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Settlement development and food supply in the hinterland of *Vindonissa*

By Volker Laska

Keywords: *Vindonissa / Roman legionary fortresses / impact of the military on the economy / settlement development / food supply / modelling*

Schlagwörter: *Vindonissa / Legionslager / Wirtschaft / Siedlungsentwicklung / Nahrungsmittelversorgung / Modelling*

Mots-clés: *Vindonissa / camp légionnaire romain fortifié / impact de la présence militaire sur l'économie / évolution de l'occupation / approvisionnement en denrées alimentaires / modélisation*

Introduction

This paper investigates the settlement development and the food supply of the Roman legionary fortress of *Vindonissa* (Aargau, CH) and its hinterland. It introduces the SIMFOOD simulation model for the supply and demand of grain and meat as the main components of the military and civilian diet. The model allows the simulation of supply and demand based on variable parameters such as settlement density, daily rations, and crop yields. *Vindonissa* and the nearby *colonia Augusta Raurica* (Basel-Land, CH) are treated as an economic area of two population centres competing for resources.

Historical context, geography, agriculture, and infrastructure

During the five centuries of their presence in Switzerland, the Romans left considerable traces in the archaeological record and in today's Swiss culture. They brought with them Mediterranean culture, technological innovations, and the money economy[1]. The traditional local culture of the *Helvetii* and *Raurici* merged with the Roman way of life. The almost 100 years of Roman military presence in *Vindonissa* during the 1st century AD triggered the economic development of the hinterland and a sustainable economic network of urban and rural settlements. This network survived well beyond the abandonment of the fortress in AD 101[2].

Mobile and stationary legionary camps played an important logistical role in the expansion of the Roman Empire. *Vindonissa* is the only legionary fortress located in present-day Switzerland. The archaeological remains are located in the communities of Brugg and Windisch in the canton Aargau *(Fig. 1)*. 125 years of archaeological research history of *Vindonissa* are well documented by more than a thousand excavations[3]. However, there is currently no comprehensive overview of the economic interactions between the military and the civilian population.

Vindonissa was initially founded as a military outpost on the periphery of the Roman Empire to protect the border along the Rhine from the riverbend at Basel (Basel-Stadt, CH) to

[1] Flutsch et al. 2002, 5.
[2] Laska 2021, 107–108.
[3] Hintermann 2012, 21.

Fig. 1. Map of Switzerland and its states (cantons) with *Vindonissa*, *Augusta Raurica* and *Aventicum*.

Lake Constance. In Flavian times, its role changed to providing logistical support for the expansion of the empire to the north and east, towards the Danube River[4]. The fortress covered an area of about 20 ha and was strategically located above the confluence of the rivers Reuss and Aare, 14 km south of the Augustan-Tiberian frontier along the river Rhine[5]. The new population centre with some 5500–6000 soldiers and their support staff created additional demand for building materials, goods, food, and services, and attracted more people[6].

The research area for this study, as described below, comprises parts of the two *civitates* of the *Helvetii* and the *Raurici* with their capital cities of *Aventicum* (Waadt, CH) and *Augusta Raurica* and the legionary fortress of *Vindonissa (Fig. 2)*. The area was initially part of the province of *Gallia Belgica*, and after a provincial reorganisation under Domitian around AD 90 became a part of *Germania Superior*.

A first small military post at *Vindonissa* may have been established as early as 15 BC during the Alpine campaign of Tiberius and Drusus, at the site of a Celtic settlement[7], and with the aim of controlling the important traffic routes to the north and south[8]. The legionary fortress was first established between AD 14 and 15 of timber and clay by *legio XIII Gemina*, with two phases of expansion for additional auxiliary units[9]. After the replacement of *legio XIII* in AD 45, *legio XXI Rapax* built a significant enlargement and reconstructions in stone. The transfer of *legio XI Claudia Pia Fidelis* to *Vindonissa* in AD 70 caused additional construction

4 Trumm 2015, 6.
5 Trumm 2015, 1.
6 Deschler-Erb / Akeret 2011, 13; Hintermann 2012, 149; Flück 2017, 469; Schucany 2021, 25; Trumm et al. 2022, 18.
7 Trumm 2011, 40–42.
8 Trumm 2015, 2.
9 Speidel 1996, 40–41; Flück 2017, 11.

Fig. 2. Map of the Roman provinces in the Alps region in AD 14 with the territories of the *civitas Helvetiorum* and *civitas Rauricorum* in the middle (part of the province *Gallia Belgica*).

and renovation activities. In AD 101, *legio XI* moved to the active military areas at the Danube River and abandoned the fortress in a well-planned manner. The civilian population took over the remaining buildings after several years of continued military administration[10].

The fortress of *Vindonissa* and its hinterland should not be viewed in isolation. Less than 40 km away and competing for resources was another large population centre: *Augusta Raurica*, the *caput* of the *civitas Rauricorum*. It was founded as a *colonia* in 44 BC and developed further between 20 and 10 BC[11]. The population in the 1st century AD is estimated at 6000 to 8000[12]. The *caput* of the *civitas Helvetiorum* – *Aventicum* – is more than 110 km from *Vindonissa* and 90 km from *Augusta Raurica*. It had its own hinterland in the western part of the Swiss Plateau[13].

The geography of the area is characterised by fertile and hilly land with many lake and river valleys, separated by mountain ranges, and different microclimates. A fertile molasse trough extends from Lake Geneva along the Jura lakes and the Aare valley to Lake Constance, bordered in the north-west by the Jura mountains and the Rhine valley[14]. Compared to today's average values for temperature and precipitation on the Swiss Plateau of 9–10 degrees Celsius and 800–1200 mm of rainfall[15], temperatures and precipitation in the first two centuries AD were

[10] Hintermann 2012, 27–31; Trumm / Flück 2016, 119.
[11] Furger 1994, 30; Hecht / Tauber 1998, 429.
[12] Bossart et al. 2006.
[13] Schucany / Wullschleger 2013, 412.
[14] Ebnöther / Schucany 1999, 67–69.
[15] Values depending on altitude and position to the sun (Federal Office for Meteorology and Climatology MeteoSwiss, Normal values per measured parameter 2024. https://www.meteoswiss.admin.ch/services-and-publications/applications/ext/climate-normtables.html [last access: 07/10/2024]).

slightly higher[16], providing good conditions for agriculture up to an altitude of 500–600 m, in a few cases up to 800 m[17].

A present-day soil and agricultural productivity map of Switzerland shows agriculturally high productive areas on the Swiss Plateau and along the Rhine[18]. The dominant soil types are brown and parabrown soils, with the best soils in the western part around the Jura lakes and Lake Geneva[19]. In the current Soil Atlas of Europe, cambisol soils predominate[20]. These soils are particularly suitable for arable farming und animal feed cultivation. The slopes of the Jura Mountain range are mostly covered with pseudogley soils, which are less suitable for agriculture, but good for pastures and forests. The Swiss Soil Monitoring network shows the soil types and the suitability for crop production of different locations in the Swiss part of the research area[21]. A similar land use map of soil quality is available for the Upper Rhine valley[22]. In today's French and German areas, the Upper Rhine valley was highly productive, whereas the areas of the Black Forest and the Vosges mountains were less suitable for agriculture, except in the valleys up to an altitude of 600 m[23].

With the arrival of the Romans in Switzerland, agriculture and animal husbandry were intensified[24]. The countryside had to produce a surplus in grain and meat to feed the growing population in the urban and military centres, which were agriculturally unproductive. Archaeobotanical and archaeozoological finds, tools, storage facilities, animal shelters and stables show a mixed operation of farming and animal husbandry, at least in the larger *villae*[25]. In mixed farming, crop farming and animal husbandry are interdependent[26]. More cattle require more pasture and labour, thus reducing the amount of land available for farming and the resulting crop surplus. More farming requires more oxen for ploughing, which in turn requires more grain for feed. In general, animal husbandry is more labour intensive than farming. Farming has peaks during sowing and harvesting, which can be covered by temporary workers, whereas cattle rearing is a full-time job[27].

Archaeobotanical evidence suggests that during the late Latène and early Roman periods, spelt *(Triticum spelta)*, barley *(Hordeum vulgare)*, millet *(Panicum miliaceum)*, and emmer *(Triticum dicoccum)* were the main crop species produced in the countryside and consumed by the military and civilian population[28]. In contrast, predominant cereals in Roman Italy were naked

16 Büntgen et al. 2011, 581; PAGES 2k Consortium 2013, 341.

17 Ebnöther / Monnier 2002, 149.

18 Swiss Soil / Fertility Map, Bundesamt für Landestopographie swisstopo (https://map.geo.admin.ch/?topic=blw&lang=de&bgLayer=ch.swisstopo.pixelkarte-farbe&catalogNodes=901&layers=ch.blw.bodeneignung-kulturtyp,ch.blw.bodeneignung-kulturland,ch.blw.bodeneignung-gruendigkeit,ch.blw.bodeneignung-naehrstoffspeichervermoegen&layers_ [last access: 27/02/2024]).

19 Boden-Serienkarte der Schweiz von H. Pallmann und H. Gessner (https://www.agroscope.admin.ch/agroscope/de/home/themen/umwelt-ressourcen/boden-gewaesser-naehrstoffe/nabo/nationale-bodeninformation/bodeninventar.html [last access: 07/10/2024]); Veit / Gnägi 2014.

20 Jones et al. 2005, 90.

21 Swiss Soil Monitoring Network, Bodenmessnetz der Schweizer Kantone (https://www.bodenmessnetz.ch/messwerte/uebersicht [last access: 01/01/2024]).

22 Kempf 2019, 803.

23 Blöck 2016, 123; Nüsslein et al. 2017, 658.

24 Deschler-Erb 2017, 426; Ferdière 2021, 466.

25 For instance: Neftenbach (Aargau, CH); Rychener 1999, 435; 442; 470). – Dietikon (Zürich, CH; Ebnöther 1995, 218; 223; Kaech 2013, 38). – Biberist (Solothurn, CH; Schucany 2006, 278–279). – Buchs (Aargau, CH; Horisberger 2004, 249).

26 Groot 2020, 31.

27 Ebersbach 2002, 157.

28 *Villae* on the Swiss Plateau: Schucany 2006, 276; 282; 584 (Biberist). – Kaech 2013, 105 (Dietikon). – Rychener 1999, 465; 472 (Neftenbach). – Vindonissa and other military sites: Vandorpe et al. 2017, 141. – *Augusta Raurica*: Jacomet 1988; Deschler-Erb et al. 2021, 326. – Southwest Germany: Stika 1996, 99; Blöck 2016, 99; 121. Also see Ebnöther / Monnier 2002, 158 for a general analysis of the grain spectrum.

wheat, barley, emmer and millet[29], with the exception of the northern regions where limited amounts of spelt were identified[30]. Cereal remains from *Vindonissa* (fortress and *canabae*) and *villae* show a mixture of spelt, barley, millet, emmer, and free-threshing bread wheat *(Triticum aestivum)*, with bread wheat not playing a dominant role[31]. Only *Augusta Raurica* and the region around Basel show a higher proportion of bread wheat already in the 1st century AD[32]. Barley was mainly used as animal feed for horses, pack animals and oxen for ploughing and transport[33]. In general, yields of spelt and emmer are lower than those of bread wheat[34].

Road and water infrastructure played an important role in the distribution of food and other goods. The area around *Vindonissa* and *Augusta Raurica* was covered by a dense network of roads and rivers. Both settlements were important hubs for military and economic purposes. Archaeological evidence comes from the remains of road bodies, milestones, and stations *(mansiones)*, as well as from the *Tabula Peuteringiana* and the *Itinerarium Antonini*. *Vindonissa* was at the centre of four important east-west and north-south roads: from Lake Constance (*vicus* Brigantium, Vorarlberg, AT) to Strasbourg (Alsace, FR), via the Aare valley to *Aventicum* and Lake Geneva, to the Danube River and Rottweil (Baden-Württemberg, DE), and via *Turicum* (Zürich, CH) and along Lake Walen to Chur (Graubünden, CH)[35]. *Augusta Raurica* was connected to *Vindonissa*, the Middle Aare valley via the Hauenstein pass, and the Upper Rhine valley road to Strasbourg. Both settlements were connected to the major alpine passes. These roads not only served transit traffic, but also supported local and regional connections[36]. Harbours and docks were located in cities on rivers and lakeshores[37]. With the military presence, the already existing river trade routes in Gaul were extended further north and west to supply the military and civil markets[38].

Most urban settlements were located near rivers or lakes. The Aare, Limmat and Reuss rivers were connected to the Mediterranean (Marseille, Lyon) via Lake Geneva and the Rhône, to the Rhine via the Rhône / Saône / Doubs River connection[39]. The Rhine provided a link to the North Sea. Aare, Limmat, and Reuss provided good downstream transport for bulk goods such as grain and timber. River transport of bulk goods was faster and cheaper than road transport – but the last few miles to and from the rivers required road transport.

Almost all rural settlements in the research area are within 15 km of a *vicus*. This means that goods such as grain and meat could be exchanged between the *vici* and most rural settlements within a day. For many settlements, even two or three *vici* are within a day's travel[40].

The settlement structure and the location of the *vici* and *villae* near the main traffic routes, as described below in the chapter on settlement development, must have allowed an economical and efficient delivery of goods between the fortress, the urban settlements, and the countryside.

29 Spurr 1986, 102.
30 Castelletti et al. 2001, 65–66.
31 Vandorpe et al. 2017, 141 fig. 3 for military sites and urban settlements in the 1st century AD. – Vindonissa: Flück 2017, 363 (lack of free-threshing wheat); Vandorpe et al. 2017, 139.
32 Vandorpe et al. 2017, 141; Deschler-Erb et al. 2021, 326.
33 Varro rust. 2; 7; 12; 14; Davies 1971, 123; Wierschowski 1984, 163; Junkelmann 1997, 91; Roth 1999, 62–64; Erdkamp 2005, 102; 317; 325.
34 Longin et al. 2016; Reddé 2018, 147–148; Rachón et al. 2020; Biel et al. 2021.
35 Matter 1943; Drack / Fellmann 1988, 93–100; Walser 1997; Herzig 2005; Schiedt / Herzig 2015.
36 Schiedt / Herzig 2015.
37 Drack / Fellmann 1988, 100.
38 Martin-Kilcher 1994, 562.
39 Each with short overland passages of 30 and 50 km (Martin-Kilcher 1994, 551–552).
40 Laska 2021, 100.

