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How Much Is Enough? First Steps to a Social Ecology of the Pergamon Microregion

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Abstract: In this study, we present a transparent and reproducible approach to model agricultural production with respect to environmental characteristics and available labour. Our research focuses on the city of Pergamon and its surroundings, with an emphasis on the transition between the Hellenistic and Roman Imperial Period, where widespread demographic changes took place. We investigated the degree of local self-sufficiency using different concepts of a city's complementary region. Using simple topographic derivatives, we derive a measure of environmental suitability that we translate into a carrying capacity index. Our results show that workforce was not a limiting factor for local self-sufficiency. However, environmental carrying capacity may have been limiting in a scenario with a large population. An active investment into the environment, e.g., by the construction of terraces, could have helped to increase the degree of self-sufficiency. Future research should investigate the level of resilience of such a coupled socio-ecological system in relation to environmental and socio-cultural dynamics.

Keywords: landscape archaeology; social ecology; land use; antiquity; reproducible research

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1. Introduction

In this study, we focus on the potential food production of Pergamon and its complementary region during the transition between the Hellenistic and Roman Imperial Period, where widespread demographic changes in the city and its complementary region are attested [1,2]. The complementary region is the area surrounding a central place that is supplied by it with central functions, e.g., in terms of administration, commerce, and cult [3,4]. In turn, this area is often thought of as the basis of the local supply for the central place [5,6]. It is not our intention to conduct a detailed analysis of the city of Pergamon as a central place (see [7] on this) or to conduct an analysis of the interactions between the city and its surrounding hamlets, villages, and cities. In this study, we focus on the potential productivity of Pergamon's complementary region in terms of cereal and leguminous production, as the main dietary share. We use three different heuristics to delineate the complementary region: (a) the reconstructed chora as the core territory or hinterland of a city, (b) the Pergamon Micro-Region, which comprises further cities with their own territories (chorai), and (c) the accompanying river catchments (Figure 1). The delineation of Pergamon's chora is, due to limited information in written sources and archaeological remains, difficult. A cautious reconstruction of its potential extent by Sommerey [8] during the Roman Imperial Period includes the Kaikos (Bakırçay) valley approximately from the modern village Tekkedere in the west to Soma in the east and was framed by the slopes and mountains of the Pindasos (Kozak and Madra Dağı) in the north and Aspordenon (Yunt Dağı) in the south (Figure 1). The geographical extent of the Pergamon Micro-Region includes the lower valley of the Kaikos (Bakırçay) up to its delta (incorporating the cities of Pitane and Elaia), the adjacent mountains of Pindasos (Kozak and Madra Dağı) in the north, Aspordenon (Yunt Dağı) in the south, and the Kane Peninsula (Kara Dağ) in the west (Figure 1; see [9–12] for further information and details on the delineation and definition of the Micro-Region). In terms of centrality, the Micro-Region must not be considered as mono-hierarchy but as integrating different centres on different functional scales: The Pergamon Micro-Region includes several urban centres. Pergamon remains the most important economic-cultural centre, but in terms of cultic and administrative functions at the urban level, e.g., Elaia and Pitane had equal importance in their territories (Chorai). To allow reproduction of our analyses, we use a 16 h walking-distance territory, to delineate the Micro-Region in subsequent analyses (Figure 1). Besides, a two day journey with 8 walking hours per day would capture a reasonable distance for (small-scale) farmers to transport their goods to the Pergamon market with only one intermediate stop. Calculations conducted using r.walk algorithm in GRASS GIS [13] with additional global friction of 1 to resemble slow cart travel [14]. A micro-region is a region not primarily defined by its geographical extent but as a an interaction space between humans and the natural environment [15]. Its extent varies in relation to the level of interaction (e.g., economic, military, sociocultural) and diachronic changes [16]. Micro-regions are characterised by distinct cultural specifications and individual cycles of production and consumption, which can be incorporated in supra-regional exchange networks [17]. By modelling the degree of self-sufficiency of the Pergamon Micro-Region, we thus get insights into its particularities and the degree of potential inter-relatedness. The third heuristic incorporates the surrounding plains and is thought of as a maximum scenario of potential local-regional supply. It is related to the historically attested wheat supply of the city by farmers of the "neighbouring land" [8] (fn. 119). For computational reproducibility we used the catchments of Bakırçay and Madra river, including the coastal zones, to delineate this territory (Figure 1).

The Pergamon Mirco-Region was settled in the Neolithic period, though the site of Pergamon was not of any major importance then [18]. By the late 4th century BCE, Pergamon was already a polis of considerable size and with everything that characterised a Hellenistic city. Under the Attalid dynasty, Pergamon saw an increase in importance as a political and social centre during the 3rd and 2nd century BCE. This period is represented by a renewal and amendment of the already built areas of the city's territory. A substantial extension of Pergamon was undertaken in the 1st century BCE, with a doubling of its size during the Roman Imperial Period, the 1st and 2nd century CE [1,2]. The development from a rather small polis to a major hub within a Roman province must have led to a population growth whose peak seemingly was described in the second half of the 2nd century CE by the Greek physician and writer Galen (129-216 CE) who estimated 120,000 people (including slaves) inhabiting the city and chora of Pergamon.

> *"Hence, they keep looking at those who have more than they and not at those who have less, and they seek to surpass those who surpass them and to have more than they do. If you will look in this way, I said, at all our fellow citizens, you will not find thirty who are wealthier than you. Hence, you are richer than all the rest of the citizens; in addition to these, it is obvious that you are richer than the slave population and the great number of women residents. If, then, our fellow citizens number about forty thousand and if you add to these the women and slaves, you will find that you are not satisfied with being richer than one hundred and twenty thousand, but that you also wish to surpass those thirty men who are richer than you."*
>
> Galen, De propriorum animi cuiuslibet affectum dignotione et curatione (Corpus Medicorum Graecorum V 4,1,1) 9,13. Translation thankfully provided by Andreas Victor Walser.

If children are added to the population estimate of Galen, it is assumed that about 180,000 people lived in the the city and chora of Pergamon [19], from which 40,000 to 65,000 people inhabited the city itself [19,20]. The population of the Pergamon Micro-Region that also includes other cities such as Elaia and Pitane must consequently be assumed to be even larger (see Table 1 for a translation of these figures into population densities).

Table 1. Area and populations densities of the complementary regions for different population sizes.

