructed.

4.5 Research trajectory

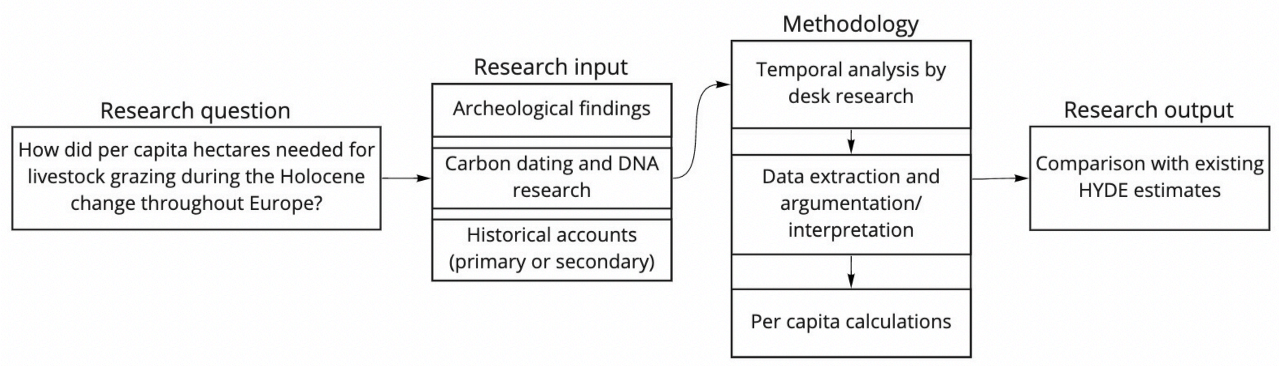

Figure 2. Schematic depiction of research trajectory. The input consists of archeological reports, carbon dating, DNA research and primary/secondary accounts. After literature research the new per capita pasture ALCC estimations will be compared with the existing data in HYDE (Klein Goldewijk *et al,* 2017a/ b).

5 Results

5.1 Pasture per capita in Gregg's subsistence model

Direct input for this study on land use by grazing cattle is provided in two sources. Gregg attempted to model Neolithic subsistence in 1988, which is cited in Williams (2000) and Müller (2015). Williams argues that a typical six household Neolithic settlement of 30 people would require a cattle herd of 30-50 heads. A smaller herd would make pastoralism economically insignificant. A herd of this size requires pastureland of roughly 18 hectares, resulting in a figure of 0.6 ha cap^{-1}.

A slightly more specific approach is opted for by Müller (2015), who argues that ethnographic archaeological research combined with calorie requirement models show that 50 hectares of pasture were needed for a five-person-household. Resulting in 10 ha cap^{-1}. This paper presents subsistence properties for a case study in the Visoko basin, present day Bosnia Herzegovina. Müller however, states that 'pedological and climatic data from the Visoko basin suggests it had similar agricultural productivity to Central Europe' (p. 72). The basis for the estimations presented in this study is also provided by Gregg's subsistence model.

5.2 Retrieving land use from bone excavations

Another approach that was identified is to formulate data for cattle head per person based on bone excavations. Ebersbach's findings result in a maximum median value of 0.88 for various sites in

Switzerland on cattle heads per household (as houses are easily identifiable in archaeological sites) during the Neolithic (Ebersbach, 2003, table 1, p. 151). A figure that is similar, but slightly lower compared to estimates in other studies (i.e. Gerling *et al.,* 2017). Assuming an average of 5-6 people per household, which is in line with Birch Chapman *et al.* (2017, average of 5.5 people per household) and Müller (2015, 5 people per household), cattle head per household can be converted to cattle head per person. The average hectares of pasture needed for one cow is estimated to be 1.5 by McClure *et al.* (2006). Combining these values gives the following results for the data provided in Ebersbach for a maximum offtake of cattle herd:

$$\frac{Cattle\ head\ per\ household}{average\ household} * ha\ per\ cattle\ head = \frac{Pasture\ (ha)}{cap}$$

$$\frac{0.88}{5.5} * 1.5 = 0.24\ \frac{ha\ pasture}{cap}$$

Using the formula described in the methods section, the following result is obtained:

$$\frac{\frac{0.88}{5.5} * 385 * 0.04 * 365}{1200} = 0.7495\ \frac{ha\ pasture}{cap}$$

The quantification method in this study therefore leads to 0.75 ha cap^{-1} of pasture as a realistic estimate for the Neolithic period (the archaeological sites included range between 4000-2500 BCE) in Switzerland. It has to be noted however that this figure represents the minimum amount of needed (converted) pasture. In reality Neolithic cattle additionally grazed and browsed in unconverted forests and grasslands, resulting in a hybrid form of natural- and converted land use, and possibly larger areas (Gregg, 1988; Sjögren & Price, 2013; Müller, 2015). Therefore, the data presented here do not represent the total area of land utilized for grazing cattle, but rather a best estimate of the area of converted pasture or grassland exclusively used for grazing. However, Slicher van Bath argues that natural grazing areas like 'forests, moors and wild meadows could likely support pigs, sheep and goat, but would offer too little for cattle keeping' (1960, p. 79), indicating the need for land conversion to maintain cattle herding as a subsistence strategy.