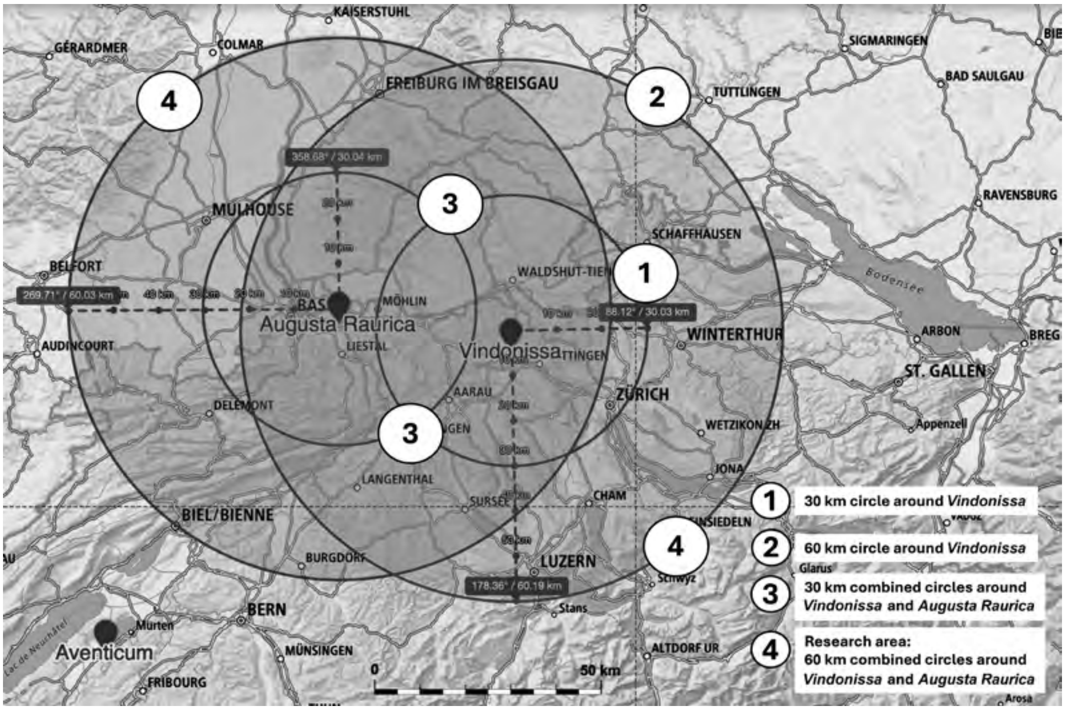

Fig. 3. SIMFOOD supply areas including research area (area 4).

Definition of the research area

The definition of the research area for the SIMFOOD model is driven by the question of what geographical area might have been necessary to supply *Vindonissa* and its hinterland with grain and meat. Four potential supply areas are considered for settlement development and the food supply model: circles of 30 km and 60 km radius around *Vindonissa*, and combined circles of either 30 km or 60 km radius around *Vindonissa* and *Augusta Raurica*. The research area is defined as the largest of the four supply areas with the combined circles of 60 km radius around *Vindonissa* and *Augusta Raurica* (area 4 in *Fig. 3*). SIMFOOD tests the hypothesis that this area was sufficient to supply the military and civilian population with grain and meat. The research area includes the main settlement clusters within a reasonable travel distance of two to three days to *Vindonissa* and *Augusta Raurica*[41], the main agricultural production areas of the Swiss Plateau, and the transport infrastructure required to move bulk goods (with the river Aare and its tributaries, and the Rhine valley).

Regional researchers have suggested that the supply area for *Vindonissa* probably included not only the immediate neighbourhood, but also some north-south running valleys in the cantons of Aargau and Lucerne, as well as the Limmat and Furt valleys in the cantons of Aargau and Zürich. It is believed to have extended eastwards towards Lake Constance, northwards into the Black Forest valleys, and southwestwards into the Aare valley[42]. This area covers a radius

[41] Kunow (1989, 384) estimates the daily travel distance on foot to be 20 km and on rivers to be 30–40 km.

[42] Ebnöther / Schucany 1999; Deschler-Erb / Akeret 2011.

of about 30 km around *Vindonissa*, representing a one-day journey for deliveries along rivers and main roads. The initial SIMFOOD calculation for a 30 km circle around *Vindonissa* and the combined 30 km circles around *Vindonissa* and *Augusta Raurica* (areas marked 1 and 3 in *Fig. 3*) indicated a significant gap in grain supply. Therefore, it seems reasonable to search for additional grain sources beyond the 30 km circles, for example in 60 km circles (areas 2 and 4 in *Fig. 3*).

The combined areas of *Vindonissa* and *Augusta Raurica* cover approximately 4700 km^2 (30 km radius) and 16,000 km^2 (60 km radius), while the individual circles cover 2800 km^2 (30 km radius) and 11,300 km^2 (60 km radius). The research area as defined above includes 33 urban settlements, compared to only 17 in the combined 30 km area (in the following text, the term "urban settlements" refers to *coloniae* and *vici*, regardless of their size and administrational status).

Caty Schucany estimates a population density of six to seven people / km^2 for the densely populated areas of the western and central Swiss Plateau in antiquity[43]. This seems to be a reasonable value for the densely populated 30 km combined supply area, resulting in a total population of about 47,000 (7 x 4700 plus 14,000 for the centres of *Vindonissa* and *Augusta Raurica*). The 60 km combined area of 16,000 km^2 was less densely settled, with a reasonable average population density of four people / km^2 (as on the eastern Swiss Plateau), giving a total population of about 78,000 people (4 x 16,000 plus 14,000). From the settlement chronology, C. Schucany estimates a population increase of 1.3 % during the 1st century AD[44]. This means that the population would have increased by about 90 % in a period of 50 years. This rapid population growth slows down in the 2nd century AD and can only be explained by the massive influx of soldiers and civilians[45]. The population figures used within the SIMFOOD model show a significant disproportion of 3–4 : 1 between the urban and rural population, meaning that each rural resident had to feed three to four people in the fortress or the *vici*[46].

Methods

The SIMFOOD model is a series of Excel spreadsheets that calculate the supply and demand of grain and meat and their temporal change during the military presence in the 1st century AD. These two components make up most of the daily diet of soldiers and civilians[47]. SIMFOOD tests the hypothesis that the hinterland of *Vindonissa* was able to produce enough grain and meat to supply the military and civilian population during the 1st century AD. Parametric models of food supply and demand have previously been developed by Peter Carrington for the legionary fortress at Chester (Cheshire, UK), Helen Goodchild for the middle Tiber valley in central Italy, and Laura I. Kooistra et al. and Marieke van Dinter et al. for the Lower Rhine delta[48].

Previous assessments of the grain supply for *Vindonissa* and its hinterland have concluded that grain had to be imported, at least initially, and have assumed sufficient supplies during the second half of the 1st century AD[49]. To date, meat demand and supply have only been studied

43 Schucany 2013, 226.
44 Schucany 2021, 28–29.
45 Reddé 2018, 132–134.
46 Well in line with Reddé 2018, 132–134.
47 Kooistra et al. 2013, 14.
48 Goodchild 2007; 2013. – Kooistra et al. 2013. – van Dinter et al. 2014. – Carrington 2008.
49 e. g. Speidel 1996, 77; Hintermann 2012, 71; Trumm 2015, 5; Schucany 2021, 27.

for the military population[50]. The SIMFOOD model goes beyond these previous calculations and assessments. It considers the diachronic growth of urban and rural settlements during the military presence in the 1st century AD, it looks at the demand and supply of the fortress and its hinterland, and it includes the food demand of military and civilian animals. It also treats *Vindonissa* and *Augusta Raurica* as an economic area of two population centres competing for resources. *Figure 4* shows a schematic input / output diagram of the SIMFOOD model, including the main input parameters. The model calculates the demand for meat and grain based on the military, urban and rural population, their daily energy requirements, and the grain requirements of the animals. It calculates the theoretical supply of meat and grain from the land available for crop and livestock production, and agricultural parameters such as field size, management practices, crop yields, and seed quantities. The calculated grain supply is adjusted for on-farm consumption, seed quantities, and losses during storage and transport.

The model and its parameters are based on evidence such as excavations of urban and rural settlements with craft workshops, granaries[51], stables and animal shelters[52], grain dryers[53], archaeobotanical and archaeozoological finds, tools for field work and food processing[54], documentary evidence such as that of the Roman agronomists Columella, Cato, Varro, and Pliny the Elder[55], epigraphic and iconographic evidence[56], historical records of agricultural practices and yields, present-day scientific studies of ancient crop species, and comparisons with other time periods and regions.

Calculations are carried out for four supply areas in the research area as defined above, separately for the first and second halves of the 1st century AD (unfortunately, a finer granularity is not supported by the available settlement foundation dates). The settlement data are in the online supplementary materials[57] *(Suppl. 1)*, and the model in *Supplement 2* as four separate Excel spreadsheets in one file (three for grain in the supply area of *Vindonissa*, that of *Augusta Raurica*, and for the combined areas, and one for meat). Parameters are highlighted in orange and can be changed for simulation purposes. All other cells are locked to protect the formulas and to prevent accidental overwriting. *Supplement 3* shows a screenshot of the SIMFOOD Excel file.

The SIMFOOD parameter choices are corroborated by archaeological or historical evidence, comparisons with other regions and time periods, and agro-scientific evidence. All assumptions are treated as input parameters that can be easily changed in the spreadsheet. The model immediately shows the effect of any change in these parameters on the output variables of demand and supply. Any geography or region of a regular shape (triangle, rectangle, square) or even irregular shape (e. g. settlement areas along river valleys and river catchment areas) can be used if regional parameters such as yield, seed quantity, and settlement density are known.

50 Deschler-Erb / Akeret 2011.

51 Vindonissa, Seeb-Winkel (Zürich, CH), Neftenbach, Biberist (Schucany 2017). – Heitersheim (Baden-Württemberg, DE; Blöck 2016, 105; 126). – Rheinfelden-Augarten (Aargau, CH; Fuchs et al. 2006, 33). – Buchs (Horisberger 2004, 90–91). – Alle (Jura, CH; Reddé 2018, 153).

52 Rychener 1999, 318; 331.

53 Dietikon (Ebnöther 1995, 223–224). – Neftenbach (Rychener 1999, 513). – Sursee (Luzern, CH; Flutsch et al. 2002, 398).

54 For typical agricultural tools such as ploughs, harrows, hoes, sickles, scythes, hay forks, see Rothenhöfer 2005, 64.

55 Erdkamp 2005, 34–51; Schucany 2006, 272–273; Goodchild 2007, 39–40; Lang et al. 2010, 14.

56 Such as scenes of ploughing, sowing, and the Gallic harvesting machine *vallus* (Rothenhöfer 2005, 65; Stoll 2016, 244; Ferdière 2021, 453; 455).

57 https://doi.org/10.11588/data/TPZIP5.

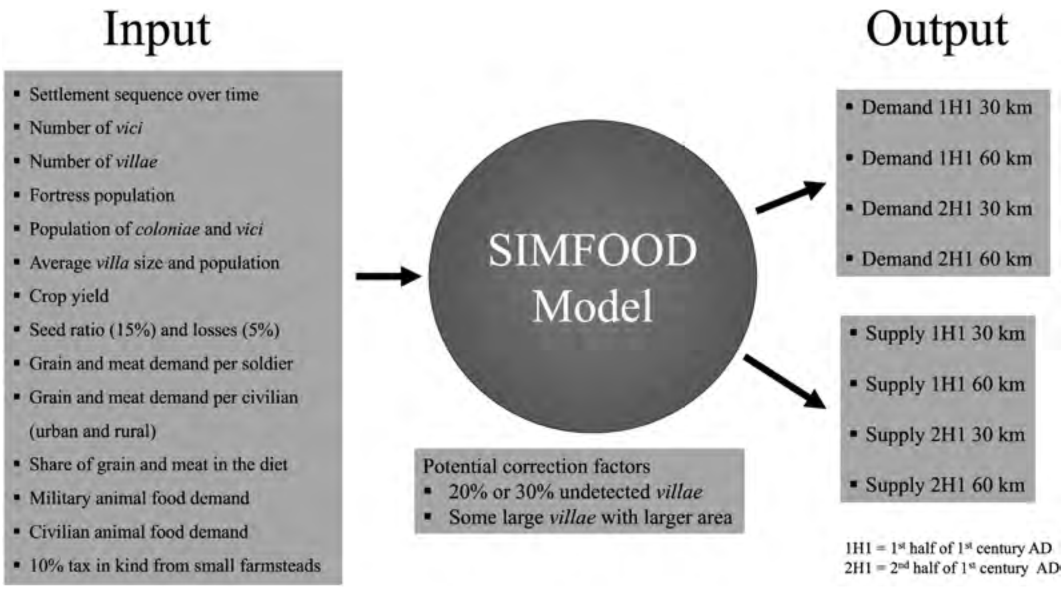

Fig. 4. Input / Output graph of the SIMFOOD Model.

The model uses an "average *villa*" with 100 ha arable land, a population of 50, and a herd of 32 cattle. The rationale for these parameters is discussed in the next chapter. For the calculation of the demand and supply, the population figures for the *vici* are based on residences per hectare and are mostly taken from Christa Ebnöther und Schucany[58]. They refer to the end of the 1st century AD. The model takes half of this value as the population for the end of the first half – this is plausible with an estimated annual population growth rate of 1.3 % for the region during the 1st century AD[59]. For small farmsteads in the research area, a size of 10 ha of land and a population of ten people seems to be a reasonable average[60]. However, the supply and demand calculations exclude the small farmsteads because they neither contributed to the supply nor consumed more than they produced for their own needs[61], but a 10 % tax in kind contribution from the small farmsteads is included in the supply calculation[62]. The model estimates five times more small farmsteads than *villae*, which would add about 15,000 people to the research area at the end of the 1st century AD. This would correspond to the estimated total population of the research area[63].