		Population Density (1/km^2)			
Area Heuristic	**Size (km^2)**	**60,000**	**120,000**	**180,000**	**200,000**
Chora	1077.29	55.70	111.39	167.09	185.65
Microregion	2660.13	22.56	45.11	67.67	75.18
Catchments	4121.23	14.56	29.12	43.68	48.53

In light of these numbers, it is clear that Pergamon was an important urban centre and the question arises whether its micro-region could provide enough resources in the form of fertile land and labour to supply the city. Earlier calculations indicate that this was not possible and that the city, like the other urban centres of Asia Minor (e.g., Smyrna and Ephesos), were dependent on large scale food imports [21]. We aim to reassess this question using a reproducible approach that builds upon a general assessment of environmental suitability and labour availability using information regarding plant energy density and the diet structure of the society. We want to focus on whether environmental or human resources were limiting factors in the production of required food. Connected to this, we aim to derive insights about the resilience of the socio-ecological system of Pergamon and its Micro-Region. We define resilience here as the capacity of a complex adaptive system to persist and adapt in the wake of short-term shocks and long-term changes within the environmental or social sphere without major deterioration of already established structures (e.g., [22,23]). Losing resilience on the social level can mean losing the ability to maintain the status quo—social norms or the rule of law—which is coupled to the functioning of the socio-ecological system. If we like to read this sentence positively, resilience is the capacity to sustain human well-being by adapting to or persisting change. It is important to note is that a system can be more resilient in some aspects and less in others (e.g., [23–25]).

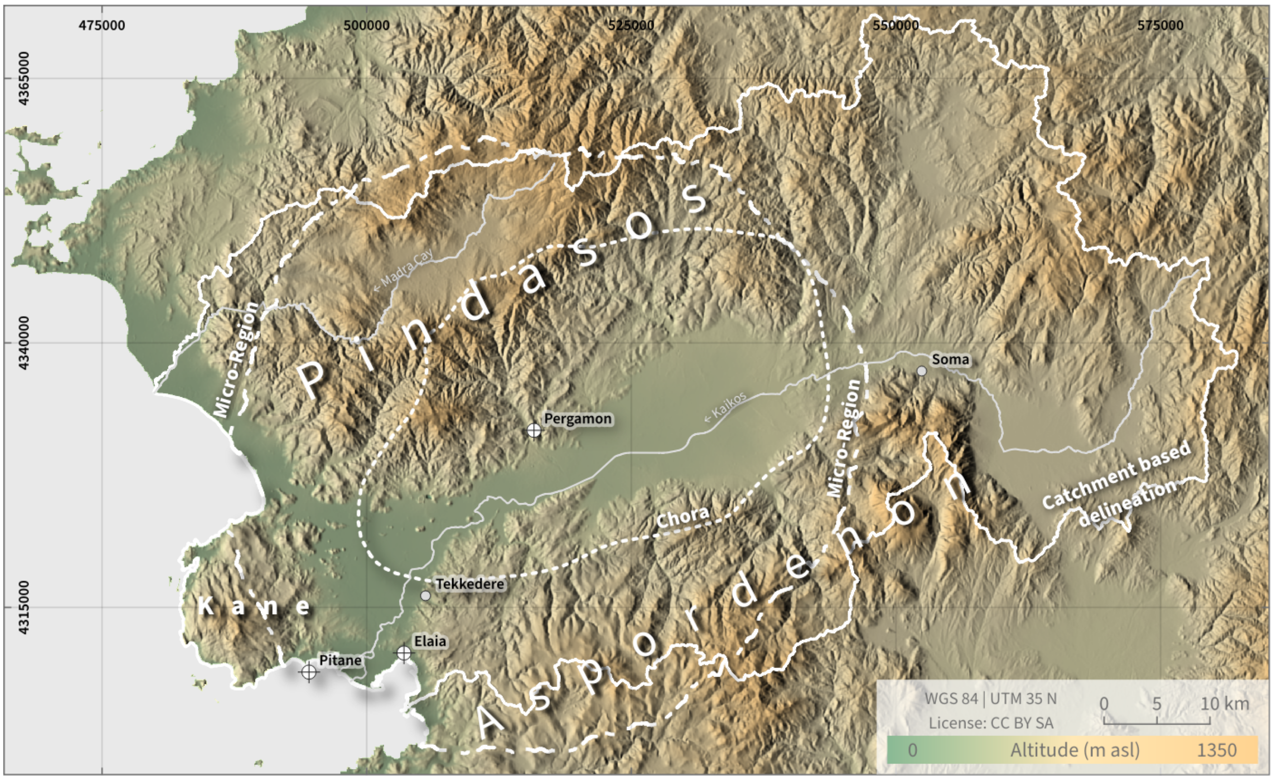

Figure 1. Map of the research area. White lines correspond to the different heuristics of the complementary region of Pergamon (Chora of Pergamon during Roman Imperial Period is based upon Sommerey [8]; the Pergamon Microregion is based upon a 16-h walking territory; Bakırçay and Madra catchment taken from Yang et al. [26]; elevation information is based upon TanDEM-X [27]).

Environmental Setting

The natural environment of the research area is highly dynamic and underwent profound changes in the last millennia [28–31]. The same holds true for the socio-economic characteristics [8], settlement distributions [2], and interaction patterns [7]. Since the connection between the natural environment and society, i.e., between the available natural resources and their human appropriation, has been investigated only in limited contexts [8,12] or at specific locations [32,33], and since comprehensive research on the connection has just begun, we cannot build our reconstruction on empirical data (for a comprehensive general overview on the environmental characteristics and development, see Yang et al. [26]).

A recent study by Becker et al. [28] investigated the Holocene geomorphodynamics of the micro-region. Their results show that geomorphodynamics follow the general trend of sediment dynamics in the eastern Mediterranean: Climatic triggers of geomorphodynamics were strongest in the Early Holocene. Low geomorphodynamics at the end of the middle Holocene were related to the 4.2-ka-BP-drought-event [34,35]. Between the Hellenistic and Roman Imperial Period, geomorphodynamics peaked in the research area, most likely triggered by urbanisation and demographic growth [28].

We still know little about the available resources, produced goods, or the local economic structure within the micro-region. The northern part is characterised by large forest areas that are assumed to have the same or even a larger extent in ancient times [36] and were most likely used for intensive forestry to meet the city's demand for timber and firewood [8]. The breeding of sheep and goats is attested by the bone remains in the archaeological records [37]. It is yet unknown to what extent they were kept in the plain; breeding in the less accessible side valleys and intra-mountainous plains was likely [8]. In terms of agriculture, the Bakırçay plain was praised for its fertility (Strabon 13,4,2 [624C]), so it is generally assumed that the agricultural production within the plain secured a considerable proportion of Pergamon's food supply. The potential of urban gardening or farming might be considered on a small scale for the 2nd century BCE, but it seemed to be abandoned during the 1st century BCE with increased building development in the city [2].