5.3 Retrieving land use from dairy consumption

A promising technique for the second method is presented by Tacail *et al.* (2021), who analyze dairy intake based on calcium isotopes. One conclusion they present is that in 100 BCE, the dairy intake in a French settlement (near present day Lyon) was roughly equivalent to dairy intake in the same region in the 19th century (40-70% of calcium intake from dairy products). Which implies that pasture per capita plausibly reached its maximum around this time in Western Europe, this notion is adopted as an assumption in the data in this study. This finding is supported by a set of both quantitative and qualitative sources that agree that dairy consumption gradually gained prevalence over the course of the Neolithic period and into the Bronze Age (Sherratt, 1981; Marciniak, 2011; Reynard *et al.,* 2011; Arbuckle, 2014; Gron *et al.,* 2015; Joyce & Verhagen, 2016; Gillis *et al.,* 2017; Charlton *et al.,* 2019).

Hence, Derived from Tacail *et al.* the area of pasture needed to produce such an amount of dairy can be obtained. Consumption in 19th century France was between 250 and 500 mg of calcium daily from dairy products (Tacail *et al.,* 2021). If we take the average - 375mg - we find that this is equivalent to around 0.3 liters of milk per day (Tunick, 1987). A prehistoric cow is estimated to give 1.78 liters of milk per day by McClure *et al.* (2006), which is in line with estimations provided by Todorova, who presents a figure of 500-600 liters per year (1978). Also, comparable numbers are found in contemporary countries where traditional pastoralism practices are still used (Van Geel *et al.,* 2018). If daily use per person is divided by milk provided per cow this gives: 0.3/1.78 = 0.1685 cattle heads per person. This is remarkably close to the previously presented estimate derived from Ebersbach, where we used cattle head per household/average household, or 0.88/5.5 = 0.16.

$$\frac{0.1685 * 385 * 0.04 * 365}{1200} = 0.7895$$

Of course, the value of cattle head per person to support dairy consumption likely is not the complete value of cattle head per person as there are other, primary and secondary, uses of livestock (i.e. meat, blood, hide, manure, traction and symbolic purposes). It is challenging to define the impact on land use of these other uses of cattle. However, there is growing evidence from different European countries that early Neolithic societies already combined meat and dairy production (Arbogast, 1993; Tresset, 1996; Kovaciková *et al.,* 2012; Gillis *et al.,* 2017). Gillis points at the consequences of cattle herding as an investing subsistence strategy, and the subsequent likelihood of dairying as a prominent subsistence strategy:

> ‘This investment had major implications on the development of the symbolic role of cattle and social inequality. Meat in a number of present-day societies is reserved for special occasions and ritual feasting events. Whereas dairy husbandry in comparison would have less impact on small herds and may have been more suitable for the establishment of LBK [Linearbandkeramik] cattle herds’ (2017, p.2).

Dual investment in meat and dairy is in contrast with the previously suspected notion of Neolithic meat consumption as a dominant subsistence strategy (Gillis *et al.*, 2017). On the other hand, milk production was not intensive during the (early) Neolithic. Suggesting a generally lower production of meat and dairy compared to later periods, like the archaeological site on which the presented estimate derived from dairy consumption intake was based (Tacail *et al.,* 2021). The findings presented by Gillis *et al.* suggest that meat production was less dominant during the Neolithic and subsequently had lower impact on the environment, making an argument for pasture estimates based on dairy consumption as a substantial portion of total minimal pasture, and gaining relative prominence over the centuries.

Another argument supporting the notion that a substantial portion of pastureland requirements should be ascribed to dairying in dual investment strategies is given by Joyce & Verhagen (2016), who modelled that livestock practices other than meat production entail substantially larger land use. In their model, a 30-head herd for meat production would require a mean of 15.607 ha (Joyce & Verhagen, 2016, table 3, p. 10), which is slightly lower than the land use modelled in Gregg (section 4.1). If the same value for cattle per person is used (0.16), a 30-head herd would provide 187.5 people, then - a figure of 15.607/187.5 = 0.0832 ha cap^{-1} is obtained. Additionally, Joyce & Verhagen argue that meat exploitation in cattle herds is an inherently riskier strategy compared to secondary uses due to a reduced growth rate. It is therefore questioned whether Neolithic farmers would have predominantly chosen such a risky subsistence strategy when other options became available, as "risk-avoidance" or "safety first" is a characteristic attitude associated with farmers (2016, p. 10)'.

Notably, the subsistence model provided in Gregg (1988) is not in accordance with the findings presented here. The value for cattle per person is much higher in Gregg compared to this study (>1 vs. 0.16). The value for ha cap^{-1} of pastureland is still comparable, indicating a much lower land use per cattle head. However, the material included in this study did not provide any quantifiable information that indicated a value for cattle per person similar to Gregg.

5.4 Scenario construction

However, the development of ha cap^{-1} of pasture across Europe should be perceived as a gradual process, stimulated by environmental change, cultural dynamics and technological advances (Manning *et al.,* 2013). In general, ha cap^{-1} from the early Neolithic into the Bronze Age is increasing. Although agricultural practices gradually improve and production intensifies – which results in lower land use per production unit - the growth of agricultural consumption is dominant in the net ha cap^{-1} pasture estimates during the first millennia of farming, showing an increase in ha cap^{-1}. This increase is resembled by a transition from mostly aquatic protein sources to wild terrestrial sources, domesticated terrestrial sources, and finally secondary terrestrial sources (Giblin, 2009; Fernandes *et al.,* 2015; Fowler *et al.*, 2015).