Potential methodological biases are considered in the chapter "Potential biases, critique of assumptions and discussion".

58 Ebnöther / Schucany 1998, 91.
59 Schucany 2021, 28–29.
60 Schucany 1999, 93; 2021, 27.
61 Wierschowski 1984, 168; Schucany 1999, 93; Erdkamp 2005, 50; Schucany 2021, 27.
62 Hopkins (1980, 103; 124) and Erdkamp (2002, 59–60) mention tax in kind, but no fixed amount. – Finley (1999, 91; 175) describes tax on land as the largest source of revenue for the empire (without giving specific amounts). – Wierschowski (1984, 152; 170) estimates 10–12 % of the harvest as tax. – Bossart et al. (2006, 105) estimate 10 % for the area of *Augusta Raurica* (this value is selected as a regional parameter for the SIMFOOD model).
63 Schucany 2013, 226.

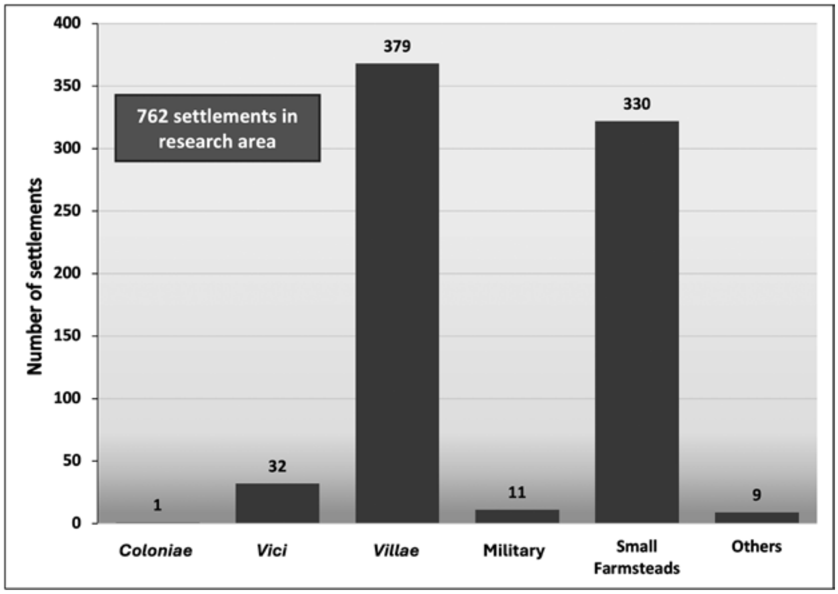

Fig. 5. Breakdown of the categories of archaeologically documented settlements in the research area.

Settlement and population development

Settlement development and sequence are important inputs to the model – they define the main locations of food production and consumption in the urban and rural settlements. For the settlement development, the author has combined several settlement and archaeological finds databases and catalogues[64]. The database covers large parts of Switzerland, the Alsace (France), and southwest Germany[65]. 90 % of the settlements in the database were discovered before 2002, and only 10 % in the last 20 years (settlement database). The combined settlement database is included as an Excel file in the supplementary materials of this article, with separate sheets containing the different data extracts for the settlements within the supply areas considered *(Suppl. 1)*. A full list of the data sources can be found in *Supplement 4*. The research area as defined above is a subset of the coverage of the database. Approximately 77 % of the settlements in the database are located within the research area of the combined 60 km circles around *Vindonissa* and *Augusta Raurica*, covering 762 entries of urban settlements, military sites, *villae*, small farmsteads, and other sites such as sanctuaries, graves, and high-altitude settlements *(Fig. 5)*.

The Romans established *coloniae* and *vici* in order to concentrate the population at selected points and to secure important elements of infrastructure and services. Most *vici* were built along major roadways, rivers, lake shores, and mountain passes[66]. The urban settlements

64 Laska 2021.

65 The local country coordinates of the settlements (like the Swiss LV03 coordinates) in the database were converted to WGS (World Geodetic System) and imported into *Google MyMaps* to create settlement maps for parts of Switzerland, France, and Germany. For each settlement, the distances to Vindonissa and *Augusta Raurica* were calculated.

66 Ebnöther / Schucany 1999, 74–75; Pauli-Gabi et al. 2002, 80; 83; Schucany 2013, 224–226.

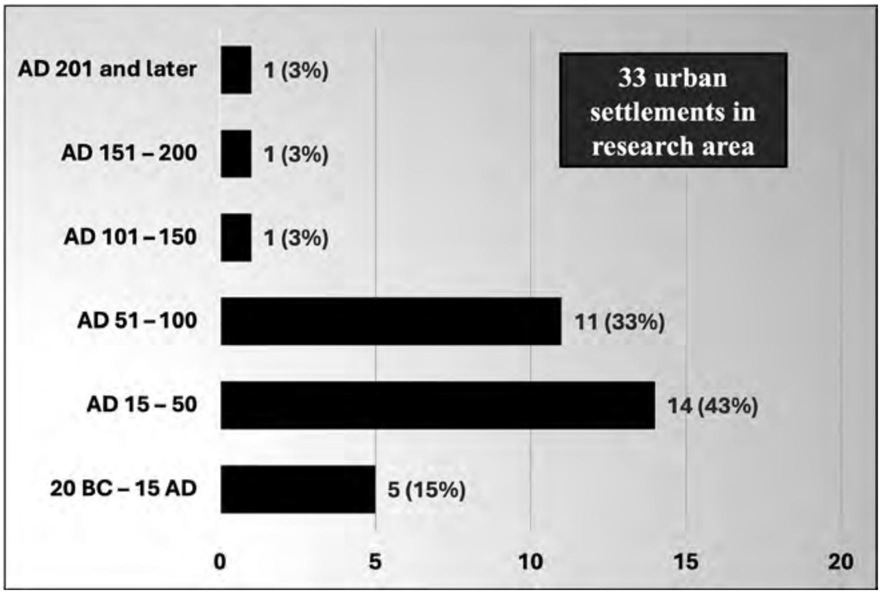

Fig. 6. Number and percentage of 33 *colonia* and *vicus* foundations in the research area per time period. Detailed data in *Supplement 5*.

played an important role as market centres and provided crafts and services for the surrounding settlements[67].

All urban settlements within the research area have been dated, mostly by terra sigillata, coins, or dendrochronology[68]. The only *colonia* in the research area was *Augusta Raurica*.

Figure 6 shows the distribution of the *vici* foundation dates. 15 % of the *vici* were established before the fortress, between 20 BC and AD 15. 43 % of *vici* foundations took place after the foundation of *Vindonissa* as legionary fortress, in the period AD 15–50. 33 % were established in the second half of the 1st century AD, and 9 % in later periods. *Supplement 5* provides a detailed list of all 33 urban settlements in the research area.

The development of rural settlements shows a gradual transition from subsistence to surplus agricultural production. The main purpose of the Roman *villa* was an agricultural surplus production, while smaller farms, as already mentioned, produced just enough for their own inhabitants[69]. Archaeologists familiar with the research area believe that the vast majority of Roman *villae* has been discovered. Within the research area, 330 small farmsteads have been found but many smaller farmsteads probably remain undiscovered due to their smaller archaeological footprint and their timber construction[70]. *Figure 7* shows a map of the urban settlements and *villae* in the research area. The settlement distribution shows a concentration of *villae* on the valley slopes around the urban settlements and close to transport routes such as roads and rivers, in order to allow for an economic distribution of the produced goods between the urban settlements and the countryside[71].

67 Doswald 1994; Amrein et al. 2012, 195; Czysz 2013, 345; Verhagen et al. 2019b, 15; Weaverdyck 2019, 183–184.

68 Pavlinec 1992, 123.

69 Rychener 1999, 15–16; Roymans / Derks 2011b, 21; Habermehl 2013, 133; Blöck 2016, 270; 279; Reddé 2018, 134.

70 Ebnöther / Schucany 1999, 69; Schucany 2016, 112.

71 Ebnöther / Schucany 1999, 80–85; Ebnöther / Monnier 2002, 149–150.

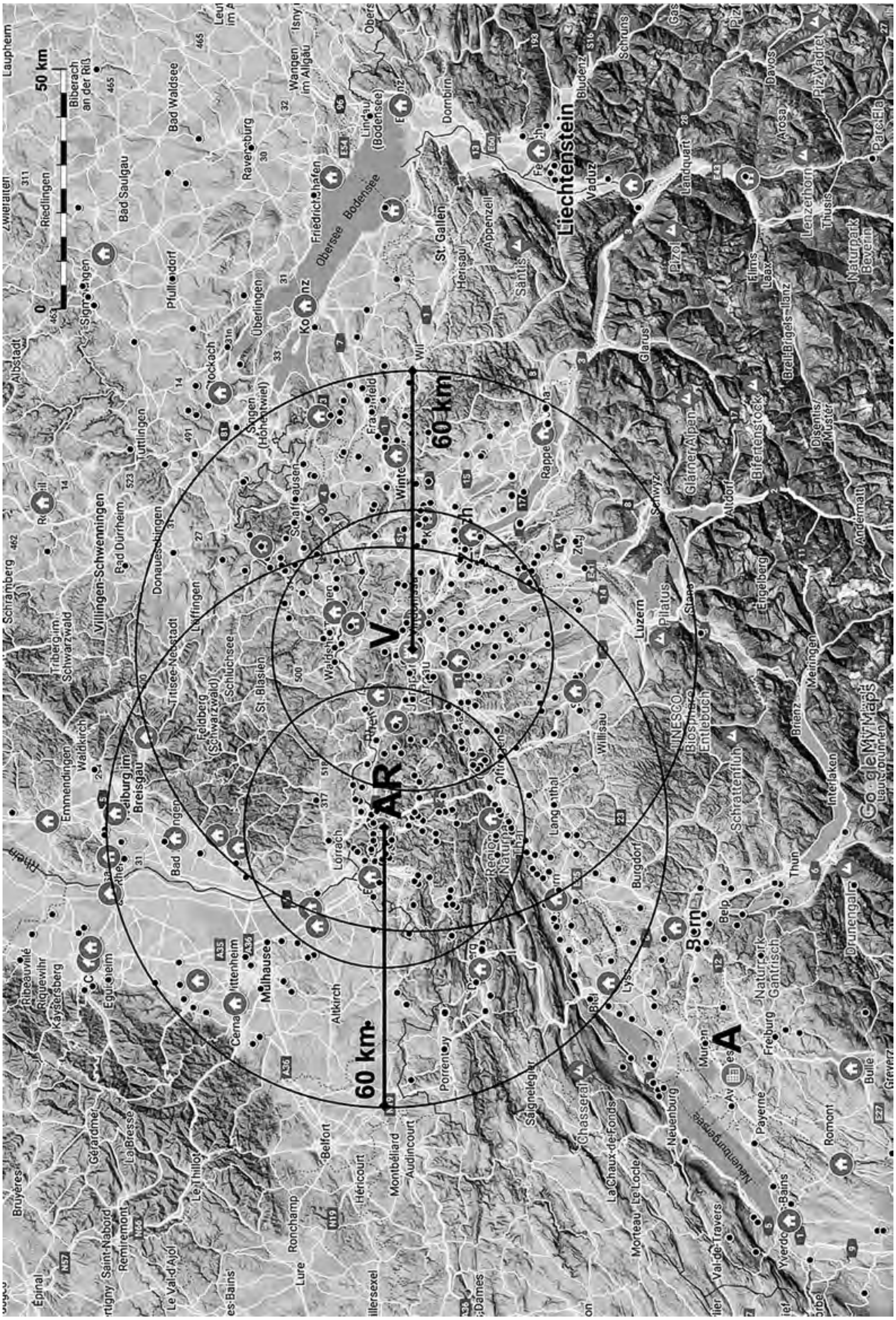

Fig. 7. Settlement map of the supply areas (circles) and combined research area (combined large circles). Black dots: *villae*, grey symbols: *vici* and *coloniae*. V = *Vindonissa*, AR = *Augusta Raurica*, A = *Aventicum*.

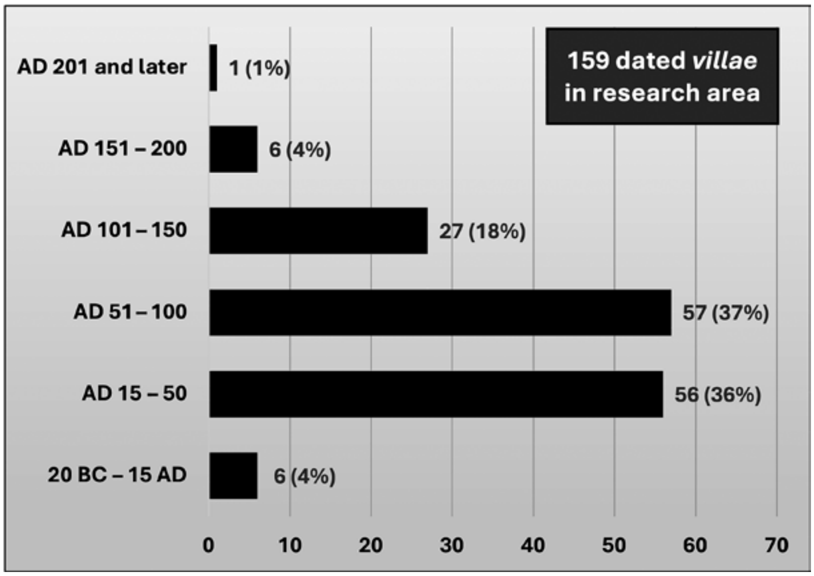

Fig. 8. Foundation of 159 dated *villae* in the research area in the different periods. Detailed data in *Supplement 6*.