2. Methods

Due to the fragmentary material remains and the complex decision and value systems of past societies, any attempts to quantify past land-use patterns have to be seen as heuristics of past realities, rather than precise reconstructions [38,39].

2.1. Carrying Capacity Assessment

The concept of carrying capacity is defined in ecology as the maximum population density that can be sustained by an area without being degraded or destroyed [40]. This concept can be transferred to the study of human populations, where it marks the upper limit of population. After Malthus [41], this limit is realised by population regulation mechanisms such as famines, diseases, or socioeconomic tensions (e.g., war), which hold the population size in a dynamic equilibrium at the edge of the carrying capacity. Malthus himself did not coin the term carrying capacity and did not use it in his work. Technological innovations are able to raise the carrying capacity [42,43]. The theory of Malthus [41] was debated and amended since its formulation and famously criticised by Boserup [44,45], who saw population pressure as a driving force behind innovations that raised the carrying capacity and believed that societies were not necessarily doomed to fail when population density increased. However, since space is still a limited resource, a search for an upper limit of population that can be sustained under given assumptions is legitimised and necessary [46,47]. In archaeology, the use of carrying capacity approaches to estimate maximum human population densities is strongly tied to the method of site-catchment analysis [48,49], which assesses environmental features within a community's area of (subsistence) economy (i.e., the so-called site-catchment). A site-catchment has a certain potential energy provision that makes it possible to estimate a maximum population size under predefined or assumed dietary needs and land-use practices [50]. Major parameters influencing the carrying capacity of agro-pastoral communities are farming practices, which are involved in (a) increasing the yield per area, viz. manuring, intensive caring, or other technologies [51], (b) increasing the available area for crop cultivation, e.g., by terracing [44,52,53], and (c) water-management techniques [54–56]. However, even with those measures, the available suitable land still remains the basic scaling factor of the possible population size. The calculation of the carrying capacity is a simple measure that helps to asses whether general assumptions about populations in an area are realistic or not; it is a tool and by no means a determining factor in the dynamics or fate of an area (on determinism, see [39]).

We assess the carrying capacity with the help of suitability maps and a calculation of the required area to cultivate food to sustain basic caloric needs of a population. In our case, the three defined heuristics of the complementary region of Pergamon function as "site"-catchments.

2.1.1. Suitability Maps

To assess the available area for the carrying capacity calculations, maps of the suitability for agricultural production are required.

The suitability of a place is a not a crisp variable. On the contrary, a place can be slightly, moderately, or highly suitable for certain practices. To take this fact into account, we employ fuzzy logic theory ([57]; for details on the method, see [58] or [59]; for applications in landscape archaeology, see [60–62], or [63]). To think of a dataset in fuzzy terms means to translate its crisp numerical characteristics into degrees of belonging. This can be regarded as a linguistic variable, e.g., flat slope or high fertility, that states the model assumptions and the integrated parameters explicitly [62,64]. We use the R [65] package FuzzyLandscapes [66], inspired by Jasiewicz [67], to conduct the analyses (see Supplementary Materials).

In this contribution, we focus primarily on agriculture and food production, so we aim to delineate suitable areas for agricultural production with a distinct focus on crops and leguminosae. The suitable locations for these practices are determined by topographical characteristics that were defined as fuzzy sets (for more elaborate approaches on these aspects, see [68,69]): We assume that agriculture cannot be practised on overly steep slopes due to erosion or on overly moist grounds due to water-logging (Figure 2A,C; slope definition based on [70–72]; topographic moisture thresholds defined via visual inspection). However, in the case of intensive labour input, steep slopes might have been terraced; thus, formerly unsuitable areas can be employed for agricultural activities (Figure 2B; following the ideas of a "colonisation of nature" (see [73,74])). Investing labour to "colonise nature" can increase the throughput of a socio-ecological system but at the same time decrease its resilience by requiring a constant labour input to maintain those cultural artefacts that enabled the surge of the net production of the requested good. Popular examples of "colonising nature" are irrigation or terrace field systems that need to be built and maintained [53].

The topographic analyses are based on a digital elevation model, derived from the TanDEM-X satellite mission provided by the German Aerospace Center (DLR) with a spatial resolution of 0.4 arcseconds (approximately 12 m) per pixel and a vertical accuracy of 2–4 m [27]. Data were aggregated to 50 by 50 m to represent general topography characteristics [75] and thus be applicable in our historical context. We derive the geomorphometric attribute slope and Topographic Wetness Index (ref. [76] as representative of moist conditions induced by topographic water concentration, along with the cumulative upslope area derived from the multiple flow direction algorithm with the r.watershed module) using GRASS GIS [13] via R [65] and the package raster [77] for use in fuzzy suitability analyses.

Our chosen model parameters are strong simplifications of an assumed reality, whose historical adequacy should be questioned. However, we take them as the starting point for first delineations of suitable areas in light of the currently incomplete and inconsistent reconstructions of past environmental conditions.

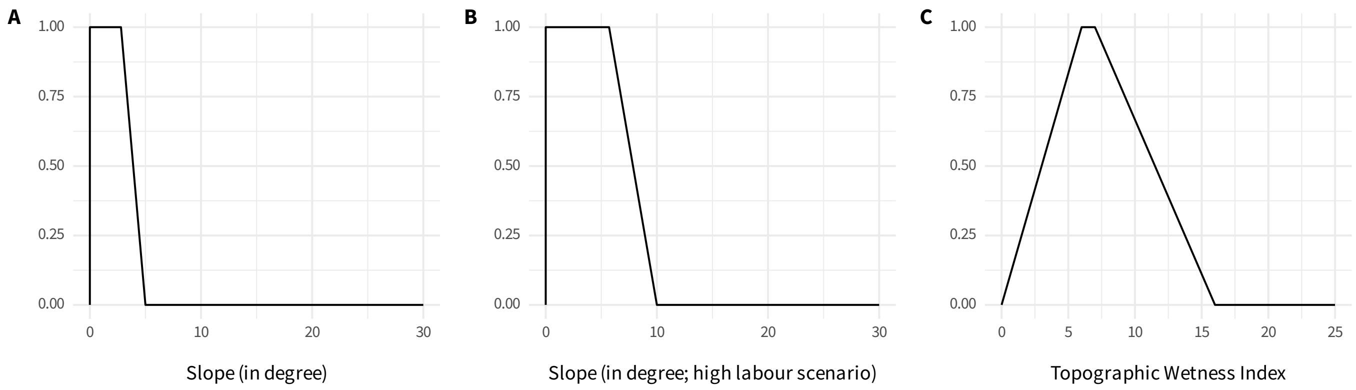

Figure 2. Fuzzy membership function to translate input raster to fuzzy sets. (**A**) suitable slope for agricultural production; (**B**) suitable slope for agricultural production under conditions of intensive labour input; (**C**) suitable moisture conditions for agricultural practices, i.e., not too moist and not too dry.