So, when the data presented in de previous section is taken as a point of departure, we can construct a scenario from the onset of agriculture until 100 BCE. This scenario mostly covers meat and dairy consumption, although bone excavations representing the presence of cattle in general is also included. For dairying, the assumption is made that this type of livestock exploitation gradually gained prevalence until the consumption reached the level that is equivalent to 19th century milk consumption, and then plateaued around 100 BCE (Tacail *et al.,* 2021). So, from the earliest indications of dairying practices around 5000 BCE (Gillis, 2017) an interpolation was made until 100 BCE. This gradual increase is in line with the notion that Neolithic societies developed lactase persistence. This implies that the quantities of human dairy consumption were not equivalent to 19th century values but are more likely to have been low in the beginning and gradually increased as lactase persistence spread through selection. This line of reasoning also works in the other direction, as the spread of lactase persistence is confirmation of the presence of dairying in early Neolithic culture and we can therefore speak of coevolution (Itan *et al.,* 2009).

The same assumption is made for the meat component of ha cap^{-1} pastureland estimates. The presented value retrieved from Ebersbach (2002, 2003) is a mean value for the period between 4000 and 2000 BCE. An interpolation was made from early findings of domesticated cattle (between 7000 and 6000 BCE) until the data for the period 4000 – 2000 BCE. For the period 4000 – 2000

Method	**Period**	**Low estimate ha cap^{-1}**	**Moderate estimate ha cap^{-1}**	**High estimate ha cap^{-1}**
Subsistence models (Gregg, 1988; Williams, 2000; Müller, 2015)	Neolithic in general (roughly 7000-2000 BCE)	0.6	5.3	10
Bone excavations (Ebersbach, 2003)	4000-2500 BCE	0.2008	0.7495	1.5096
Dairy consumption (Tacail *et al.,* 2021)	100 BCE	0.3076	0.7895	2.5046

Figure 3. Summary of presented results using three different methods. The moderate estimate for subsistence models is the average of the low and high estimates. The calculations for low and high estimates for methods bone excavations and dairy consumption are provided in appendix I.