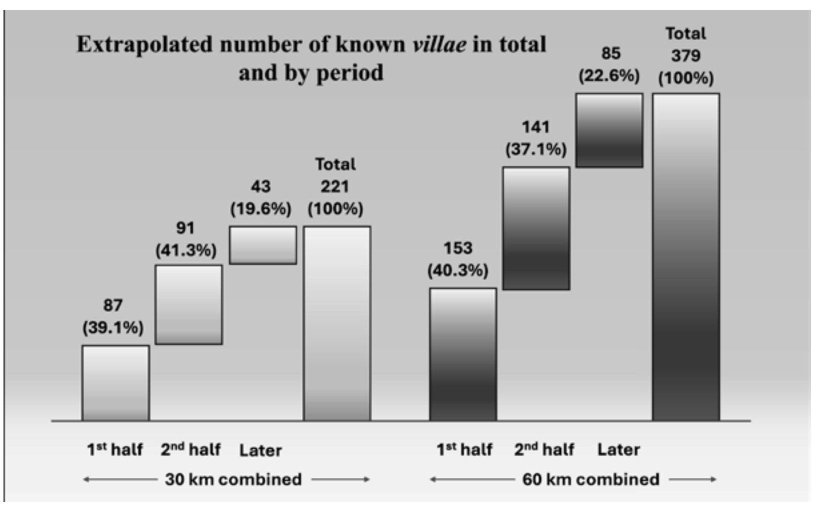

Fig. 9. Extrapolated number of known *villae* in total and by period for 30 km (in light grey bars) and 60 km (in dark grey bars) combined supply areas.

The 159 dated *villae* in the research area show a different temporal development than the urban settlements, with the majority being established in the second half of the 1st century AD (37 %) or later (23 %) *(Fig. 8)*. Only six *villae* (4 %) were found to predate the fortress, 56 (36 %) were established between AD 15 and 50 *(Fig. 8)*.

The almost equal ratio first half / second half corresponds to an average annual population growth rate of 1.3 %[72]. This means that the number of *villae* almost doubled in the second half of the 1st century AD.

[72] Schucany 2021, 29.

The ratio of dated to undated *villae* is approximately 40 to 60. The percentages of *villae* dated to the first half of the 1st century AD, the second half of the 1st century AD and later are used to extrapolate the total number of *villae* per time interval. This seems reasonable, as the percentages are in the same range for all supply areas. *Figure 9* summarises the settlement statistics for *villae* for the combined supply areas (details in *Suppl. 6*).

The settlement distribution over time is essential for calculating food demand and supply. Previous estimates are simply based on the total number of *vici* and *villae*, regardless of when they were established, and therefore do not show the real settlement picture over time. For the demand and supply calculation in the model, each of the four supply areas has a slightly different *villa* distribution over time[73].

In summary, the development of urban settlements in the research area already began well before the construction of the *Vindonissa* fortress, during the first military presence in the Augustan period, and continued with a significant building boom in the first half of the 1st century AD. This continued into the second half of the 1st century AD, including a major transition from timber to stone construction[74]. The development of the *villa* landscape began somewhat later but continued well into the second half of the 1st century AD, with new areas of development along the Upper Rhine, in the Klettgau and Hegau region (both Baden-Württemberg, DE), and in the Alsace. Hardly any of the existing *villae* were abandoned before the 3rd century AD[75]. After the abandonment of the *Vindonissa* fortress in AD 101, the settlement development continued with new *villa* constructions, luxury improvements, and investments in new businesses[76].

SIMFOOD model parameters, assumptions, and results

Models work with parameters and assumptions that can be easily questioned and challenged. It is therefore important to use documentary sources critically, to work with regional parameters as much as possible, and to draw information from comparisons with other regions. If parameters and assumptions from other regions are used, they must be examined to see if and how they can be applied to the research area. Critical assessments of similar calculations and models of food supply – such as those by Felix Lang, and more recently, Michel Reddé – should also be considered[77].

Villa sizes

Researchers of the north-western provinces estimate average *villa* sizes of 100 ha of land and 50 inhabitants[78]. Unfortunately, it is not clear whether this figure refers to the total size, the usable area (economic area), or the arable land.

A reasonable estimate of the average *villa* size and the associated arable land requires a closer look at the different settlement patterns in the research area. A *villa* distance of 1 km would provide a maximum of 100 ha of total land, 2 km up to 400 ha[79]. For the Delsberg Basin in

73 See *Supplement 6* for the different values for Vindonissa and the combined areas.

74 Ebnöther / Monnier 2002, 173.

75 Ebnöther / Schucany 1999, 80; 89.

76 Laska 2021, 89.

77 Lang 2009; Reddé 2018.

78 For instance: Wierschowski 1984, 170; Spitzing 1988, 145; Schucany 1999, 93; 2021, 27.

79 Assuming rectangles, Thiessen polygons would be around 20 % less total land.

the northern Jura, *villa* distances between 1.5 and 2.5 km and sizes of 250–300 ha total area are found[80]. Around the *vicus Vitodurum* (Zürich, CH), *villae* are in distances of two to five kilometres[81]. The Furt valley was densely settled, with distances between settlements ranging from less than one to up to three km[82]. In the Limmat valley the distances are about one to two km, in the Reuss valley two to three km[83]. In the Frick valley, 25 *villae* are scattered around the *vici* of Frick and Laufenberg (both Aargau, CH), with distances of mostly two km, a few up to four km (sizes between 350 and 600 ha)[84]. In the area south of *Vindonissa*, the distance between the large *villae* is between two and five km, with smaller *villae* scattered in between[85]. Around *Augusta Raurica* is a very dense rural settlement pattern with *villa* distances less than one km, in the Ergolz valley one to two km[86]. In some areas, *villae* of different sizes are grouped together within a short distance – they can be seen as part of a *fundus* or domain, where several dependent settlements share the land[87].

Not all the land is usable. Usable land (or economic area) consists of fields, pastures, and wooded areas. Several regional examples suggest that only about a third of the total land was usable for agriculture[88]. Based on the regional *villa* distances and sizes mentioned above, an average of 300–400 ha total land and 100 ha of arable land seems reasonable for the research area. This is more than in other areas such as the Cologne loess belt (50 ha total size) and the Neckar valley, where *villae* have less usable land and the settlement densities are higher[89].

Many researchers agree that half of the arable land was used as fallow land or for the cultivation of vegetables[90]. Long-term wheat cultivation experiments at Rothamsted, southern England, have shown rapid soil depletion when the land is farmed year over year without fallow or manure, with yields falling from 1.0 t / ha to 0.4 t / ha over 50 years[91].

Labour resources were a limiting factor in the operation of *villae*. In addition to the owner's or leaseholder's family and their servants, workers were needed for farming, animal husbandry, food processing, and maintenance. Paul Erdkamp estimates 14–18 workers per 50 ha of farmed area[92]. According to Renate Ebersbach, one full-time person can manage four to five cattle or two to three cattle in dairy production[93]. With additional labour needed for maintenance work, 50 persons seem to be a reasonable estimate.

80 Martin-Kilcher 1976, 139–140.
81 Rychener 1999, 338.
82 Horisberger 2004, 332.
83 Ebnöther / Schucany 1999, 83.
84 Matter / Schwarz 2016.
85 Schucany 2021.
86 Hecht / Tauber 1998, 435–437.
87 Furt valley: Horisberger 2004, 331. – Middle Aare valley: Schucany 1999, 90; 2011, 277–279. – Limmat valley: Ebnöther 1995, 226–227.
88 Horisberger 2004, 330 estimates 1/3 fields, pasture, and forest for Buchs. – Rychener 1999, 448–449: 50 % fields and pastures at Neftenbach. – Schucany 2011, 277–279: 30 % for fields for Biberist and 55 % fields and pastures for Bellach (Solothurn, CH). – Ebnöther 1995, 227: 50–60 % for fields and pastures for Dietikon. – Ratios per *villa* depend on individual topographies.
89 Cologne loess zone: Gaitzsch 2011, 287; Brüggler et al. 2017, 39; Reddé 2018, 159. – Neckar valley: Spitzing 1988, 146.
90 For instance: Spitzing 1988, 142; Kreuz 1997; Hecht / Tauber 1998, 431; Völling 2005, 238; Lang 2009, 400; van Dinter et al. 2014; Blöck 2016; Brüggler et al. 2017; Schucany 2017; Reddé 2018, 140.
91 Bawden 1968, 43; Lüning 1980, 118; Moss et al. 2004, 866.
92 Erdkamp 2005, 47.
93 Ebersbach 2002, 156–157. – Although R. Ebersbach's study refers to the Neolithic, it appears reasonable that estimates of cattle related workload, grazing needs and hay consumption are transferable to the 1st century AD. They are corroborated by various other authors like Spitzing 1988, Horisberger 2004 and Huntley 2013.

Demand and daily rations / Total energy expenditure (TEE)

The main consumers of grain and meat were the soldiers in their fortress and the civilian population in the *vici* and the countryside. Other consumers of grain were the military animals (horses and pack animals), the animals needed in the rural settlements for ploughing and draught, and the animals reared to supply the military and civilian population with meat, dairy products, and hides. In addition, a considerable amount of grain was needed as seed for the following year.

In the literature, estimates of daily food requirements (or caloric intake) for the Roman period vary widely, with annual grain requirements ranging from 240 to 450 kg / year *(Suppl. 7)*[94]. Given these ranges, it makes little sense to use an average for further calculations. Rather than using an average, the total energy expenditure (TEE) for soldiers in combat and in training is taken from contemporary military sources[95]. Present-day values are adjusted downward by 10 % to reflect the smaller size and weight of people in the Roman period[96]. The SIMFOOD model assumes an average daily caloric demand of 3600 kcal[97].

The caloric demand for heavy agricultural work is between 400 and 600 kcal per hour, and for typical craft activities between 300 and 600 kcal per hour[98]. This suggests that civilians in the countryside and in the *vici* may have had requirements comparable to those of soldiers. However, for the total energy expenditure of the rural and urban civilians, the model uses contemporary FAO data from a joint FAO / WHO / UN expert commission[99], allowing for differentiation by gender, age group, body mass index (BMI), and physical activity levels (PAL)[100].

[94] Schucany 2021, 26 calculates for the research area with 0.5 m^3 (or 0.375 t) for soldiers and *villa* inhabitants and 0.3 m^3 (or 0.225 t) for *vici* inhabitants. – Bossart et al. 2006, 105: 0.4 t per adult in urban settlements and in the countryside. – Bennett 2013, 322: 0.327 t of medium to heavy wheat (for Anatolia). – Polak / Kooistra 2013, 399 use 0.26 to 0.33 t.

[95] The Scientific Advisory Committee on Nutrition (Sacn) statement on military dietary reference values for energygives a median estimated average requirement (EAR) between 3600 and 4600 kcal / day depending on activity levels (p. 9: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/583321/SACN_military_DRVs_for_energy_position_statement.pdf [last access: 07/10/2024]). The estimate for the general population is 2900 kcal / day. Baker-Fulco 1995, Margolis et al. 2014 and Bob Reinert (Army Studies Special Operators' Nutritional Needs. https://www.military.com/special-operations/army-study-special-forces-nutrition.html [last access: 07/10/2024]) estimate 3600–4600 kcal for active soldiers and 3250 kcal for moderately active soldiers in garrison. As Roman soldiers on the frontiers were constantly in training or involved in construction, transport and craft production, the model assumes an average daily caloric demand of 4000 kcal, adjusted downwards by 10 % to 3600 kcal.

[96] The 10 % lower weight is explained by the size difference of approx. 10 cm between antiquity and today (calculated for a normal BMI range of 20–25). Today, average sizes in Switzerland are 178 cm for men and 165 cm for women (Bundesamt für Statistik Schweiz, Durchschnittliche Körpergrösse [in cm]. https://www.bfs.admin.ch/asset/de/30305714 [last access: 07/10/2024]). The size of adult males in ancient times ranged from 162 to 171 cm, with soldiers taller than average males (Roth 1999, 9). For Roman Italy, average heights for men are estimated to around 168 cm (Kron 2005, 72). For the research area, burial data from the civilian settlement of Vindonissa from the 3rd century suggest male height averages of slightly less than 170 cm and about 155 cm for women (Baumann 2024, 54–55).

[97] Downward adjustment of 10 % to an average height of 170 cm and an average weight of 70 kg (calculated using the Mifflin-St. Jeor formula, Mifflin et al. 1990).

[98] Beck 1986, 182 estimates 600 kcal / hour for harvesting, 430 for ploughing and harrowing, 370 for manuring, and 320–680 for forest working. – FAO 2001 uses a PAL factor of 2.0–2.4 of the daily basic metabolic rate for farm and forest working. – D-A-CH reference values for light craft activities are PAL factors of 1.8–1.9 (Elmadfa et al. 2023, 75).

[99] FAO 2001.

[100] TEE is calculated from the basic metabolic rate

	Total energy expenditure (TEE, kcal/day)	Thereof 75 % in cereals (kcal/day)	Cereals per day at 3300 kcal/kg (kg/day)	Yearly demand in cereals (kg/year)
Soldiers	3600	2700	0.818	299
Civilians: *Villa*	2669	2002	0.607	221
Civilians: *Vicus*	2534	1901	0.576	210

Tab. 1. Calculation of cereal demand per year and person, derived from daily total energy expenditure of individuals. Detailed calculation in *Supplement 8*.

TEE is used to calculate the daily grain demand based on the assumption that about 75 % of the daily diet is provided by cereals, 15 % by other foods such as vegetables, fruits, and nuts[101], and about 10 % by meat. Meat rations of 100 g / day provide about 200 kcal, less than 10 % of the daily demand[102]. One kilogram of grain provides about 3300 kcal, depending on the crop species[103]. The calculations (details in *Suppl. 8*) result in a grain demand of 818 g / day for soldiers, 607 g / day for the rural population, and 576 g / day for the urban population. The value for soldiers matches relatively well with the 850 g / day military wheat rations quoted in some documentary sources[104].

Grain was needed not only for soldiers and civilians, but also for the military animals (horses and pack animals). In addition to the normal 120 cavalry horses of the legion, stamped military tiles and inscriptions attest to the presence of at least one *cohors equitata* with an average of 120 horses during the 1st century AD alone, and at least one *ala* with 560 horses in the first half only[105]. This requirement for up to 800 cavalry horses in the first half is estimated at about 2.5 kg of barley per day or 730 t / year (240 horses for the second half with 219 t / year)[106]. 1400 pack animals required about 766 tonnes / year[107].

A full legion with its animals therefore had a grain demand of 3000 to 3500 t / per year, not counting the associated population in the *canabae*[108]. 1000 tonnes of grain would feed about 4600 people in the urban and rural settlements (calculated at an average of 0.215 t / year, see *Tab. 1*).