2.1.2. Quantifying Ancient Land-Use

To link the modelled suitability areas to the concept of carrying capacity, we need to calculate the land required to meet the caloric needs of the people in the study area. Data on the diet characteristics are taken from [78,79], and [80] and are complemented by the results of first investigations on the diet structure of the Pergamean people (see [81]; Table 2). Available isotopic data of bone material is in agreement with the proposed diet composition (see [82]).

Based on isotopic data, a rather plant-based diet for the "average" Pergamean can be assumed [82]. According to this, and because we are able to quantify the required workforce for their harvest (see below), we focus solely on cereals and leguminosae (see Table 2; see (e.g., [83,84]) for problems regarding isotope data). They made up the majority of the diet and are important sources for calories and proteins. Cereal soups—of barley or wheat—and bread were the most common diet for the lower class [81]. There are different models for Roman diets and the proportion of cereals, varying between 60 and 85%, often neglecting other food sources (see Goodchild [85] for a compilation of Roman dietary compositions). We assume a proportion of 71% cereals and 14% leguminosae, the remaining 15% of the dietary composition are provided by a mixture of olives, wine, meat, milk, cheese, and a variety of fruits and nuts.

Table 2. Assumed diet characteristics in the research area (based on [79,80,86] adjusted according to isotope-analyses results of [81,82].

Product	Proportion (%)	Productivity (kg/ha)	Caloric Content (kcal/kg)	Reference
Barley	38.00	770.00	3540	[87,88]
Common Wheat	33.00	625.00	3320	[87,88]
Lentil	5.00	350.00	3520	[87]
Fava Bean	4.00	800.00	880	[87]
Pea	3.00	600.00	810	[87]
Chickpea	2.00	580.00	1640	[87,89]

Soil fertility depletes over time. Thus, fallowing for one season was suggested by the Roman writer Plinius the Elder to preserve or restore soil quality [90,91]. To represent this, we add 0%, 50%, and 100% to the calculated area that needs to be cultivated to reach the caloric requirements for one year, in order to model fallow cycles of 2:1 and 1:1 (for further discussion, see [92]).

2.1.3. Carrying Capacity Index

Thanks to fuzzy methodology, we receive a continuous measure for the suitability of an area. Based on this, different carrying capacity scenarios can be established, depending on the least required suitability of a plot of land to be cultivated. It is important to note that we assume that the calculated suitability represents a potential impact on the yield, even though we will not use it as a yield-altering factor for further calculations. Thus, we define a lower limit of suitability where cultivation will no longer be considered. This enables us to assess how resilient a population would be, when it is required to use unsuitable land for cultivation in order to fulfill its caloric requirements.

We computed the areal demand for cereals and leguminosae, for a range of population sizes, which is translated into the area needed to sustain the population (A_{need}). From the suitability maps, we retrieve the available area (A_{have}) based on the suitability value that must be met for cultivation. Here we exclude all areas below a suitability of 0.1, as their use for cereal and leguminosae cultivation seems very unlikely due to erosion or other extreme limiting local conditions. By dividing A_{have} and A_{need}, we obtain the carrying capacity Index (CCI), whose values range between 0 and ∞, where values below 1.0 indicate the exceeding of the carrying capacity. For each population size (j) and each set suitability threshold (i), we can calculate and interpret the CCI_{ij}.

$$CCI_{ij} = \frac{A_{have\ i}}{A_{need\ j}} \tag{1}$$

2.2. Labour Availability

When dealing with the conceptualisation of a socio-ecological system and accompanied land-use practices, it is necessary to investigate the societal limitations as well. While the carrying capacity represents an ecological limit, the labour force available to conduct labour on the fields can represent a social limit [93]. In order to assess this, we need to accompany information on past population size, diet, and land-use practices with an assessment of the available labour. In addition, an assessment of local self-sufficiency at a given level of labour input informs us about the required fraction of a population engaged in farming, information that can be used to check whether calculations seem reasonable when compared to ancient sources.

One of the most labour-intensive periods in farming is the harvest time. Ripe plants need to be cut, brought in, threshed, and processed in a rather short period of time. The harvest season therefore marks a period of the year that represents a peak of labour input in an ancient farming system [52,94]. Hence, the necessary labour during this period can be considered the limiting factor—or a socio-cultural carrying capacity—for population size. If the available labour is smaller than the required labour, the already invested energy during crop growing is wasted and plants are spoiled on the fields. The actual harvest is less than expected, and the resulting lack of energy may lead to hunger and population decline—at least if the people are not able to compensate for the losses, e.g., via food import.

To calculate the required labour for agricultural tasks, we use information from a cross-culturally informed dataset The Cologne TableauThe Cologne Tableau [95] that we complement with information (a) from ancient writers, such as Cato, Columella, or Plinius the Elder compiled, for example, in White [91], Sherwood et al. [90], Reden [96], Nissen et al. [97], and Christmann [98] and (b) from extensive ethno-archaeological studies in rural Greece by Halstead [94]. The collected data we are using concerning reaping cereals and leguminosae, threshing, and winnowing cereals can be found in the Supplementary Materials. It is interesting to note that Romans writers, rather concerned with bigger farming endeavours, were eager to standardise work speed and flows [91,99]. This becomes obvious when different labour days per ha are compared: Columella (compiled in [90]) assumes about 3.7–5.6 days for reaping 1 ha. These numbers are nearly twice as high as those collected by Halstead [94] with ca. 10 days per ha (mean of a range). The sources from Halstead [94] suggest that younger labourers under pressure would reach similar outcomes to those of Columella. This indicates that Roman agriculture in part was highly concerned with its productivity.

Besides that, all considered sources show that the type of plant that is reaped has a high influence on the labour investment. The data on threshing include different methods, including trampling by humans and animals, flailing, and the use of animal-drawn threshing sledges [94]. All of these threshing techniques were known and applied from the Hellenistic to the Roman Imperial Period [90,91,98]. As we assume that all such techniques were in practice simultaneously, we use the average of those to inform the labour investment for threshing. Data on labour input for winnowing are rather scarce, and those accounts mentioned by Halstead [94] are often non full-day tasks, as conditions needed to be favourable (no rain, not too windy, etc.). A general factor that impacts the harvest-related labour input is the plant density that is highly dependent on the suitability of the field location, the weather conditions, and the choices in fallowing, manuring, intercropping, and weeding during the growth phase of the plants [53,97].