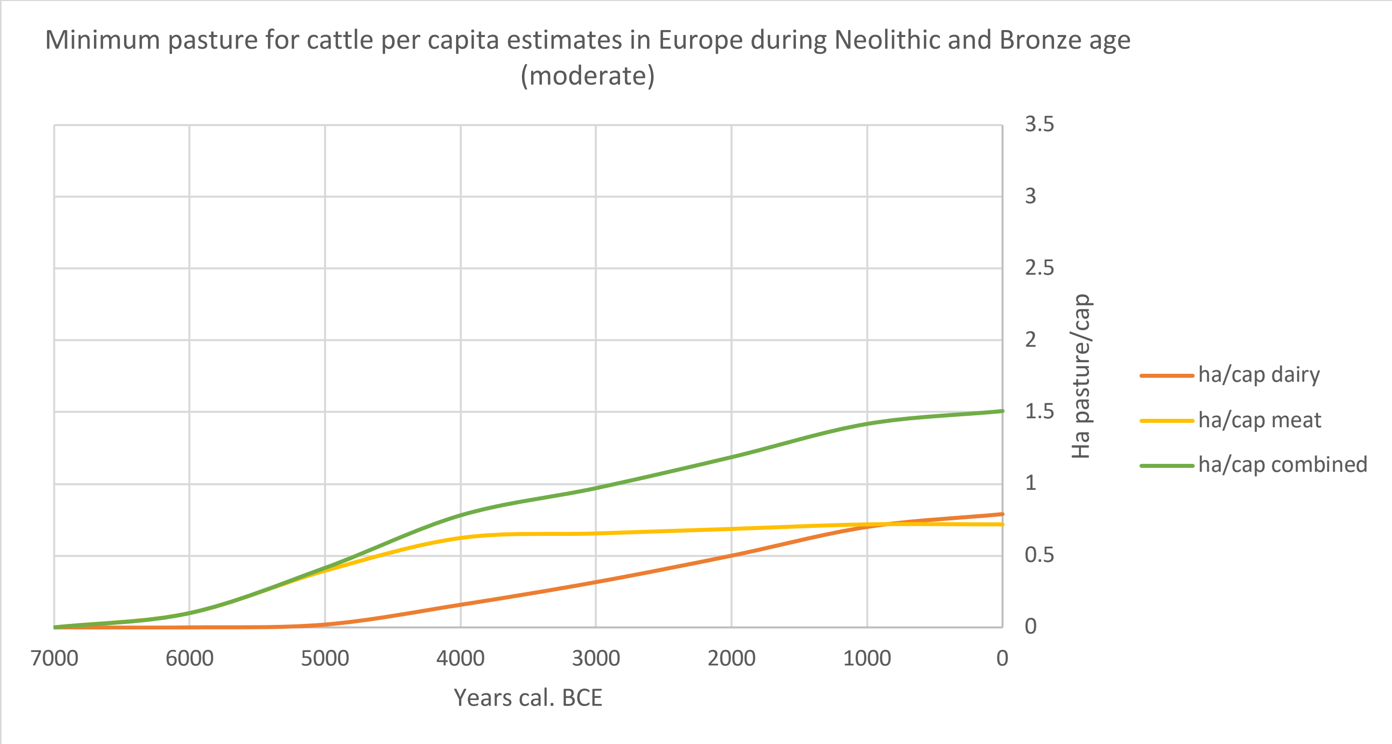

Figure 4. Depiction and quantitative interpretation of presented moderate estimates. Dual investment (primary and secondary cattle use) gained prevalence during the Neolithic revolution and Bronze Age, resulting in growing pasture per capita estimates. The increase in ha cap^{-1} is especially rapid in the early Neolithic, as agriculture was first introduced during this time and production levels increased relatively quickly due to a shift from aquatic and wild to domesticated protein sources (Fernandes *et al.,* 2015). Values for ha cap^{-1} dairy are an interpolation between values derived from Tacail *et al.,* (2021) as presented above, and represent the gradual increase of dairying as a subsistence practice. Values for ha cap^{-1} meat are based on Gregg (1988), Ebersbach (2003) and Joyce & Verhagen (2016), with the assumption that the earliest domesticated cattle were exclusively exploited for meat. Due to a lack of direct data from the Bronze Age the missing data points were obtained by interpolation.

BCE the data points for dairying were subtracted from the total land-use value to obtain values for meat. Lastly, to represent the narrative of a rising subsistence dependence on livestock keeping during the Neolithic period rather than a sudden shift from wild to domesticated protein sources, the subtraction of interpolated diary data was decreased at each time step. The plateauing or slightly decreasing trend from the middle into the late Neolithic is in line with documentation of lower relative meat consumption, which is replaced by cultivated crops (Vaiglova, 2014).

6 Discussion

6.1 Comparison: the early Anthropocene hypothesis and HYDE

The results presented here indicate that the minimal size of pasture needed to sustain the dairy and meat consumption of one person during and after the onset of agriculture steadily increased over the course of the Neolithic and Bronze Age. Subsistence strategies based on agricultural food provision steadily gained prevalence, as indicated by dietary shifts from aquatic to terrestrial protein sources and later from primary to secondary cattle exploitation (Giblin, 2009; Fernandes, 2015). Estimates for ha cap^{-1} of pastureland are therefore low initially and increase over the course of several millennia, until plateauing around 100 BCE. Agricultural intensification and increased mobility likely cause ha cap^{-1} to decrease in successive periods. However, formulating estimations for these periods was beyond the scope of this study.

The notion of relatively low pasture related land use in the early and middle Neolithic is in contrast with the early Anthropocene hypothesis as put forward by Ruddiman (2003; 2007). The results give no indication of substantial environmental impact related to pasturing in the early Neolithic, as land conversion to sustain cattle was relatively low and subsistence strategies were not focused on cattle exploitation for meat or dairy. Rather, they show that the spread and establishment of pasturing dominated the value of ha cap^{-1} for millennia, even though agricultural production efficiency improved.

When the results are compared with the data in HYDE, we find that ha cap^{-1} also plateaus around 0 BCE in the estimations provided in HYDE. Europe is subcategorized into Western- and Central Europe, with a large difference in estimations between these two categories. The results in this study do not provide reliable information that can either confirm or oppose this difference. The estimates for Western Europe are substantially higher than the results presented here, plateauing at 22.40 ha cap^{-1} in 0 BCE. Estimates for Central Europe are more conservative, plateauing at 0.51 ha cap^{-1} in 0 BCE. The estimates presented here plateau at 1.51.

6.2 Uncertainties

There are a lot of uncertainties in the methods and results presented here. The data is based on a few and very specific sources, often considering one particular archaeological site. The generalization of these case studies to Europe as a whole is uncertain. The numbers that were adopted in the calculations are highly specific and could potentially differ substantially between various spatial and temporal contexts. However, the narrative of a gradual agricultural transition and various data points indicate that the magnitude of the presented values is plausible. Comparison with the HYDE database indicates the same. Another cause of great uncertainty in terms of the relevance of the presented results for databases like HYDE is the ratio of permanent pasture versus natural grazing area, which will be elaborated on in section 6.3.

Uncertainty is enlarged by the accumulation of assumptions due to the method of data extraction from literature. For example, the data adopted from Ebersbach (2003) related to cattle heads per household, were already a product of a quantification method with uncertainties of its own. The same is true for the dairy consumption data adopted from Tacail *et al.* (2021), who puts total calcium intake from dairy consumption at 40-70%, a large bandwidth in itself. The low and high estimates provided in section 5.4 aimed at giving insight in these uncertainties by integrating the lowest and highest values for various properties in the robust ha cap^{-1} equation identified in literature (also see appendix I).

The robust equation is a very loose approximation of the relation between individual cattle, grassland productivity and land use, and thereby a source of uncertainty. The formula was opted for based on the availability of data in historical sources, rather than the other way around. A more advanced formula integrating more components that influence land use for grazing would decrease uncertainty. For example, the relation between the use of fodder, hay or leaf hay and land area has not been included in this research. Also, the results make no distinction in terms of feeding needs and bodyweight of individual cattle between different forms of cattle exploitation, like meat production and dairying, but also manuring and traction (Joyce & Verhagen, 2016).