An additional grain fodder demand came from ploughing and draught animals in the countryside (mainly oxen and horses) and from animals reared and slaughtered for the military and civilian supply with meat and dairy products. The diet of cattle and sheep consisted mainly of grass and hay[109]. Cereals were used as hard fodder for cattle[110]. The average hard fodder

(BMR) multiplied by the physical activity level (PAL). Separate tables are available for men, women and children by age group and BMI.

101 Carrington 2008, pos. 669; Polak / Kooistra 2013, 433.

102 Average nutrition values for beef, pork and lamb (and their processed products) are taken from the official Swiss nutritional value database (Schweizer Nährwertdatenbank; https://naehrwertdaten.ch/de/ [last access: 10/04/2024]) and from Elmadfa et al. 2023, 44–51.

103 Schucany 2006, 282; Elmadfa et al. 2023, 24–26; Kooistra et al. 2013, 14. An average value of 3300 kcal is used for wheat species like free-threshing wheat, spelt, emmer and einkorn.

104 e. g. Roth 1999, 24; 43; 48; Kehne 2007, 334.

105 Hartmann / Speidel 1992; Speidel 1996, 45; 76; Trumm et al. 2022, 75.

106 Davies 1989, 187; Roth 1999, 64; Herz 2007, 317; Kehne 2007, 325; Polak / Kooistra 2013, 400.

107 Roth 1999, 83 estimates about 1400 pack animals per legion, with a daily grain consumption of 1.5 to 2.0 kg / day. The model uses 1.5 kg / day. See also Roth 1999, 65; 67 and Polak / Kooistra 2013, 400.

108 They are accounted for by the population of the *vicus* Windisch.

109 Roth 1999, 125; van Dinter et al. 2014, 19.

110 Wierschowski 1984, 170; Lang 2009, 402; Lang et al. 2010, 18; Blöck 2016, 102; Groot 2020, 34; Ferdière 2021, 458; Schucany 2021, 26.

consumption is estimated to be 1.5 m³ per year for a pair of oxen, or 0.555 t / year and cattle[111]. This value is used in the model[112]. Schucany estimates that one pair of oxen is needed to plough 8 ha of farmland, or about six pairs for 50 ha[113]. An average herd size of 32 animals per *villa* (twelve oxen, 20 cows, calves, and bulls), as proposed below, requires about 17.8 t of grain fodder per year. Any grain fodder for other livestock (horses, sheep, goats, and pigs) is neglected in the model.

Crop yield and seed quantities

Good yields required manure to increase productivity and to avoid soil exhaustion. As suggested by the Roman agronomists, Roman agriculture used livestock manure as fertiliser[114]. Manure was at least partially used in the research area[115]. Manure management would require the collection of manure, which would be difficult when cattle were grazing outside. Cows produce about 40 kg of fresh manure per day, resulting in 20 kg of rotten (condensed) manure[116]. One ha fields require about 50 t of rotten manure, which results in a need of 2500 t / year for 50 ha of cultivated land[117]. This would require 340 cattle. An average herd of 32 cattle as proposed below would produce about 235 t / year of rotten manure, enough for only 5 ha of fields (or more if used in smaller quantities). However, cattle manure could be supplemented to some extent by manure from other animals, as well as potash, chalk, and calcium carbonate[118], or green manure from leguminous crops such as lupines[119]. In the research area, only a fraction of the arable land could be fertilised, and manure probably had to be concentrated on the less fertile land.

A regional estimate by Schucany for the fertile Swiss Plateau is an average yield of 1500 l / ha or 1125 kg / ha, based on the climate and soil conditions of the research area in the Roman period, comparable to Italy and Sicily[120]. Julia Bossart et al. estimate a yield of 1 t / ha for the *Augusta Raurica* area[121]. Lars Blöck assumes yields between 800 and 1000 kg / ha for southwest Germany[122]. All areas are dominated by brown and parabrown soils. Lang uses a value of 1100 kg / ha for the very fertile Cologne loess belt (parabrown soil) but considers this to be optimistic[123]. Yield estimates for other parts of *Germania Superior* and *Inferior* are lower, for instance 750 kg / ha for Saalburg (Hessen, DE)[124], 1000 l / ha for the Neckar valley (Baden-Württemberg, DE)[125], and 1000 kg / ha for the Lower Rhine delta[126]. As much of the agricultural land in the research area is located on the Swiss Plateau, the SIMFOOD model uses Schucany's estimate of 1125 kg / ha.

111 Schucany 2006, 283; Schnetz 2013, 80; Schucany 2021, 26.

112 In comparison, modern grain fodder (mash) requirements for dairy cows and calves in Switzerland are in the range of 2 kg / day or 0.7 t / year (Schweizer Bauer, Wer frisst was? https://www.schweizerbauer.ch/pflanzen/futterbau/wer-frisst-was/ [last access: 07/10/2024]; Schori / Münger 2021; swissmilk, Bei uns finden Milchkühe ohne Mühe Futter. https://www.swissmilk.ch/de/schweizer-milch/unsere-kuehe/bei-uns-finden-milchkuehe-ohne-muehe-futter/ [last access: 07/10/2024]).

113 Schucany 2006, 283.

114 Spurr 1986, 126–127.

115 Varro rust. 1, 7, 8; Ebnöther / Monnier 2002, 159–160; Schucany 2006, 280.

116 Spurr 1986, 130.

117 Spurr 1986, 127–131.

118 Goodchild 2007, 268 and Kron 2012, 159.

119 Goodchild 2007, 268.

120 Schucany 2006, 280; 2021, 26.

121 Bossart et al. 2006, 105.

122 Blöck 2016, 100–101; 127.

123 Lang 2009, 402.

124 Kreuz 1997, 173.

125 Spitzing 1988, 148.

126 van Dinter et al. 2014, 45.

Several further historical and present-day sources are used to corroborate this estimate for the research area. *Supplement 9* summarises yield estimates by Roman agronomists for Italy, regional authors from the north-western provinces, historical yield data from the pre-industrial period, yields from the modern period, and yields since the introduction of present-day agricultural management. Contemporary studies of ancient crops and recent climate and crop growth models are also considered for corroboration.

The Roman agronomists reported yields in multiples of the seed quantity. Their estimates vary from 4 : 1 for the whole of Italy (Colum. 2,9,1 and 3,3,4) to 8 : 1 to 10 : 1 (Cic. Verr. II 3,112 for the *ager Leontini*, the most fertile part of Sicily) to 10 : 1 to 15 : 1 (Varro rust. 1,44,1–2 with 15 : 1 for Etruria)[127]. These estimates refer to Roman Italy and to naked wheat, the main crop in Italy[128]. The agronomists estimated seed quantities between four and eight *modii* per *iugerum*[129], equivalent to 100–200 kg / ha, and emphasised different sowing approaches for different soil, temperature, and rainfall levels. For spelt, Varro (rust. 1,44,1–2) explicitly suggests ten *modii* per *iugerum* (260 kg / ha), for emmer Columella (de re rust. 2,9,1) nine to ten *modii* (236–260 kg / ha). Pre-industrial seed quantities for spelt are in a comparable range of 165–220 kg / ha[130]. Modern farmers have optimised the seed rates for maximum yield. A local farmer close to *Vindonissa* who specialises on spelt (Loohof farm, Endingen [CH]) uses about 200 kg / ha of seed, with drill sowing, to achieve yields of 4.5 t / ha[131]. Higher seed quantities may not increase yields due to intraspecies competition for nutrients and increased risk of lodging of the stems[132]. In line with the above figures, SIMFOOD uses a reasonable 15 % of the yield as seed saved for the following year (approximately 170 kg / ha).

Several researchers argue that Roman yield and seed levels were comparable to late medieval or pre-industrial levels[133]. Lang et al. describe a slow and steady increase of crop yields between 1100 and 1800 in central Europe and estimate that the yield to seed ratio was 3 : 1 in medieval times, 4 : 1 around AD 1500, and 5 : 1 in the 18th century AD[134].

What can we learn from pre-industrial historical records and contemporary agronomic data? Yields reported for pre-industrial periods are in the range between 0.6 to 1.4 t / ha *(Suppl. 9)*. As might be expected, the figures show variation by location and over time. Average yields are only meaningful for small regions and over long periods of time.

Discussions about yields in the Roman period frequently make use of two long-term wheat cultivation experiments. The Broadbalk wheat experiments at Rothamsted, southern England, show the effects of different farm management practices on crop yields[135]. The studies have been running since 1843. Between 1852 and 1925, yields from unmanured fields on 2 x 2 m plots declined over time from 1.0 t / ha to 0.45 t / ha. With the introduction of fallow land from 1925, yields improved to just over 1.0 t / ha[136]. With the introduction of liming, pesticides,

127 M. S. Spurr (1986, 83) rejects an exceptional value of 1 : 100 from Sybaris, southern Italy (mentioned by Varro rust. 1,44,2), because it probably means a growth of 100 ears from a single seed.

128 In comparison, researchers' estimates for the north-western provinces vary between 10 : 1 (Kreuz 1997, 173), 8 : 1 (Drexhage et al. 2002, 67); 5 : 1 (Wierschowski 1984, 169–170; Spitzing 1988, 149) to 4 : 1 (Blöck 2016, 201). Eck (2007, 215) estimates a range from 4 : 1 to 15 : 1 for the area of Cologne.

129 Spurr 1986, 56; Erdkamp 2005, 43; Lang et al. 2010, 14; Goodchild 2013, 69.

130 Lang 2009, 396; Blöck 2016, 101.

131 Pers. comm. Markus Hauenstein, farmer of Loohof, Endingen (CH) on 25th January 2024.

132 Dorval et al. 2015, 842; 846.

133 Eck 2007, 215; Lang 2009, 399; Lang et al. 2010, 15–16; Blöck 2016, 100–101; 103; Reddé 2018, 141–142.

134 Lang et al. 2010, 15.

135 Bawden 1968; Moss et al. 2004.

136 Bawden 1968, 43 with tab. 3,16 and a summary in Lüning 1980, 118.

and modern wheat varieties, yields increased by a factor of three to four[137]. This illustrates the productivity gains achieved by the introduction of chemical fertilisers and pesticides since the middle of the last century.

The Butser Ancient Farm project in Hampshire, southern England, gave average yield values of 1.49 t / ha for spelt and 1.65 t / ha for emmer over 15 years[138]. Lang and Reddé question the validity and comparability of these results for Roman times – the project used small plots of previously uncultivated land, used furrow sowing instead of broadcast sowing, and took extreme care of the crops during the growth phase. Both suggest that the use of ancient literary sources and comparisons with high middle-age and with pre-industrial periods provide better input for the Roman period[139].

In recent years, ancient wheat species such as spelt, emmer, and einkorn have gained considerable interest as alternative crops to improve biodiversity and nutritional value. They have a higher tolerance to diseases and lower soil quality[140]. Experiments have been carried out under both ancient and modern growing conditions. However, many recent yield studies have focused on the current potential of modern agricultural management with automated sowing, nitrogen fertilisation, pesticide use, and seed pre-treatment. These studies show spelt yields between 2.5 and 4.5 t / ha[141], mostly on cambisol or chernozem soils and in a central European climate. Soil and climatic conditions, seeding rates, and fertilisation levels vary between studies. Most of these results are therefore not directly comparable with ancient crop production. Predictions of potential prehistoric yields would require much larger plot sizes than the 1–10 m^2 used in these experiments[142]. These small plots are much easier to weed and maintain than large fields. Another important difference is the method of sowing. Modern experiments tend to use row or drill seeding rather than the broadcast seeding of ancient agriculture.

A potentially useful indicator is a recent multi-year, multi-location study of ancient crop yields of spelt, emmer and einkorn, conducted in the Czech Republic between 2014 and 2016[143]. Due to comparable soils (chernozem [black soil] and cambisol [brown soil]), average temperatures, and precipitation data, results may be comparable to the research area in the Roman period. Average yields across years and sites without nitrogen fertilisation and herbicide use ranged from 0.97 t / ha to 1.11 t / ha.

Modelling results also support the yield estimate for the research area. A recent simulation model of grain yields using the PCR-GLOBWB hydrological model – based on the History Database of the Global Environment (HYDE) 3.1 by Brian J. Dermody et al.[144] – confirms earlier yield estimates for Roman Italy by Erdkamp and Goodchild[145]. For the Swiss Plateau and the Rhine valley, it shows crop yields between 0.5 and 1.5 t / ha for AD 200, with most areas in the 0.5 to 1.0 t / ha range[146]. Jamie Joyce's ROMFARMS agent-based model for the Dutch Roman *limes* uses 1000 kg / ha with 20 % yield variation depending on temperature and rainfall[147].

137 Moss et al. 2004, 866 fig. 1 summarizes wheat yields depending on different farm management changes between 1850 and 2000.

138 Reynolds 1990, 70.

139 Lang 2009, 396–398; 400; 402; Reddé 2018, 141–142.

140 Rachón et al. 2020, 2.

141 For instance: Marino et al. 2009; Konvalina et al. 2014; Longin et al. 2016, 308; Hirschi 2018; Magistrali et al. 2020; Rachón et al. 2020, 6; Vojnov et al. 2020; Biel et al. 2021, 1827.

142 van der Veen / Palmer 1997, 165.

143 Hlisnikovský et al. 2019.

144 Dermody et al. 2022.

145 Erdkamp 2005, 50; Goodchild 2007, 251–253.

146 Dermody et al. 2022, suppl. S5.

147 Joyce 2019.

As seen above, yields increased by at least a factor 3 to 4 during the transition from ancient to modern methods since 1900, caused by the introduction of nitrogen fertilisers, pesticides, seed treatments, and genetic adaptations. The AD 1900 figures are based on three-field systems, row seeding and fertilisation. Taking this increase factor into account, the assumed average yield of 1125 kg / ha for the research area seems very reasonable. It is supported by regional experts, corroborated by ancient sources, recent simulation models, and contemporary yield studies of ancient wheat varieties, and is consistent with documented pre-industrial yield levels.

Meat results

Archaeozoological evidence from the research area shows meat consumption at military, urban[148] and rural sites[149], the spectrum of meats consumed, and allows comparisons of consumption between sites and over time. They rarely provide information on how much was consumed. Meat production and consumption in civilian sites is documented by the bones of slaughtered animals and by the tools used for food processing. For example, *Augusta Raurica* has a high density of evidence for meat processing[150].