Based on the area under cultivation, it is possible to estimate the labour necessary for harvest and subsequent tasks, such as threshing and winnowing [52]. It needs to be kept in mind that the labour investment in the calculated tasks are averages of the cross-cultural dataset (see Supplementary Materials). The calculation of the total labour days (Ld_{total}) for the harvest time can be transformed into a proportion of the population (P_{labour}) working for a certain amount of labour days ($d_{havest\ time}$) to fulfill this task.

$$P_{labour} = \frac{Ld_{total}}{d_{havest\ time}} \quad (2)$$

An agricultural working day starts at dawn and lasts until dusk and includes time for travelling to the fields [96].

For the research area, no exact numbers on labourers are available, but we can consider Galen's estimate of 120,000 inhabitants (men, women, and slaves) as a potentially available labour force. As we are interested in mere labour availability, we do not consider the social status of the labourers and thus do not separate slave labour. Furthermore, we assume that free workers and slaves worked within the same range of efficiency.

3. Results

3.1. Suitability Maps

The results of the fuzzy analysis highlight the high suitability of the Bakırçay plain for agricultural needs (Figure 3, left column). In the scenario of high labour input, the suitable areas are extended and now include numerous patches in the surrounding mountains (Figure 3, right column).

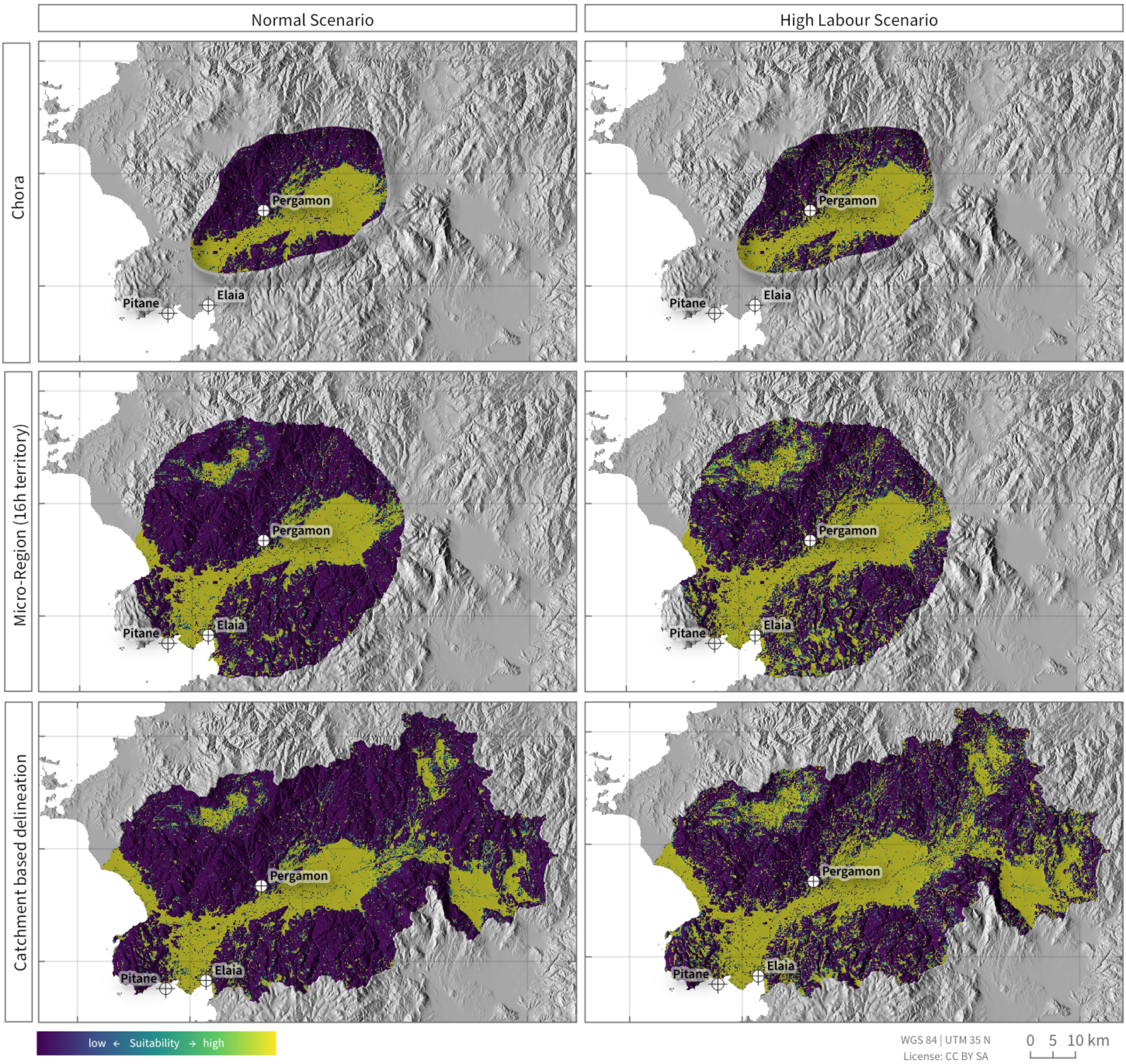

Figure 3. Maps of the suitability for certain land-uses.

3.2. Carrying Capacity Index

For assessing the results concerning the carrying capacity of the given scenarios, we assume that high suitability areas are desired. Areas with low suitability values should be considered marginal and less productive (yields below the used averages of Table 2) and population sizes sustained by low to very low suitability numbers should be treated with caution. A *CCI* of 1.0 should also be considered as a fuzzy value, since the specific assumptions in the model (e.g., energy intake, mean yields, etc.) are averages and are therefore causing an inherent uncertainty.

The results indicate that none of the three heuristics of the complementary region of Pergamon offer reliably sufficient land to sustain a population of 180,000 or even above (Figure 4). In the high labour input scenario, the amount of arable land increases by 20–47%, as steeper slopes are considered for cultivation (cf. Figure 3). However, even the higher labour investment does not considerably change this observation (Figure 5).