6.3 Land conversion and mobility

As presented in section 4.1, Müller modelled a substantially higher figure (10 ha cap^{-1}) for the Visoko basin (present day Bosnia-Herzegovina). The difference is likely related to the documented mobility of Neolithic farmers. Müller describes a form of pastoralism that is highly mobile, with a combination of arable, open landscapes along the Bosna river and stock farming in mountainous areas. These practices entail vast areas of land being used by livestock, but there is low pressure on the land and a low necessity for land conversion due to abundant productive grassland. The subsistence strategy as described here is representable for more locations in south-east Europe during this period (Müller, 2015).

In contrast, Bogaard (2004) proposes that Linearbandkeramik (LBK) communities (early Neolithic culture in Central Europe) kept cattle close to settlements, implicating permanent pastures. Livestock farming was part of a land-use-efficient integrated agricultural system (Bogucki, 2013). Halstead (1989) coins the term 'intensive garden cultivation' to describe this form of agriculturalism, which is adopted by Bogaard (2004). In addition, intensive garden cultivation entails a subsistence strategy where cattle were especially valuable because of their dung for manure, as the fertile soil in the limited area used for agriculture had to be sustained. A study by Giguet-Covex *et al.* (2014), also confirms the presence of permanent pastures around settlements during the Neolithic.

The idea of intensive local exploitation of cattle in Neolithic societies is substantiated by Knipper (2011). By isotopic analysis of cattle teeth, she shows that cows grazed in areas with comparable biogeochemical properties for the full duration of their lives. Contradicting the notion of vast land use proposed by Müller (2015). The variety in historical descriptions put forward here might indicate a variety in subsistence strategies across Europe. The geographical and ecological distance between cases presented is large, and cultural differences related to agricultural subsistence strategies have been documented, even in comparable climatic or ecological contexts (Siebke *et al.,* 2020). It is therefore likely that cattle were kept using a hybrid form of browsing, fallow, temporary meadows and converted natural ecosystems for intensive local exploitation, on a macro-scale across Europe, but also in individual settlements.

The discussion between intensive local exploitation and low-impact highly mobile exploitation compromises the findings presented in this study, and enhances uncertainty. It is difficult to determine how much area of natural ecosystems was converted for grazing cattle with the methods used in this study. For prehistoric situations with intensive local exploitation of cattle, the results are a good indication of the minimal size of permanent pasture per person. In the case of a highly mobile form of cattle exploitation, like the case in Müller (2015), other factors are more significant in terms of land conversion.

Conclusion

This study attempted to quantify historical pasturing in the Neolithic and Bronze Age on the European continent. Following the onset of agriculture, cattle exploitation gained prevalence and ha cap^{-1} of pastureland grew. Two methods were identified and deemed suitable and feasible for quantification. The first method is derived from Ebersbach (2003), who compares cattle bones to houses in archaeological sites, providing data for cattle heads per household. The second method is derived from Tacail *et al.* (2021), who reconstruct dairy intake based on stable calcium isotopes. Dairy consumption was then related to milk production by cows to calculate the number of cows needed to sustain the dairy intake of one individual. The data collected using these methods was then integrated into a robust, universal equation integrating number of cattle, cattle bodyweight, a feed utilization rate, grazing days and grassland productivity. The equation was used to formulate ha cap^{-1} estimates.

Exploring these methods in combination with desk research creating a plausible narrative for the development of pasturing, results in a gradual increase of ha cap^{-1} pastureland from the early Neolithic into the Bronze Age, plateauing around 100 BC at 1.51 ha cap^{-1}. These results should be perceived as an indication of the magnitude of prehistoric pasturing in Europe, and come with large uncertainties, mostly related to the simplified formula, uncertainties in studies consulted for this research and the great variety in the ratio between permanent (converted) pastures and natural grazing area. More research on this specific difference in agricultural practice would greatly help to better indicate the significance of the findings in this study. The results are a best estimate of the minimal size of pasture per person, meaning that the total area of land used for grazing is likely substantially larger.

In comparison with existing databases like HYDE, we see roughly comparable trends although there is variation in the magnitude of the estimates. Especially with the estimates for Western Europe provided in HYDE (Klein Goldewijk, 2017a). However, this study has proposed a new approach to quantifying historical pasture per capita that can be further developed and applied to different regions, contributing to the development of historical land-use estimates.

Acknowledgements

I want to thank my supervisor dr.ir. Klein Goldewijk for guiding me through the research project and providing comments, suggestions and critique that greatly improved the quality of my paper. Also, I want to thank dr.ir. Klein Goldewijk for providing the data in the HYDE-database.

References

Ammerman, A. J., & Cavalli-Sforza, L. L. (1971). Measuring the rate of spread of early farming in Europe. *Man*, 674-688.

Arbogast, R. M. (1993). Restes osseux d'annimaux du Rabané du nord-est de la France, 148 p. Paris, France: Èditions de la Maison des Sciences de L'Homme.

Arbuckle, B. S. (2014). The rise of cattle cultures in Bronze Age Anatolia. *Journal of Eastern Mediterranean Archaeology & Heritage Studies*, *2*(4), 277-297.

Barker, G. (1985). Prehistoric farming in Europe. *CUP Archive*.

Bevan, A., Colledge, S., Fuller, D., Fyfe, R., Shennan, S., & Stevens, C. (2017). Holocene fluctuations in human population demonstrate repeated links to food production and climate. *Proceedings of the National Academy of Sciences*, 114(49), E10524-E10531.