The SIMFOOD meat demand and supply calculations extend a previous regional model used by Deschler-Erb and Akeret for the meat demand of the 6000 soldiers in *Vindonissa*[151]. Their calculation is based on a meat ration of 100 g per day and soldier – about 7–8 % of the daily diet. The new SIMFOOD calculation also considers the demand of the civilian population and the changing settlement density during the 1st century AD.

Based on a calculation for *Augusta Raurica*, different meat rations are assumed for soldiers and civilians. Unlike the soldiers, the civilians may not have eaten meat every day. Based on the quantities and composition of bones, Jürg Rychener has calculated an average daily consumption of 16.5 g of meat per person per day from a domestic waste deposit in quarter 9D in *Augusta Raurica* (for the first half of the 1st century AD)[152]. This does not take into account any processed meat consumed without bones and cannot necessarily be extrapolated to the entire population of the urban settlements. For the meat demand and consumption model, a value of 30 g / day per civilian person is used.

Half of the daily meat ration was provided by cattle, the other half by pigs (30 %), and sheep and goats (20 %)[153]. Cattle were mostly slaughtered at an adult age[154] and close to processing and consumption[155]. The adult age at slaughter suggests that animals were primarily kept for ploughing, draught power, and industrial use (dairy products, hides and horns)[156].

Some other authors use different meat rations. Jonathan P. Roth argues for 165 g / day[157]. Van Dinter et al. use 220–250 g / day[158]. If we assume a 75 % grain and 15 % meat share in the

148 Examples of military and urban sites in Groot / Deschler-Erb 2017.

149 Ebnöther 1995, 254–263 (Dietikon). – Schucany 2006, 664 (Biberist). – Harb / Wullschleger 2010, 163–185 (Langendorf, Solothurn, CH). – Rychener 1999, 450 (Neftenbach) and 457 (Dietikon). – Horisberger 2004, 246; 249 (Buchs).

150 Amrein et al. 2012, 143; Laska 2021, 30.

151 Deschler-Erb / Akeret 2011, 28–30.

152 Rychener 2016, 146–147.

153 Deschler-Erb / Akeret 2011, 28.

154 Deschler-Erb 2009, 69; Flück 2017, 335; 345; Groot / Deschler-Erb 2017, 102–103; Deschler-Erb et al. 2021, 304; Wyss Schildknecht 2020, 187.

155 Amrein et al. 2012, 22.

156 Amrein et al. 2012, 151; Groot / Deschler-Erb 2017, 106; Deschler-Erb at al. 2021, 304.

157 Roth 1999, 32. – Supported by Polak / Kooistra 2013, 400; 401.

158 van Dinter et al. 2014, 45–46.

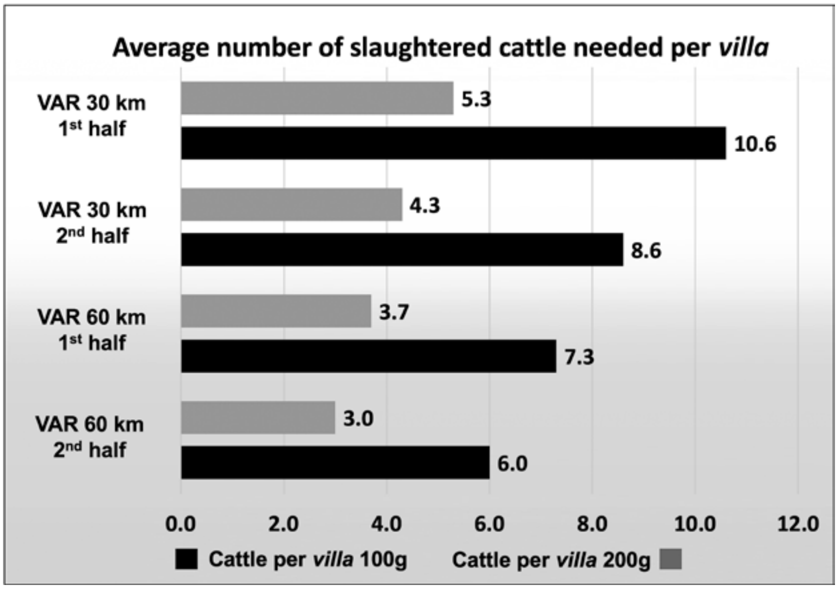

Fig. 10. Average number (rounded) of slaughtered cattle needed per villa to feed the whole population (VAR = combined area of *Vindonissa* and *Augusta Raurica*).

diet, this will result in about 200 g / day for soldiers. The model therefore calculates both 100 g and 200 g rations for soldiers and 30 g and 60 g for civilians[159].

To meet the needs of 6000 soldiers, approximately 250 adult cattle would have to be slaughtered per year (one cattle provided ca. 8600 daily beef rations of 50 g)[160]. Using the civilian population figures from the SIMFOOD model and the number of known *villae*, this would require the slaughter of three to five cattle per year per average *villa* (*Fig. 10* for the research area, detailed calculation for all four supply areas in *Suppl. 10*). Only about 20 % of a herd could be slaughtered per year[161]. This requires a minimum herd size of about 15–25 cattle (not including oxen required for ploughing). The calculation takes the average value for the research area and uses an average herd size of 32 (including twelve oxen for ploughing)[162].

Does the average *villa* have enough labour and land resources to manage this herd size? According to Ebersbach, one full-time person can manage four to five cattle[163]. It is estimated that 0.5 to 1 ha of pasture is needed for grazing per cattle[164]. An average herd of 32 requires 16–32 ha for grazing, but some rotation of pasture is required to avoid overgrazing[165]. Grazing

159 An exceptional value of 650 g / day of meat from an Egyptian papyrus from the 4th century appears questionable and is challenged – it may refer to the ration for a whole family (Deschler-Erb / Akeret 2011, 28) or even as a conversion error (Roth 1999, 32).

160 Deschler-Erb / Akeret 2011, 28 estimate 430 kg (86 %) of usable beef from adult cattle weighing 500 kg.

161 Ebersbach 2002, 161; Amrein et al. 2012, 129.

162 A herd size of 32 corroborates well with the economically viable herd size of at least 30 as postulated by van Dinter et al. 2014, 46 and Joyce 2019, 111 for the lower Rhine delta; the figure of 24 used by Schucany 2021, 26 for the Aare valley; and the average herd size of 30–40 used by Brüggler 2018, 295 for the Rhineland.

163 Ebersbach 2002, 156–157.

164 Spitzing 1988, 148; Ebersbach 2002, 214; Horisberger 2004, 331; 337.

165 Huntley 2013, 48.

on harvested stubble and on fallow land was also possible[166]. The annual hay demand of 2.8 t per animal[167] required about 0.4 ha of meadow per cattle, or 15 ha for the average herd size in the model[168]. It is possible to use the same land for spring and fall grazing, and to grow hay on the same land during the summer months[169]. "Together with the summer pastures, the annual upkeep of a cow requires at least 1 ha, or rather 1.5 ha of intensively used meadows"[170]. In summary, the average *villa* has enough land and labour resources to manage an average herd size of 32 cattle. Even a herd size of 100 animals is feasible from a grazing / hay / labour perspective. Estimates for some of the larger *villae* such as Buchs and Neftenbach indicate the capacity for herd sizes of 50 cattle or more and 150 sheep / goats per 100 ha of pasture[171].

An average meat ration of 200 g / day (of which 100 g beef) for soldiers and 60 g / day for civilians would require the slaughter of 6–10 cattle per average *villa*, almost doubling the minimal herd size to around 30–50 (plus oxen). This would require up to 50–75 ha of pasture for grazing and hay making, well within the available land of an average *villa*.

Similar calculations for sheep / goats and pigs lead to the same conclusion of sufficient meat supply for both assumed rations (details in *Suppl. 10*). However, the *vici* may have had some self-supply of meat from keeping livestock in their economic areas[172].

In summary, it appears that the *villae* in the research area theoretically had sufficient capacity to supply a meat demand of up to 200 g / day for the military and 60 g / day for the civilian population, confirming the initial hypothesis of this study for meat. Even with higher meat rations for civilians, the capacity would have been sufficient.

Grain results

Using the most plausible parameters as summarised in *Supplement 11* (all values can be changed for simulation purposes), the model calculates a gross yield of 56.3 t / year for an average *villa* with 100 ha of arable land and 50 people. The net surplus – after deducting 11.1 t / year personal consumption (at an average of 0.22 t / year per *villa* inhabitant, see *Tab. 1*), 17.8 t / year for animal fodder, and 20 % for seed and losses – is 16.2 t / year (SIMFOOD model). This surplus would feed about 75 additional people.

In a similar argumentation, Erdkamp estimates a "gross surplus" of 140 to 650 kg / ha for small market-oriented farms, up to 1000 kg / ha for large estates, and no surplus at all for small peasant farms with seven to ten persons[173]. The term "gross surplus" is defined as the quantity harvested minus the demand of crop farming related workers. To obtain the net surplus available to the market, this value must be adjusted for seed quantity and losses, the food demand of animals, and the food demand of additional workers. For farms with 100 ha arable land (thereof 50 % cultivated), Erdkamp's yield estimate would be about 50 t, which is in good agreement with the SIMFOOD model figures.

The model results show a significant grain gap in all four supply areas investigated (both for *Vindonissa* alone and for the combined area with *Augusta Raurica*) and for both halves of the 1st century AD, ranging from 3000 t to more than 6000 t per year, which is at least of the

166 van Dinter et al. 2014, 47.
167 Ebersbach 2002, 156; Huntley 2013, 46.
168 Ebersbach 2002, 155–156.
169 Ebersbach 2002, 156.
170 Ebersbach 2002, 214.
171 Horisberger 2004, 331 for Buchs: 60 cows and 150 sheep on 75 ha. – Rychener 1999, 449 for Neftenbach: 240–300 cows on 475–630 ha.
172 Czysz 2013, 299.
173 Erdkamp 2005, 50.

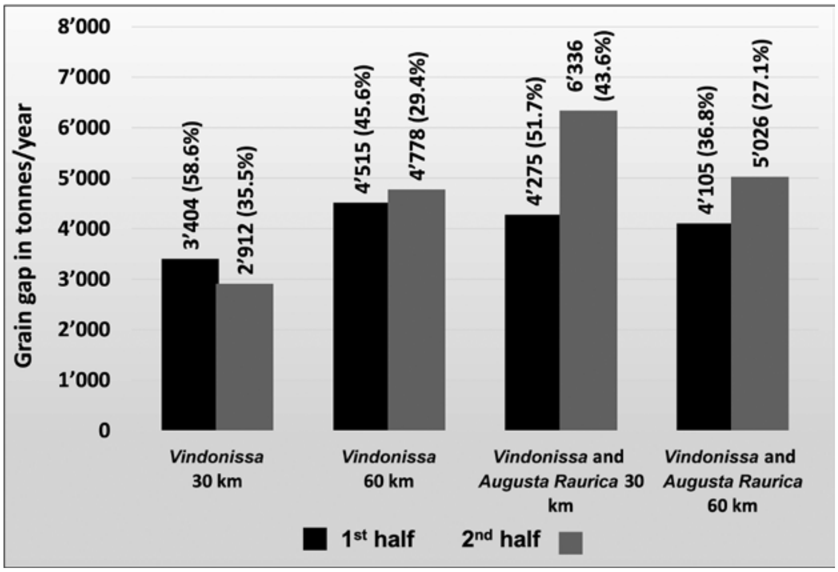

Fig. 11. Supply gap for the four supply areas in the first half (black) and second half (grey) of the 1st century AD in tonnes / year and % gap (calculated by author, details in *Supplement 12*).

size of the military demand. With increasing rural settlement and agricultural intensification, the gap becomes proportionally smaller (in percentages), but even at the end of the 1st century AD, the available supply only covers about 75 % of the demand. *Figure 11* shows the gaps in tonnes / year and in missing percent of the total supply. The detailed results table in *Supplement 12* also shows the total demand and supply values and the "*villa* gap" – the number of additional *villae* needed to close the gap[174].

Sufficient supply or oversupply can only be achieved if we double the crop yield (very unrealistic and outside of any values in the literature), or double to triple the number of *villae* in the supply areas (doubling the number of *villae* results in a supply / demand break-even only for the second half and the 60 km radius, a break-even for the first half requires almost three times the number of *villae*).

Is it realistic to think that there are hundreds of undiscovered *villae* in the research area? Certainly, *villa* remains may have been destroyed by development activities over the last few centuries. The research area has undergone significant urban and industrial development in recent decades, most of which has been accompanied by archaeological assessments and rescue excavations. As early as 1999, regional archaeologists estimated that most of the *villae* had been discovered[175]. Schucany recently concluded that all larger settlements are known for the late second half of the 1st century AD based on their stone construction[176]. In the settlement database, only 10 % more *villae* have been discovered since 2002 (settlement database). Some of the new discoveries in the research area are previously unknown *villae* (for instance at Charmoille, Jura, CH)[177]), while others are just extensions of known *villae* (for instance at Busskirch,

174 Calculated with a 16.2 t / year surplus of an average *villa* in the model.

175 Ebnöther / Schucany 1999.

176 Schucany 2021, 27; 29.

177 Robert-Charrue Linder 2022.

St. Gallen, CH)[178]). Additional *villae* in the densely settled areas of the research area would hardly increase the amount of agricultural land as they would be part of the already cultivated land. Additional *villae* in less densely populated areas could be discovered by future LiDAR analysis or rescue excavations. However, a simulation shows that even 20–30 % additional *villae* would not close the supply gap.

Can we extend the research area further to cover or reduce the grain gap? If we extend the research area to 90 km circles around *Vindonissa* and *Augusta Raurica* (as documented in *Suppl. 1*), only two additional settlement clusters are included: one east of *Vindonissa* around Lake Constance (the hinterland for the *vici* of Constance and Orsingen, both Baden-Württemberg, DE), one southwest close to *Aventicum* (part of the hinterland of *Aventicum*). In total, this adds eight urban settlements (including *Aventicum*) and 67 *villae* (thereof 19 in the first half, additional 22 in the second half, and 26 later, see settlement database, *Suppl. 1*). The corresponding theoretical surplus production in the first half is 314 t / year, for the second half 664 t / year. This surplus does not even cover the grain demand of the additional urban settlements (excluding *Aventicum*) and does not reduce the gap at all. Going further out would include the southern and western hinterland of *Aventicum*, the *vici* around Lake Geneva in the west and Chur in the east, without reducing the gap any further.