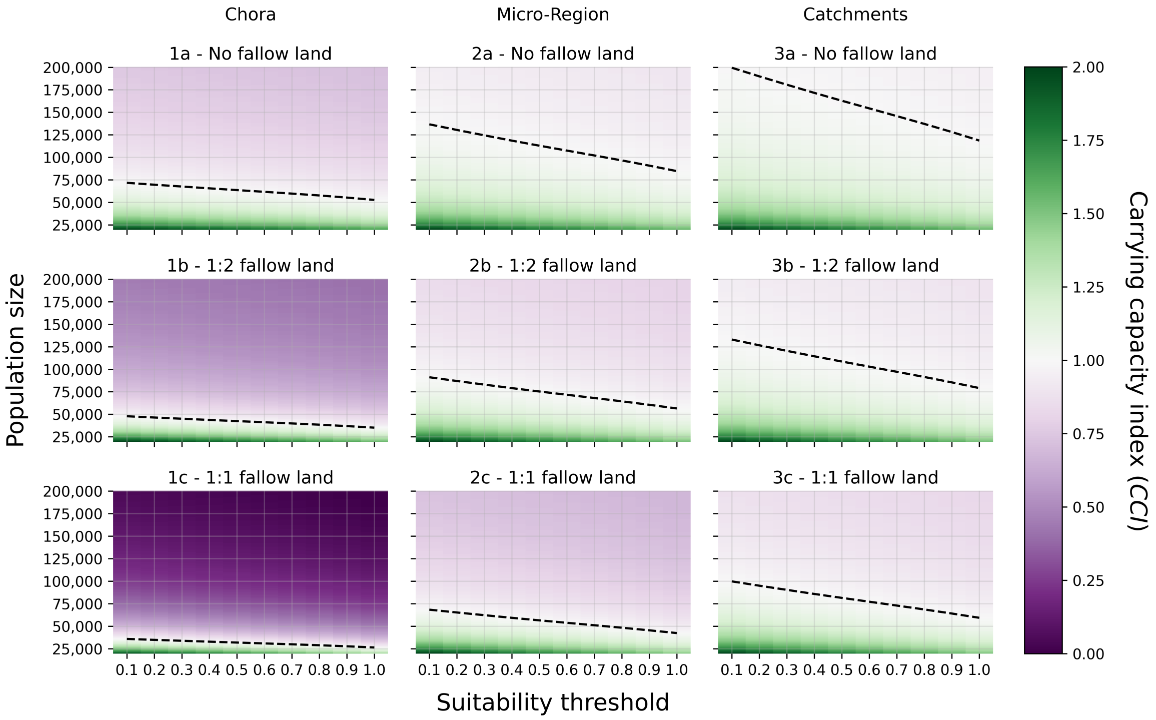

Figure 4. Carrying capacity estimation of the **normal labour scenario** for the different heuristics of the Pergamon's complementary area (**1** chora; **2** Micro-Region; **3** catchment-based delineation), under three different fallow land scenarios (**a** no fallow; **b** 1:2 fallow; **c** 1:1 fallow land) and 2100 kcal daily calorie requirements. Green colours ($CCI > 1.0$) indicate that carrying capacity is not reached, and enough land for cultivation is available. The opposite is true for purple colours ($CCI < 1.0$); white ($CCI \approx 1.0$) indicates that the carrying capacity is met or almost met. The black line shows where the CCI is exactly 1.0.

In both scenarios, the chora can be dismissed as being a basis of a self-sufficient supply of the population. Yet, the arable area of the chora would have sustained a minimum of 40,000, and maybe even a maximum of 65,000 citizens of Pergamon (cf. Figures 4(1a) and 5(1a,1b)) estimated by Hanson and Ortman [20]. The results are similar for the Micro-Region, or the 16-hour walking distance, heuristic. Only under the assumption of a high labour investment without fallowing might population sizes of about 160,000 inhabitants have been possible (cf. Figure 5(2a)), but a sustainable and more resilient estimate would suggest less than 100,000 inhabitants (cf. Figures 4(2a,2c) and 5(2b,2c)). Considering a self-sufficient supply of the population, a more extensive catchment-based heuristic seems to be the most plausible. Nevertheless, only in the no fallow or high labour input scenario would it have been possible to supply population numbers close to the estimated 180,000 inhabitants (cf. Figure 5(3a)). Depending on the degree of invested labour, the use of areas of lower suitability and the applied fallowing regime the Pergamon Micro-Region could sustain populations above 100,000 inhabitants.

The change of CCI values along the population axis can be considered as a simplified demographic development: It shows a steady decreasing CCI with increasing population size, respectively increasing population pressure over time.

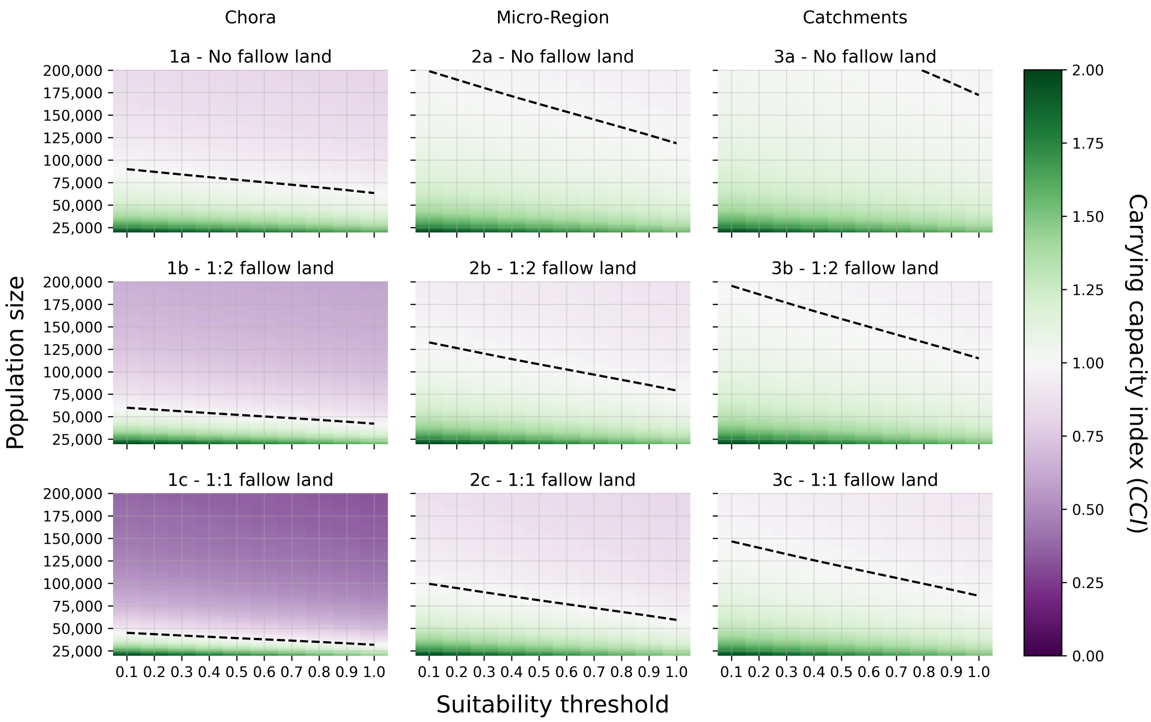

Figure 5. Carrying capacity estimation of the **high labour scenario** for the different heuristics of the Pergamon's complementary area (**1** chora; **2** Micro-Region; **3** catchment-based delineation), under three different fallow land scenarios (**a** no fallow; **b** 1:2 fallow; **c** 1:1 fallow land) and 2100 kcal daily calorie requirements. Green colours ($CCI > 1.0$) indicate that carrying capacity is not reached and enough land for cultivation is available. The opposite is true for purple colours ($CCI < 1.0$); white ($CCI \approx 1.0$) indicates that the carrying capacity is met or almost met. The black line shows where the CCI is exactly 1.0.