Birch-Chapman, S., Jenkins, E., Coward, F., & Maltby, M. (2017). Estimating population size, density and dynamics of Pre-Pottery Neolithic villages in the central and southern Levant: an analysis of Beidha, southern Jordan. *Levant*, *49*(1), 1-23.

Bogaard, A. (2004). *Neolithic farming in central Europe: an archaeobotanical study of crop husbandry practices*. Psychology Press.

Bogucki, P. (2013). Open-Range Cattle Grazing and the Spread of Farming in Neolithic Central Europe. *Environment and Subsistence–Forty Years after Janusz Kruk's 'Settlement studies*, 1-14.

Charlton, S., Ramsøe, A., Collins, M., Craig, O. E., Fischer, R., Alexander, M., & Speller, C. F. (2019). New insights into Neolithic milk consumption through proteomic analysis of dental calculus. *Archaeological and Anthropological Sciences*, *11*(11), 6183-6196.

Childe, V.G. (1951). Man Makes Himself.

Cummings, V., & Morris, J. (2018). Neolithic Explanations Revisited: Modelling the Arrival and Spread of Domesticated Cattle into Neolithic Britain. *Environmental archaeology*, 1-11.

Ebersbach, R. (2002). Von Bauern und Rindern. Eine Ökosystemanalyse zur Bedeutung der Rinderhaltung in bäuerlichen Gesellschaften als Grundlage zur Modellbildung im Neolithikum. Basler Beiträge zur Ur- und Frühgeschichte. *Basel, Schwabe*.

Ebersbach, R. (2003). Quantitative approaches to reconstructing prehistoric stock breeding. *Economic archaeology: from structure to performance in European archaeology. Bonn: Habelt*, 143-160.

Fernandes, R., Grootes, P., Nadeau, M. J., & Nehlich, O. (2015). Quantitative diet reconstruction of a Neolithic population using a Bayesian mixing model (FRUITS): the case study of Ostorf (Germany). *American Journal of Physical Anthropology*, *158*(2), 325-340.

Fowler, C., Harding, J., & Hofmann, D. (Eds.). (2015). *The Oxford Handbook of Neolithic Europe*. OUP Oxford.

Gerling, C., Doppler, T., Heyd, V., Knipper, C., Kuhn, T., Lehmann, M. F., ... & Schibler, J. (2017). High-resolution isotopic evidence of specialised cattle herding in the European Neolithic. *PloS one*, *12*(7), e0180164.

Giblin, J. I. (2009). Strontium isotope analysis of Neolithic and Copper Age populations on the Great Hungarian Plain. *Journal of archaeological science*, *36*(2), 491-497.

Giguet-Covex, C., Pansu, J., Arnaud, F., Rey, P. J., Griggo, C., Gielly, L., ... & Taberlet, P. (2014). Long livestock farming history and human landscape shaping revealed by lake sediment DNA. *Nature communications*, 5(1), 1-7.

Gillis, R. E., Kovačiková, L., Bréhard, S., Guthmann, E., Vostrovská, I., Nohálová, H., ... & Vigne, J. D. (2017). The evolution of dual meat and milk cattle husbandry in Linearbandkeramik societies. *Proceedings of the Royal Society B: Biological Sciences*, *284*(1860), 20170905.

Gregg, S. A. (1988). Foragers and farmers: population interaction and agricultural expansion in prehistoric Europe. *University of Chicago Press.*

Gron, K. J., Montgomery, J., & Rowley-Conwy, P. (2015). Cattle management for dairying in Scandinavia's earliest Neolithic. *PLoS One*, *10*(7), e0131267.

Halstead, P. (1989). “Like rising damp?” An ecological approach to the spread of farming in southeast and central Europe. In Milles A, Williams D, Gardner N (eds.). The beginnings of agriculture. B.A.R. International Series 496. *Oxford: B.A.R*, p. 23–53.

Hejcmanová, P., Stejskalová, M., & Hejcman, M. (2014). Forage quality of leaf-fodder from the main broad-leaved woody species and its possible consequences for the Holocene development of forest vegetation in Central Europe. *Vegetation History and Archaeobotany*, *23*(5), 607-613.

Hijink, J. W. F., & Meijer, A. B. (1987). *Het koemodel* (No. 50). Proefstation voor de Rundveehouderij, Schapenhouderij enPaardenhouderij.

Houghton, R. A., Hobbie, J. E., Melillo, J. M., Moore, B., Peterson, B. J., Shaver, G. R., & Woodwell, G. M. (1983). Changes in the Carbon Content of Terrestrial Biota and Soils between 1860 and 1980: A Net Release of CO" 2 to the Atmosphere. *Ecological monographs*, *53*(3), 235-262.

Houghton, R. A., House, J. I., Pongratz, J., Van Der Werf, G. R., DeFries, R. S., Hansen, M.C., ... & Ramankutty, N. (2012). Carbon emissions from land use and land-cover change. *Biogeosciences*, 9(12), 5125-5142.

Itan, Y., Powell, A., Beaumont, M. A., Burger, J., & Thomas, M. G. (2009). The origins of lactase persistence in Europe. *PLoS Comput Biol*, *5*(8), e1000491.