It is therefore quite plausible that there was a significant grain gap during the full military presence in the 1st century AD. The SIMFOOD model does NOT support the initial hypothesis of this study that the hinterland was able to produce enough grain for the military and civilian population.

Potential biases, critique of assumptions, and discussion

This chapter discusses potential methodological biases and reviews and challenges the plausibility of the model assumptions and the validity of the results. The model is highly sensitive to the number and size of *villae*, crop yields, and the daily food demand per person. Simulations were carried out by changing the assumptions and documenting the impact on demand and supply. *Supplement 13* summarizes the simulation results.

Both Lang and Reddé have criticised calculations and extrapolations of agricultural productivity on a large geographical scale, due to variations in landscape, soil quality, cultivated crops, and settlement structures[179]. However, for the research area of this study, variations in settlement structure, soil quality, and landscape are relatively well understood.

Chronology and dating

Chronology determines the ratio of *villa* numbers for the first and second halves of the 1st century AD. Establishing chronologies is one of the major problems, although the settlement record for the 1st century AD is better than for the late Latène period and subsequent centuries. All the *vici* are dated, but only about 40 % of the *villae* in the research area have reliable foundation dates. Dates were mostly established by terra sigillata, coins, or dendrochronology[180]. A lot of foundation dates are given as first half, mid-century, second half, end of 1st century etc.

178 Lecture on 4th November 2022 by Regula Ackermann at the Annual Meeting of the Working Group for the Provincial Roman Research in Switzerland ARS in Delémont "Neue Erkenntnisse zum Gutshof von Busskirch (Rapperswil-Jona SG)".

179 Lang 2009; Reddé 2018.

180 Pavlinec 1992, 123.

The model therefore uses a granularity of half a century. Variations in the settlement distribution between first and second halves of the 1st century AD can be simulated in the model, but they only affect the demand and supply results for the first half.

Settlement and population biases

The settlement picture is clearly biased towards larger stone settlements and may disregard earlier and smaller settlements with timber structures. More recent excavations are much better documented and dated than the earlier ones. This bias may lead to an overestimation of the average *villa* size.

Stone *villae* might have had wooden predecessors that were not discovered during excavation. This could increase the number of *villae* especially in the first half. For several *villae* however, earlier timber constructions were identified and used to define the foundation date[181]. Any earlier construction phases should have left behind datable artefacts such as sigillata or coins. In any case, these earlier constructions were probably of a smaller size and not well suited for a surplus production[182].

Although the number of small settlements in the database is almost as high as the number of *villae*, there is a significant potential for undiscovered smaller rural settlements. However, the argument that these undiscovered small farmsteads would increase the supply is incorrect. A size of 10 ha of land and a population of ten people seems to be a reasonable average[183]. A small farm with ten people (six adults, four children) needs about 2.15 t / year of grain. Considering one or two oxen or horses for ploughing and 30 % of the harvest for taxes in kind, losses, and seed, this requires a harvest of at least 4 t / year or 3.6 ha of farmed land (7.2 ha including fallow land). This leaves little land for grazing and vegetable production, and no surplus at all. Therefore, except for a possible tax in kind of 10 %, the contribution of small farms to a surplus production is not relevant for the supply.

Of the dated *villae*, about 40 % were established during the first half of the 1st century (or earlier), 37 % in the second half. About 23 % were established after the abandonment of *Vindonissa*. The almost twofold increase in the number of *villae* corresponds to the postulated population growth of 1.3 %. There is no reason why the undated *villae* should have a different temporal distribution. The model therefore extrapolates the ratio to the entire *villa* sample. Even the assumption that the *villae* dated in the second half were already established during the first half results in a considerable supply gap in both halves of the 1st century.

A smaller *villa* size would reduce the achievable surplus while at the same time reduce the *villa* population. A larger *villa* size (and more arable land) means more people living and working there – increasing supply but also demand (doubling the arable land would require double the number of farm workers and oxen for ploughing). Simulations have been performed for 50 ha arable land / 25 people (increased gap) and 200 ha / 100 people (smaller gap for 30 km, no gap for 60 km, but unrealistic *villa* size due to the documented average *villa* distance).

Vici may have supplied themselves partially by growing crops and raising cattle[184]. However, there is no archaeological or documentary evidence and a lack of typical finds related to the *vici* as point of grain production[185]. Most of the economic areas around the *vici* were used for

181 Schucany 2006, 253 for Biberist. – Ebnöther 1995, 207 for Dietikon. – Rychener 1999, 436 for Neftenbach. – Horisberger 2004, 46 for Buchs.

182 Schucany 2021, 27.

183 Schucany 1999, 93; 2021, 27.

184 Schucany 2021, 28.

185 Hanel 2007, 411; Amrein et al. 2012, 196; Czysz 2013, 265.

grazing of domestic animals and for fruit and vegetable gardens[186]. A theoretical self-supply of *vici* can be simulated in the model – even an unrealistic high contribution of 50 % still leaves significant gaps.

Population estimates for the Roman period are a difficult task[187]. For *vici*, they are usually based on the total area of the *vicus* or the number and size of its strip houses (ten persons per strip house of 400 m^2)[188]. For *villae* they are based on cemeteries (for instance at Corroux, Jura, CH or Neu-Allschwil Basel-Land, CH)[189]) or the size of the excavated living quarters in the *pars urbana* or *rustica*[190]. However, not all of the buildings may have been inhabited at all times. The estimates are then scaled up by considering the settlement density. There is a risk of circularity in the use of these figures, especially when they are used to corroborate settlement development.

The population estimates used by SIMFOOD are consistent with an estimated population growth of 1.3 % during the 1st century AD[191]. A lower population in the *vici* would reduce the demand but not enough to match supply. A higher population in the *vici* would widen the gap. The estimated civilian population number of 2300 for *Vindonissa* is low[192]. *Augusta Raurica* experienced a massive development and growth phase in the second half of the 1st century AD[193]. The estimate of a population of 6000 (mid 1st century) or 8000 (end 1st century) for *Augusta Raurica* may also be on the low side[194]. It could be argued that the number of soldiers in *Vindonissa* was lower than 6000 due to detachments to the Upper Rhine valley as far as Strasbourg / *Argentorate*[195] and participation in the military expansion to the Danube limes and the Chatti wars[196]. These detachments could still have been supplied from *Vindonissa* or from within the research area. Even 3000 fewer soldiers would not make the gap disappear – the simulation shows it just shrinks by about 25 %.

Research area

In contrast to the SIMFOOD model with its four different supply areas, Schucany postulates a supply area 30 km upstream and south of *Vindonissa*[197]. This approach does not consider the civilian food needs outside Schucany's area. The settlement map *(Fig. 7)* shows significant urban and rural settlements north and north-east of *Vindonissa* (German and Swiss parts of Klett-

186 Czysz 2013, 299.
187 Reddé 2018, 131–133.
188 Ebnöther / Schucany 1999, 91.
189 Martin-Kilcher 1976, 102; 139–149.
190 For instance, Rychener 1999, 449; Horisberger 2004, 330–331.
191 Schucany 2021, 29.
192 The 1998 estimate of 2300 people at the end of the 1st century AD by Ebnöther / Schucany 1999 was based on an area of 13 ha, more recent estimates are 45 ha and 3000–6000 people at the end of the 1st century AD (Trumm 2012, 19–20; Flück 2017, 468).
193 Furger 1994, 31–32; Berger 2012, 23.
194 Extrapolated from estimates of 9000–15,000 in Bossart et al. 2006,103 for the 2nd century AD, using a population growth rate of 1.3 % per year (this number may be too low for a rapidly growing colony). – Rychener 2016, 145–146 states that a population of 4000 is too small for the first half. – Furger 1994, 31–32 and Hecht / Tauber 1998, 442 speak of a large-scale early settlement with timber buildings, followed by a transition to stone buildings and a significant building boom from the middle of the 1st century AD. A population of 6000 by mid 1st century AD is therefore plausible, 8000 for the end of the 1st century AD may be too low.
195 Speidel 1996, 42; Nuber 1997, 13; Jeanloz 2022, 26.
196 Nuber 1997, 14; Kemkes 1998, 24; Trumm 2002, 213; Jeanloz 2022, 26.
197 Schucany 2021, 27.

gau) and south-west and north-west of *Augusta Raurica* (Delsberg Basin, southern part of the Alsace dép. Haut-Rhin) that may well have contributed to the supply – all close to major roads and waterways. Schucany emphasises downstream river transport, dismissing food production and road transport from areas north. For example, most of the *villae* supplying the fortress of Regensburg (Bayern, DE) were located downstream and required road transport[198]. Interestingly, if the Schucany supply area is used as SIMFOOD model input, the model provides comparable gap results for the first half of the 1st century AD. For the second half, the model calculates a significant gap, whereas Schucany estimates that the supply was sufficient for the military[199] (in which case there would still be insufficient supply for the civilian population).

The author believes that the SIMFOOD model, with its carefully chosen parameters, may still provide an overly optimistic supply situation for the following reasons:

(1) The model assumes that 100 % of the arable land is fully utilised, which seems unrealistic. Any lower land use will lead to an increase in the gap.

(2) It is unclear whether the reported yield values for hulled wheat species such as spelt and emmer include the husks. They are harvested, stored, and sown with the husks. In the case of including the husks, the net yield should be corrected to about 75 %[200]. If this is included in the model, the gap widens even further.

(3) A seeding rate of 15 % with a yield of 1125 kg / ha means about 170 kg / ha seed for spelt. Compared to historical and current values[201], this may be on the low side.

(4) Bad years with weather fluctuations and frequent flooding in the river valleys are not considered and may reduce the supply.

(5) The estimate of 5 % for combined losses from threshing, transport and storage is likely underestimated. Storage losses alone are estimated at around 3 % today and may have been much higher in antiquity[202]. Already Cato and Varro wrote about mildew and rust reducing the crop harvests[203]. Goodchild and P. Carrington use even 20 % of the harvest as waste and losses[204].

Taking these factors into account, the grain gap is probably even larger than calculated.

Comparison with other regions

How do the settlement development and food supply calculations for *Vindonissa* and *Augusta Raurica* compare with other regions? It is generally assumed that all of *Germania Inferior* and most of the north-western provinces required imported grain[205]. Beyond these rather general and broad statements, we can look at more specific regional examples.

Comparable structures to the combination of a legionary fortress and a nearby *colonia* such as *Vindonissa* and *Augusta Raurica* can be found in *Germania Inferior* with *Vetera* / CUT (*Co-*

[198] Fischer 1990, 103; 109; Czysz 2013, 295.

[199] Model simulation with Schucany's numbers for *villae* (Schucany 2021, tab. 26; 28). Schucany 2021, 27 states that the supply for the fortress in the later 1st century AD was sufficient.

[200] Castagna et al. 1995, 373; Lang 2009, 395; Reddé 2018, 143; 147; "Verein zur Erhaltung und Rekultivierung von Nutzpflanzen" (VERN e. V.), Weizen. (https://landsorten.de/sorten/weizen/ [last access: 07/10/2024]); Pers. comm. Markus Hauenstein.

[201] Beck 1986, 158; Lang 2009, 396; Blöck 2016, 101; Pers. comm. Markus Hauenstein.

[202] G. Breuer, Getreide: selbst lagern kann lohnen. Top Agrar – Österr. Journal. https://boku.ac.at/fileadmin/data/H03000/H73000/H73300/pub/LBWL/TA_Getreidelagerung.pdf (last access: 07/10/2024); IVA 2017.

[203] Jaskolla 2006, 3.

[204] Goodchild 2007, 338; Carrington 2008.

[205] Wierschowski 1984, 171; Stoll 2016, 247; Reddé 2018, 150; 158.

lonia Ulpia Traiana, Xanten), *Bonna* / Bonn and CCAA (*Colonia Claudia Ara Agrippinensium,* Cologne), all located in present-day Rhineland on the Lower Rhine. The southern part with the hinterland of *Bonna* and the CCAA had a densely settled *villa* landscape with more than one *villa* per km^2 on a very fertile loess soil[206]. The northern part with the hinterland of CUT had a non-*villa* landscape with Latène-like wooden byre houses on less fertile clay and sandy soils[207]. In both *coloniae*, spelt was the dominant grain species consumed[208]. The CUT hinterland theoretically had enough arable land to fully supply the military and civilian population with grain[209]. However, archaeobotanical evidence shows that the farmers in this area did not grow the spelt consumed at the *colonia*, but mainly barley and millet[210]. Spelt may have been imported from the loess belt to the south[211]. Surprisingly, given the dominant role of animal husbandry in the area, it did not produce enough meat to feed the military and the population in the urban settlements and countryside[212]. In contrast, CCAA and the *Bonna* fortress could be completely supplied with grain from the densely settled loess belt[213]. An assessment of the meat production for this area is not available due to the lack of well-preserved animal bones in the soil[214].

The result of similar calculations for the Lower Rhine delta shows that the rural population was autarchic in food supply but unable to meet the full grain demand of the military. The area was probably unable to provide enough meat for the civilian and military population and had to import it[215].

At the legionary fortress of Regensburg, founded around AD 178, about 160 years later than *Vindonissa*, only marginal settlement development was observed before the military presence of the 3rd legion. Development of new *villae* started only slowly with the arrival of the first military detachments and the construction of the first two *castrae* in the period of Vespasian (AD 69–79). With the arrival of the 3rd legion around AD 178, a significant settlement development and building boom began, mostly downstream of the fortress and supported by the military[216]. Sommer believes (without providing a detailed estimate or calculation) that the rural settlements were sufficient to supply the fortress and the associated *castrae* upstream of the Danube River[217].