3.3. *Labour Availability*

Our results of labour estimation show that sufficient labour is available over the assumed harvest period to reap, thresh, and winnow the cultivated area of cereals and leguminosae (Figure 6). We consider a harvest period of five to seven weeks (July to August), as suggested by Halstead [94], for mainland Greece as appropriate for the Pergamon region. The time window is given for a regime where leguminosae and winter- and spring-sown cereals need to be reaped and processed further. Depending on the duration of the harvest period, between 18% and 32% of the population would need to work during the harvest to manage all considered tasks. However, we have to keep in mind that the workload of transporting the cut plants is not considered yet. The labour investment for this task is highly dependent on the distance to the processing location and the means of transportation (e.g., human, animals, or carts). This would raise the overall labour input and lets us assume that the numbers working in the farming sector during harvest are slightly higher that we estimate here.

The harvest period itself is of course not fixed but varies spatially and temporally. Some plots ripe earlier due to their location; due to the climatic variability, some years will shorten and thus prolong the ripening process of the plants [94,97]. We suggest that the minimum farming population will orient between the labour requirements for rather short and long harvest periods. Accordingly, a farming population of about 25% seem realistic on the basis of our calculations to manage the harvest under usual circumstances.

Based on the available data on labour input (see Supplementary Materials), we assume that one full labourer needs on average 16.56 days to harvest (6.45 days), thresh (7.67 days), and winnow (2.44 days) 1 ha of cereals. In a harvest period of 5–7 weeks, one person can harvest about 2–3 ha. This range would translate into a minimum farming population density of 0.33–0.5 people per ha under cultivation.

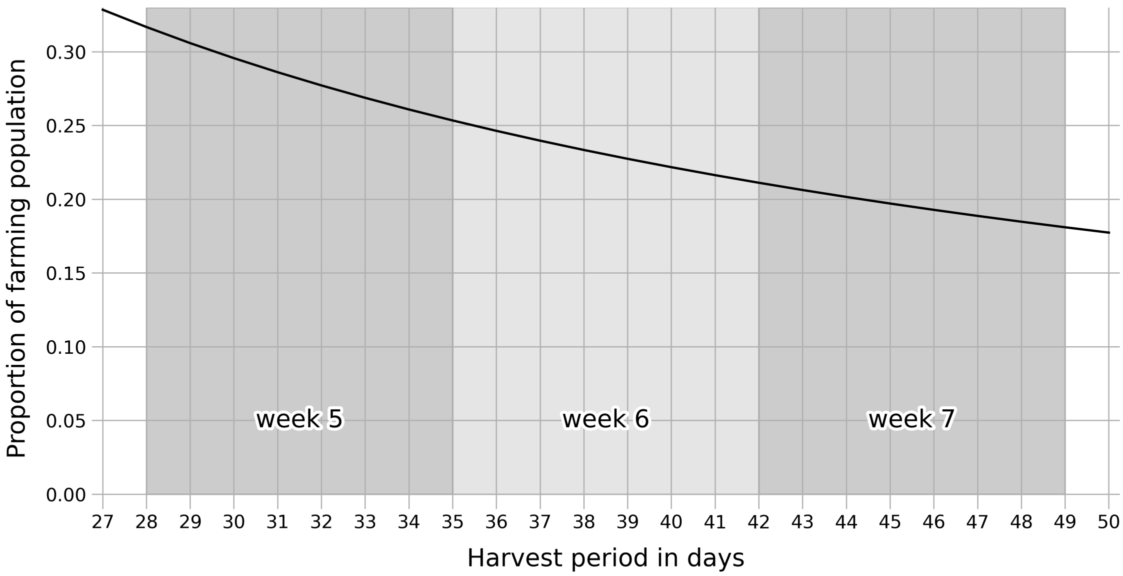

Figure 6. Proportion of the population that needs to be involved in the harvest of cereals and leguminosae within a given length of days. Considered harvest tasks are reaping, threshing, and winnowing.

4. Discussion

We investigated the potential for local supply with cereals and leguminosae using different heuristics of the complementary region of Pergamon. Comparisons of population densities with other regions allow conclusions to be drawn whether our heuristics seem plausible: The population densities of the Pergamon Micro-Region and the large, catchment-based territory, with population sizes below 120,000 inhabitants, are comparable to estimates of Italy and European provinces during the Roman Imperial Period (approximately 2nd century CE), with 27.4 and 14.4 P/km^2 [100]. On the basis of field surveys, population densities in the *Suburbium* of Rome between 27 BCE and 100 CE are reconstructed with 60–119 P/km^2 [101]. Accordingly, most of the population densities seem plausible for an urban centre such as Pergamon and its complementary region, with the exception of the very high population sizes (above 120,000 inhabitants) within the chora. Thus, the estimates of Galen and our subsequent question of regional self-sufficiency are related to a complementary region that is larger than the chora of Pergamon.

The results of the labour investment estimations show that the labour availability was no limiting factor for agricultural production. We only calculated the full-labourers as the farming population; non-labourers, such as children and old people, and people working in other economic sectors were not considered. Assuming that a minimum 25% of the population were involved in farming activities connected to subsistence and about 22–36% of the population lived in the city of Pergamon (40,000–65,000 inhabitants of 180,000 total) and were not or only partly involved in agricultural activities, approximately 39–53% of the population inhabited one of the other cities or the rural areas of the Micro-Region. These "free" labourers could have been allocated to *colonise* the environment, e.g., in order to expand agricultural land (see [102] for the accompanied problem of underemployment).

The estimation of a rural or farming population raises the question of how dense and in what kind of manner the landscape of the Pergamon Micro-Region was settled. We know the Pergamon Micro-Region was characterised by a high diversity of small-scale settlements, villages, and individual farmsteads [8] that underwent dynamic changes during the transition from the Hellenistic to the Roman Imperial Period [2,19]. For the latter period, we might consider a lower range of smaller farmsteads, since we can expect larger estates owned by the aristocracy [9]. Information about farm sizes and infrastructure provided by archaeological (e.g., [9,103–105]) and historical (e.g., [85,90,91,106]) records can be integrated with the estimated farming population as well as further environmental evaluation. This would allow one to estimate farmstead/estate quantities and to model their spatial distribution. From such models, interaction analyses of the Pergamon Micro-Region can be performed to gain a deeper understanding of the social-ecological significance of specified scenarios.