Joyce, J., & Verhagen, P. (2016, October). Simulating the farm: computational modelling of cattle and sheep herd dynamics for the analysis of past animal husbandry practices. In *LAC 2014 proceedings* (p. 17).

Kaplan, J. O., Krumhardt, K. M., Ellis, E. C., Ruddiman, W. F., Lemmen, C., & Goldewijk, K. K. (2011). Holocene carbon emissions as a result of anthropogenic land cover change. *The Holocene*, 21(5), 775-791.

Klein Goldewijk, K., Beusen, A., & Janssen, P. (2010). Long-term dynamic modeling of global population and built-up area in a spatially explicit way: HYDE 3.1. *The Holocene*, *20*(4), 565-573.

Klein Goldewijk, K., Beusen, A., Doelman, J., & Stehfest, E. (2017a). Anthropogenic land use estimates for the Holocene–HYDE 3.2. *Earth System Science Data*, 9(2), 927-953

Klein Goldewijk, K., Dekker, S.C. & van Zanden, J.L. (2017b) Per-capita estimations of long-term historical land use and the consequences for global change research. *Journal of Land Use Science*, 12, 313- 337.

Knipper, C. 2011. Die räumliche Organisation der linearbandkeramischen Rinderhaltung: naturwissenschaftliche und archäologische Untersuchungen. *Oxford: Archaeopress.*

Kovaciková, L., Bre´hard, S., Sumberova, R., Balasse, M., Tresset, A. (2012). The new insights into the subsistence and early farming from Neolithic settlements in Central Europe: the archaeozoological evidence from the Czech Republic. *Archaeofauna,* 21, 71–79.

Manning, K., Downey, S. S., Colledge, S., Conolly, J., Stopp, B., Dobney, K., & Shennan, S. (2013). The origins and spread of stock-keeping: the role of cultural and environmental influences on early Neolithic animal exploitation in Europe. *Antiquity*, *87*(338), 1046-1059.

Manning, K., Timpson, A., Shennan, S., & Crema, E. (2015). Size reduction in early European domestic cattle relates to intensification of Neolithic herding strategies. *PloS one*, *10*(12), e0141873.

Marciniak, A. (2011). The secondary products revolution: Empirical evidence and its current zooarchaeological critique. *Journal of World Prehistory*, *24*(2), 117-130.

Mengistu, A. (2004). Pasture and forage resource profiles of Ethiopia.

Morrison, K. D., Hammer, E., Boles, O., Madella, M., Whitehouse, N., Gaillard, M. J., ... & Zanon, M. (2021). Mapping past human land use using archaeological data: A new classification for global land use synthesis and data harmonization. *PloS one*, *16*(4), e0246662.

Pielke, R. A. (2005). Land use and climate change. *Science*, 310(5754), 1625-1626.

Reynard, L. M., Henderson, G. M., & Hedges, R. E. (2011). Calcium isotopes in archaeological bones and their relationship to dairy consumption. *Journal of Archaeological Science*, *38*(3), 657-664.

Roberts, N. (2013). The Holocene: an environmental history. *John Wiley & Sons.*

Ruddiman, W. F. (2003). The anthropogenic greenhouse era began thousands of years ago. *Climatic change,* 61(3), 261-293.

Ruddiman, W. F. (2007). The early anthropogenic hypothesis: Challenges and 14 responses. *Reviews of Geophysics*, 45(4).

Ruddiman, W. F., & Ellis, E. C. (2009). Effect of per-capita land use changes on Holocene forest clearance and CO2 emissions. *Quaternary Science Reviews*, *28*(27-28), 3011-3015.

Sherratt, A. (1981). Plough and pastoralism: aspects of the secondary. *Pattern of the Past: Studies in the Honour of David Clarke*, 261.

Siebke, I., Furtwängler, A., Steuri, N., Hafner, A., Ramstein, M., Krause, J., & Lösch, S. (2020). Crops vs. animals: regional differences in subsistence strategies of Swiss Neolithic farmers revealed by stable isotopes. *Archaeological and anthropological sciences*, *12*(10), 1-30.

Slicher van Bath, B. (1960). De agrarische geschiedenis van West-Europa 500-1850. *Het Spectrum.* Utrecht/Antwerpen.

Sprinkle, J., & Bailey, D. (2004). How many animals can I graze on my pasture? Determining carrying capacity on small land tracts. *University of Arizona Cooperative Extenstion*.

Todorova, K., & Zhelyaskova, V. (1978). *The eneolithic period in Bulgaria in the fifth millenium BC*. BAR.

Tunick, M. H. (1987). Calcium in dairy products. *Journal of dairy science*, *70*(11), 2429-2438.

Vaiglova, P., Bogaard, A., Collins, M., Cavanagh, W., Mee, C., Renard, J., ... & Fraser, R. (2014). An integrated stable isotope study of plants and animals from Kouphovouno, southern Greece: a new look at Neolithic farming. *Journal of Archaeological Science*, *42*, 201-215.

Van Geel, S., Vellinga, T., Van Doremalen, L., Wierda, C., Claasen, F., Dros, J.M. (2018). From subsistence to professional dairy businesses: feasibility study for climate-smart livelihoods through improved livestock systems in Oromia, Ethiopia. *Worldbank.*

Williams, M. (2000). Dark ages and dark areas: global deforestation in the deep past. *Journal of historical geography*, 26(1), 28-46.