For the legionary fortress of Chester in north-west England, its extramural settlement and the hinterland, Carrington has provided a parametric model of demand and supply for locally grown spelt, emmer and barley[218]. In the absence of a *villa* system, the hinterland consisted of small farmsteads of 6–12 ha arable land (one per two km^2) with 5.2–7.6 people. He uses higher TEE figures than the SIMFOOD model (323.5 kg / year for soldiers, 242.5 for civilians), higher demand of horses (0.9–1.2 t / year), an average yield of 1 t / ha, and a yield to seed ratio of 4 : 1. Theoretically, a hinterland of 43.5–61.5 km radius could be sufficient for the grain supply, but Carrington still expects at least an initial grain shortage, with temporary gaps to be filled later by imports from other regions[219]. Compared to *Vindonissa* and its hinterland, the military

206 Jeneson 2011, 269–271.
207 Brüggler et al. 2017, 19; Zerl et al. 2019, 223.
208 Brüggler et al. 2017, 83; Gerlach et al. 2017, 120.
209 Brüggler et al. 2017, 70; Brüggler 2018, 300.
210 Brüggler et al. 2017, 82–83; Gerlach et al. 2017, 119–120.
211 Brüggler et al. 2017, 70 and Gerlach et al. 2017, 120 indicate the origin of lime-loving weeds from grain storage areas at Xanten from the loess areas south.
212 Brüggler 2018, 300.
213 Eck 2007, 214–216; Gerlach et al. 2017, 120; Zerl et al. 2018, 112.
214 Brüggler et al. 2017, 62.
215 van Dinter et al. 2014, 23–24; 27; 30.
216 Fischer 1990, 24; 112–120; Schnetz 2013, 81; Sommer 2013, 137; Reddé 2018, 151.
217 Sommer 2013, 137–138.
218 Carrington 2008.
219 Carrington 2008, pos. 661.

population is smaller, with a significant proportion on detachments. The population of the five *vici* in the hinterland is estimated at just under 5000 (a total of 15,000 for the fortress, its extramural settlement, and the *vici*). The non-agricultural population around Chester is therefore only a third of the population of the research area, making the grain supply situation much less challenging.

Simulations

Supplement 13 summarises the detailed results of simulation runs with different parameters. Lower yields, higher seeding rates, less farmed land, and higher daily rations all lead to a reduction in supply and an increase in the grain gap. Even using the lowest daily ration estimates from the literature[220], there are still significant gaps in both halves of the 1st century AD. If we add 20 % or 30 % to the number of *villae* to account for undiscovered *villae*, the supply gap narrows but is still significant. If we add several very large *villa* domains such as Neftenbach, Dietikon, Seeb-Winkel or Biberist with 400 ha of arable land and 200 inhabitants, the gaps remain (both correction factors can be used in the SIMFOOD model, although larger settlements would be balanced out by smaller ones in the average *villa* size estimate). Reducing the average *villa* population from 50 to 30 reduces the gap by only 20 %. If we disregard the hard fodder needs of animals in the countryside except for the oxen[221], there is still a significant gap. A 50 % reduction of the *vici* population does not result in sufficient supply. Removing the 10 % tax contribution from small farmsteads further reduces the supply.

The grain gap in the research area suggests that grain imports, probably along river routes from the Mediterranean and from southern Gaul, were necessary throughout the military presence at *Vindonissa*. So far, the only possible evidence for grain imports comes from archaeobotanical investigations at two sites. In the *Augusta Raurica* area, non-native remains of *Myagrum perfoliatum*, a weed of Mediterranean grain fields, were identified[222]. Four Mediterranean weeds were found in Oedenburg (Alsace, FR)[223]. The presence of free-threshing wheat in *Augusta Raurica* and the lack of evidence for a significant cultivation of free-threshing wheat in the hinterland[224] also point to imports. In the future, more archaeobotanical data could confirm the possibility of imports. As an alternative to importing grain, the gap in grain supply may have been filled by reducing daily rations or increasing the proportion of vegetables, fruits, or meat in the daily diet.

On the other hand, it appears that the local grain supply was almost sufficient for the civilian population when the military left (simulation table in *Suppl. 13*). With the establishment of additional 85 *villae* with a net surplus production of 1370 t / year in the 2nd century AD, the grain supply was probably sufficient for the civilian population[225].

220 The lowest estimate (van Dinter et al. 2014, 45) is about 0.221 t / year for soldiers and 0.169 t / year for *vici* and *villa* residents.

221 It could be argued that there was no grain fodder except for the oxen, although Schucany 2021; Wierschowski 1984, 170; Lang 2009, 402; Blöck 2016, 102 and Ferdière 2021, 458 propose the use of grain as hard fodder for all cattle.

222 Jacomet / Brombacher 2009, 64.

223 Vandorpe 2010, 77–79 and 131–132. – However, Vandorpe argues that these finds are not conclusive of imports, they could have migrated by other means.

224 For *Augusta Raurica* see Jacomet 1988. – For the grain portfolios at *villae* see Schucany 2006, 584 (Biberist). – Kaech 2013, 105 (Dietikon). – Rychener 1999, 465 (Neftenbach). See also Blöck 2016, 99; 121.

225 Number from settlement database. Calculated with a net surplus of 16.2 t / year per average *villa*.

Conclusion

There is no single answer to the question of how the Roman army was fed. The discussion above shows a variety of responses to the Roman military presence. Supplies depend on regional history, settlement patterns, land use, and environmental and geographical parameters. The SIMFOOD model therefore uses regional parameters of the research area as much as possible. The model goes beyond previous calculations and assessments. It considers diachronic settlement growth, the supply and demand of the fortress and its hinterland, and the food requirements of military and civilian animals. It also treats *Vindonissa* and *Augusta Raurica* as an economic area of two population centres competing for resources.

For *Vindonissa* and its hinterland, both Speidel and Hintermann have previously argued for grain imports during the initial military presence, but sufficient supplies for the military and civilian population in the second half of the 1st century[226]. More recently, Schucany has concluded that supplies to the fortress must have been sufficient in the second half[227]. These conclusions – and the initial hypothesis of this paper that the hinterland was able to provide enough grain for the military and civilian population – are NOT confirmed by the SIMFOOD model. The combination of the settlement analysis and the demand-supply calculation indicates a significant gap in grain supply throughout the military presence at *Vindonissa*. However, the meat supply capacity in the research area was theoretically sufficient for daily rations of up to 200 g per day for the military and 60 g for the civilian population.

The settlement analysis in the research area shows that the development of new *vici* was almost completed by the middle of the 1st century AD. The number of *villae* almost doubled in the second half of the 1st century AD. The urban and rural population also increased, by an average of 1.3 % per year. The available grain supply increased by an estimated 100 % in the second half. This was still not enough to close the gap. In percentage terms, the gap narrowed from about 50 % to 30 %. In absolute terms, the gaps in both halves of the 1st century AD were larger than the total military grain demand of 3000–3500 t per year. It seems unrealistic that the gap could have been filled by a significant number of yet unknown rural settlements. A predictive modelling approach, such as that used for the Somme valley by Nicolas Revert[228] or for the Upper Rhine valley by Michael Kempf[229], could help to either confirm this or to identify / predict areas where additional *villae* should be sought.

Of course, it can be argued that all of this is too speculative to draw any meaningful conclusions because it is not based on sufficient archaeological evidence. Apart from the records of economic transactions on the Vindolanda and *Vindonissa* tablets[230], we only have the written accounts of Roman authors such as Cicero, Columella, and Varro. They mostly refer to the situation in Italy and the southern provinces. It is debatable whether their accounts are easily transferable to the research area. All we have are archaeological sources from excavations, some of which are incomplete, difficult to interpret and may only give a "distorted view of a complex reality. And yet they are all we have"[231]. In a situation of such uncertainty, models are useful for testing hypotheses and simulating different outcomes for different parameter sets. The SIMFOOD model allows demand and supply to be simulated with different sets of input parameters, and to explore plausible ranges for assumptions from historical sources, from comparisons with other periods, and from comparisons between different regions. Although

226 Speidel 1996, 77; Hintermann 2012, 71.
227 Schucany 2021, 27.
228 Revert 2018.
229 Kempf 2019.
230 Speidel 1996; Whittaker 2002.
231 Reddé 2018, 160.

the model is focused on *Vindonissa* and its hinterland, it could be adapted to other regions and periods with their region-specific parameters. This would, however, require an understanding of the military presence and urban and rural settlement structures for the period(s) in question.

The conclusion of an insufficient grain supply in the research area is well in line with Reddé, who argues that the changes in the agrarian economy in the 1st century AD were too slow to respond quickly to the rapid growth of the military and civilian population[232].

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Supplementary Material

Digital supplements on the model and the data can be found online at https://doi.org/10.11588/data/TPZIP5.

Suppl. 1. Settlement database (Excel).
Suppl. 2. SIMFOOD Model (Excel).
Suppl. 3. Partial screenshot of the SIMFOOD model (PDF).
Suppl. 4. List of data sources for settlement database (PDF).
Suppl. 5. List of urban settlements in the research area (PDF).
Suppl. 6. Settlement statistics for known *villae* in the four supply areas (PDF).
Suppl. 7. Grain demand summary (PDF).
Suppl. 8. Calculation of Total Energy Expenditure (TEE) from FAO data (PDF).
Suppl. 9. Summary of Roman, pre-industrial and modern yield data (PDF).
Suppl. 10. Summary meat calculation (PDF).
Suppl. 11. Summary of input parameters (PDF).
Suppl. 12. Calculated grain supply and demand with supply gap (PDF).
Suppl. 13. Simulation results for combined supply area (PDF).

232 Reddé 2018, 158.

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Abstract: Settlement development and food supply in the hinterland of *Vindonissa*

This paper is based on the results of an MA thesis (2021) on the economic impact of the Roman legionary fortress of *Vindonissa* (Switzerland) and the economic interactions with its hinterland. It analyses the settlement structures and diachronic settlement development during the military presence and introduces the SIMFOOD model to calculate the food demand and supply of the military and civilian population, focusing on meat and grain as the main components of the daily diet. It also treats *Vindonissa* and the nearby *colonia Augusta Raurica* as an economic area of two population centres competing for resources. The model calculates demand and supply based on various assumptions and parameters. The results indicate an adequate supply of meat but a significant gap in the supply of grain in the research area throughout the military presence at *Vindonissa*.

Zusammenfassung: Siedlungsentwicklung und Nahrungsmittelversorgung im Hinterland von *Vindonissa*

Dieser Beitrag basiert auf den Ergebnissen einer Masterarbeit (2021) über die wirtschaftlichen Interaktionen des römischen Legionslagers *Vindonissa* (Schweiz) mit seinem Hinterland. Basierend auf einer Analyse der Siedlungsstrukturen und der diachronen Siedlungsentwicklung während der militärischen Präsenz, analysiert das Simulationsmodell SIMFOOD das vorhandene Nahrungsangebot und den Nahrungsmittelbedarf der Militär- und Zivilbevölkerung. Dabei stehen Fleisch und Getreide als Hauptbestandteile der täglichen Ernährung im Vordergrund. *Vindonissa* und die nahe gelegene *Colonia Augusta Raurica* werden dabei als gemeinsamer Wirtschaftsraum mit zwei um Ressourcen konkurrierenden Bevölkerungszentren betrachtet. Das Modell berechnet auf der Grundlage verschiedener Parameter und Annahmen Angebot und Nachfrage für Getreide und Fleisch. Die Ergebnisse deuten darauf hin, dass im Untersuchungsgebiet eine ausreichende Fleischversorgung existierte, es aber während der gesamten Militärpräsenz in *Vindonissa* eine erhebliche Lücke in der Getreideversorgung gab.

Résumé : Évolution de l'occupation et approvisionnement en denrées alimentaires dans l'arrière-pays de *Vindonissa*

Cet article se base sur les résultats d'un travail de master (2021) portant sur l'impact économique du camp légionnaire romain fortifié de *Vindonissa* (Suisse) et sur les échanges commerciaux avec son arrière-pays. Les structures d'habitat et l'évolution de l'occupation tout au long de la présence militaire y sont analysées et le modèle SIMFOOD introduit afin de calculer les besoins et l'approvisionnement en denrées alimentaires des populations militaire et civile en se focalisant sur la viande et le blé en tant que composantes principales de la diète quotidienne. *Vindonissa* et la *colonia Augusta Raurica* voisine sont considérés comme deux centres de popu-

lation en compétition par rapport aux ressources. Le modèle calcule les besoins et l'approvisionnement sur la base d'hypothèses et de paramètres variés. Les résultats témoignent d'une part d'un approvisionnement suffisant en viande et d'autre part d'un approvisionnement en blé insuffisant traduisant une disette importante dans l'aire étudiée durant toute la durée de la présence militaire à *Vindonissa*.

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Fig. 1. after Swisstopo, Bundesamt für Landestopographie swisstopo, Kantonskarte (https://backend.swisstopo.admin.ch/fileservice/sdweb-docs-prod-swisstopoch-files/files/2023/11/14/8b28cece-0be0-4461-ab51-c475e2ad9d4e.zip [last access: 08/03/2024]; modified). – *Fig. 2*: after commons.wikimedia.org 2024, Roman provinces in the Alps around AD 14. https://commons.wikimedia.org/wiki/File:Roemische_Provinzen_Alpenraum_ca_14_n_Chr.jpg (accessed: 08/03/2024). – *Fig. 3*: after Swisstopo, Bundesamt für Landestopographie swisstopo, Map of Switzerland (https://map.geo.admin.ch/#/map?lang=de&center=2680063.63,1176892.68&z=1.387&bgLayer=ch.swisstopo.pixelkarte-grau&topic=ech&layers=ch.swisstopo.zeitreihen@year=1864,f;ch.bfs.gebaeude_wohnungs_register,f;ch.bav.haltestellen-oev,f;ch.swisstopo.swisstlm3d-wanderwege,f;ch.vbs.schiessanzeigen,f;ch.astra.wanderland-sperrungen_umleitungen,f [last access: 08/03/2024]; modified). – *Fig. 4–6; 8–11*: author. – *Fig. 7*: author after Google My Maps, https://www.google.com/intl/de_ch/maps/about/mymaps/ (accessed 2022–24; last access: 07/10/2024), using settlement database. – *Tab. 1*: author. – Graphics: Lara Hies (RGK), Oliver Wagner (RGK).