Despite our model's simplicity, we could show that labour availability was no limiting factor in the production of cereals or leguminosae; rather, the availability of space was. Hence, the surplus of labour might have been invested into environmental modification, e.g., by erecting terraces, in order to extend the available area. This process, which in social ecology is referred to as the colonisation of nature (e.g., [107]), increases the level of metabolism between the environment and people, since *colonised* areas have to be continuously taken care of. This allows for higher population numbers, but in turn lowers resilience, since the increase is only backed by the colonised interventions, whose functioning depends on active care; thus, a certain degree of energy is locked for these activities (see [108], in particular [22]). In our case, we modeled a colonised state of the environment as a high labour input scenario. Only under this assumption and little fallowing do population sizes of about 180,000 inhabitants seem to be sustainable. However, such a situation has to be considered to present little resilience when a self-sufficient subsistence is targeted. Under other circumstances, e.g., less labour input and thus less suitable areas and/or more fallow land, maximum populations would operate continuously at the upper limits of the carrying capacity. This causes lower resilience against even moderate storage losses or crop failures. This holds true even if we assume higher mean yields.

Furthermore, in our current scenarios, we suggest that the foremost endeavour of the primary sector was to sustain human subsistence and to maximise this first by cultivating mostly cereals and leguminosae on suitable land, before producing for a non-essential market. The cultivation of profitable foods for export or elites, such as olives and wine, might have decreased the area for subsistence farming further, causing conflicts of land [21,109]. We currently assume that livestock was grazed on fallow land or plots that were rather unsuitable for cereal and leguminosae cultivation, especially on steeper slopes of the adjacent hilly and mountainous landscapes of the complementary territories. The explicit cultivation of animal fodder crops, such as clover or oat, or hey meadows for animals are not taken into account, although those practices were widespread [90,91]. Growing "cash-crops" and/or animal fodder in larger scales would have deteriorated the limiting space situation.

Besides these socio-economic aspects, environmental challenges are common, too. The Mediterranean climate is highly variable, causing frequent droughts, impacting the size of harvests and influencing societal stability (e.g., [21,110–112]). Furthermore, disastrous events such as earthquakes or flash-floods can cause the loss of lives—and thus labour—and infrastructure, which influences the availability and distribution of food [113]. The earthquake of 178 CE had caused severe damage to the city of Pergamon [2], which should have impacted the food production and distribution sector in the complementary region as well. The role of the earthquake and its aftermath in the decreasing importance of Pergamon in the following centuries is hard to assess. Moreover, social stressors (e.g., political rivalry, military service, warfare, and besiegements), attested by written sources in the research area [8], might have decreased yields or increased food demand. Depending on their timing, they might have also had a lasting effect due to the hindering sowing of new grain or caring of field [114]. The impact of short-term hazardous events and long-term deterioration of either environmental or socio-cultural elements of the system are of high interest for future research and model extensions. Such investigations can help to explore different decision-making and adaptation strategies in the wake of a system's perturbation in greater detail.

Even if population estimates from the times before Galen's testimony are not available, the building development in Pergamon itself suggests a significant period of growth in the

1st century BCE caused by centralisation [2], both in area and population, from a polis and residence in the Hellenistic Period to the enlarged urban centre it eventually became during the Roman Imperial Period (e.g., [2,8]). If one follows the development of the population in relation to the Carrying Capacity Index (Figures 4 and 5), their inverse proportionality becomes obvious, which directly indicates a decreasing resilience of the social-ecological system. Even if we do not assume a linear demographic growth in Pergamon's population, at some point in time, the population pressure demanded political action to sustain growth or the status quo. In light of these aspects, it is of little surprise that Pergamon relied on external food imports [8], though these created a lowered resilience within the socio-political sphere concerned with foreign affairs and trade due to the reliance on functioning exchange networks and political control [114].

Based on our findings, questions arise that go beyond assessing the rather ecological side of the socio-ecological system of Pergamon and its complementary region and focus more on the social realm. As there seemed to exist a shortage of land, the organisation of the production and the distribution of the goods became more crucial, which especially includes the question of land ownership and power relations within the region. To sustain the low resilience of the supply system of Pergamon, stability was needed, not only in foreign affairs, concerning trade and exchange, but in the politically controlled region itself. Therefore, the relationship between the city and its food supplying complementary region must have been of high importance, and possibly fragile. Thanks to external supply, a successful but prone subsistence system emerged from this arrangement that became stable enough to sustain the area and enable growth. Perhaps this is one reason for the demographic and economic upswing that started during the reign of Augustus, where the accompanied *pax romana* secured trade and exchange networks but also fiscal stability [2,19], though this upswing is visible archaeologically only from the 2nd century CE onward.

A more comprehensive discussion of the potentially exceeded carrying capacity and its various consequences is not possible here (see [115] for a discussion in Greece; see [116,117] regarding grain imports; for related socio-economic crisis and depths, see [118–120]). As noted at the beginning of the Methods section, we consider our integrative modelling approach as a heuristic [38], a transparent scenario—one of numerous others—that can help us to gain a better understanding of the socio-ecological complexity of the complementary region of Pergamon. Different setups (in terms of input data and chosen algorithms) and different empirical values will change the results and potentially the interpretations, and we want to encourage interested colleagues to apply and extend our current approach to other settings and scenarios.

5. Conclusions

We present an integrative modelling approach to assess whether social or environmental carrying capacity limited the self-sufficient supply of the complementary region of Pergamon. Different heuristics of complementary regions are considered, showing that only the catchment-based heuristic seems plausible in terms of a sufficient local supply with cereals and leguminosae. Labour investments in the extensions of agricultural fields were able to relax the situation at the expense of resilience, since colonised areas required continuous care. However, the Pergamon Micro-Region still depended on imports in order to sustain a reliable food supply.

A system operating at its upper limits—even just for a short period—demonstrates little resilience. Phases of food shortages due to crop or storage failures would have resulted in socio-economic tensions and population decline, which might have further deteriorated conditions. Since the archaeological or historical record does not indicate any major abrupt events for the investigated period, we assume that the import of supplementary food from other regions was common and worked well. Hence, Pergamon's resilience was to its integration into supra-regional networks, supporting the understanding of the Micro-Region as interconnected entities in the Mediterranean.

We like to stress the reproducibility of the presented study and therefore encourage the use of our approach in other settings to assess whether similar or quite different situations occur elsewhere. An application is possible on nearly every scale, and a set of well suited case studies can be combined to gain insights into the socio-ecological potentials of a network of interconnected micro-regions and to investigate their mutual interdependence.

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