Tresset, A. (1996). Le rôle des relations homme-animal dans l'évolution économique et culturelle des sociétés des Vème-VIème millénaires en Bassin Parisien. Paris, France: Université de Paris I, Panthéon-Sorbonne.

Trondman, A. K., Gaillard, M. J., Mazier, F., Sugita, S., Fyfe, R., Nielsen, A. B., ... & Wick, L. (2015). Pollen-based quantitative reconstructions of Holocene regional vegetation cover (plant-functional types and land-cover types) in Europe suitable for climate modelling. *Global change biology*, *21*(2), 676-697.

Appendix I: low and high estimates calculations

For the low and high estimates, the lowest and highest estimates provided in literature were adopted for each property in the equations for the methods based on bone excavations and dairy consumption. All the values are discussed in the methods and results sections. For the high estimate in the bone excavation method a value of 2 cattle heads per household is adopted from Gerling *et al.* (2017).

Bone excavation method, low:

$$\frac{\frac{0.44}{6} * 300 * 0.04 * 365}{1600} = 0.2008$$

Bone excavation method, high:

$$\frac{\frac{2}{5} * 470 * 0.04 * 365}{800} = 1.5096$$

Dairy consumption method, low:

Daily dairy consumption: 250mg calcium/day. 0.2 liters of milk/day. 0.2/1.78 = 0.1124

$$\frac{0.1124 * 300 * 0.04 * 365}{1600} = 0.3076$$

Dairy consumption method, high:

Daily dairy consumption: 500mg calcium/day. 0.4 liters of milk/day. 0.4/1.3699 = 0.2920

$$\frac{0.2920 * 470 * 0.04 * 365}{800} = 2.5046$$

Appendix II: overview of data extraction from literature

Robust equation

Bodyweight of cattle. Cummings & Morris: 280-300 kg, Neolithic cows in Britain. Manning *et al.:* weight loss of aurochs of 33%, indicating 470 kg	Cummings & Morris (2018); Manning *et al.* (2015)
Utilization rate of 4% bodyweight feed requirement cattle	Hijink & Meijer (1987); Sprinkle & Bailey (2004)
Pasture yields in production systems, 800 kg representable for Europe, opted for slightly higher due to variability across continent: 1200 kg	Ebersbach (2003)

Bone excavations

Herd size calculation is provided by Ebersbach based on number of identified cattle individuals in a given archaeological site	Ebersbach (2003)
Household average is estimated to be between 5 and 6 by Birch Chapman and Müller	Birch Chapman *et al.* (2017); Müller (2015)
Cattle heads per household is calculated by Ebersbach derived from herd size calculations and number of houses in a given settlement, Gerling *et al.* estimate the number provided in Ebersbach (0.44-0.88) to be slightly higher (1-2)	Ebersbach (2003); Gerling *et al.* (2017)
Average hectares per cow is given in section 5.2 providing an estimate without using the robust equation. The figure of 1.5 hectares per cow is given by McClure *et al.*	McClure *et al.* (2006)
Indications of larger areas than estimated in this study are provided by various existing models. Sjögren & Price show that Neolithic cows in Sweden were sustained on very large areas indicating mobility among farming communities	Gregg (1988); Sjögren & Price (2013); Müller (2015)
Need for pastures in cattle herding is emphasized by Slicher van Bath, who states that land must be converted in order to sustain herds of cattle.	Slicher van Bath (1960)

Dairy consumption

Dairy intake (40-70% calcium from dairy) in France near Lyon 100 BCE	Tacail *et al.* (2021)
Gradual increase in dairy intake during Neolithic and Bronze Age is documented by various sources.	Sherratt (1981); Marciniak (2011); Reynard *et al.* (2011); Arbuckle (2014); Gron *et al.* (2015); Joyce & Verhagen (2016); Gillis *et al.* (2017); Charlton *et al. (2019)*

Average daily dairy intake is derived from the findings in Tacail *et al.* (250-500 mg calcium). The equivalent in milk consumption (0.3 liters of milk) is derived from Tunick	Tunick (1987)
Milk production of prehistoric cows is given in McClure *et al.*. Also, estimations (500-600 liters per year) are provided in Todorova	McClure *et al.* (2006); Todorova (1978)
Comparison with present day societies that are likely representations of past agricultural productivity is provided by Van Geel *et al.*	Van Geel *et al.* (2018)
Dual investment in primary and secondary cattle products is put forward in these sources. The findings in these sources also indicate that the importance of agriculture increased gradually rather than drastically	Arbogast (1993); Tresset (1996); Kovaciková *et al.* (2012); Gillis *et al.,* 2017
Relative land use of different forms of cattle exploitation is modelled by Joyce & Verhagen. Meat is especially low in terms of land use, indicating that the meat component in ha pasture/cap estimate is probably not very substantial	Joyce & Verhagen (2016)

Scenario construction

Onset of pasturing as gradual process is a narrative substantiated by several authors, an important component of this argument is a documented transition from aquatic to terrestrial protein sources to primary and secondary domesticated protein sources	Manning *et al.* (2013); Giblin (2009); Fernandes *et al.* (2015); Fowler *et al.* (2015)
Lactase persistence indicates the presence of dairying in early Neolithic	Itan *et al.* (2009)
Slight decrease in meat consumption into the late Neolithic as attention shifted to crop cultivation	Vaiglova (2014)