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Caught in a Deadlock: Small Ruminant Farming on the Greek Island of Samothrace. The Importance of Regional Contexts for Effective EU Agricultural Policies

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Abstract: Sedentary extensive small ruminant farming systems are highly important for the preservation of High Nature Value (HNV) farmland. Both the abandonment of grazing and overgrazing have led to environmental degradation in many Mediterranean regions. On the Greek island of Samothrace, decades of overgrazing by sheep and goats has caused severe degradation of local ecosystems. The present study highlights the importance of regional contexts for national and EU agricultural policies in regard to sustainable development of sedentary extensive livestock systems. By utilizing the conceptual framework of socio-ecological systems research, we analyze the interdependencies of environmental, economic and social factors on a local island level. Results show that between 1929 and 2016, the livestock and land-use system of Samothrace transformed from a diverse system towards a simplified system, solely used for small ruminant production. Total livestock units increased from 2200 in 1929 to 7850 in 2002, declining to 5100 thereafter. The metabolic analysis conducted for the years 1993–2016 shows that 80–90% of the feed demand of small ruminants was covered by grazing, exceeding available grazing resources for at least a decade. The regional implementation of CAP (Common Agricultural Policy) continues to support excessively high animal numbers, while farmers are highly dependent on subsidies and find themselves in an economic deadlock.

Keywords: overgrazing; soil erosion; rural abandonment; sedentary extensive livestock systems; Common Agricultural Policy (CAP); socio-ecological systems; social metabolism; material flow analysis (MFA); mixed methods approach

1. Introduction

Livestock represents a key element in society-nature interactions and is responsible for more than a third of global land use in a wide range of ecosystems [1]. Extensive, pasture-based ruminant and mixed crop-livestock systems provide 70% of milk and 60% of meat globally, utilizing 80% of all agricultural land [2]. In the Mediterranean, extensive, pasture-based ruminant systems have a long tradition dating back to antiquity. This form of livestock management created characteristic landscapes, dominated by heterogeneous plant communities of forests, bushes, herbaceous undergrowth and grassland. A long co-evolutionary process generated “resilient ecosystems with a high species diversity, productivity and utility to society” [3]. As the specific environmental conditions in these regions limit intensive and specialized farming, extensive, pasture-based ruminant systems continue to shape many rural areas up until today [4]. In Europe, these types of ecosystems are considered High Nature Value (HNV)

farmland (HNV farmland describes agriculturally used areas with high levels of biodiversity and is one of 35 EU indicators for the integration of environmental aspects into the Common Agricultural Policy (CAP) [5]), with its highest proportions in Portugal, Spain and Greece [6]. In these regions, rough grazing biomass is transformed into high value products, traditionally by small, but increasingly also by large ruminants. The preservation of extensive, pasture-based small ruminant farming systems (SRFSs) is highly important for the protection of HNV farmland and rural communities throughout the Mediterranean [7]. In Greece, small ruminant farms produce 60% of milk and 65% of red meat for the national market, which is unique in Europe and indicates the sector's social and economic importance [8]. The present study addresses the sustainability of extensive SRFSs with a special focus on the Greek island of Samothrace.

Traditionally, SRFSs in Greece were, in most regions, characterized through transhumant activities. Since the beginning of the 20th century, nomadic lifestyles have been in decline, mainly morphing into semi-nomadic or sedentary extensive SRFSs. This model primarily uses common grazing land, provides supplementary feed and is characterized by low investment and productivity [9]. Today, sedentary extensive SRFSs shape rural Greece, and are currently threatened by a multitude of factors. While some regions suffer from complete abandonment of grazing, others are heavily overgrazed [10]. Both trends lead to ecosystem degradation and demonstrate the current economic and social crisis this type of SRFS is experiencing. If grazing is abandoned, shrub and bush encroachment changes species composition and often leads to increased fire risk, while high grazing pressure mostly results in biodiversity loss and soil erosion [11]. Global agricultural industrialization has led to a decline in feed prices and production costs, even though transport distances are larger [1]. Consequently, prices for agricultural products have declined, while extensive, small-scale farms have an increasing difficulty competing in the market. The demand for wool and skins has become so low that today many farmers prefer to dump them.

The EU Common Agricultural Policy (CAP) plays a special role in the transformation of grazing-based farming systems throughout the EU. In some regions, subsidy schemes supported the abandonment of grazing through the conversion of extensive pastures into forests or crop production; while in other regions, grazing was intensified through direct payments that initiated higher animal stocking rates [12]. Local socio-economic contexts and needs are often insufficiently taken into consideration by EU-wide agricultural policies, resulting in mixed outcomes for farmers [13]. The aim of the present study is to highlight such a local socio-economic context on the Greek island of Samothrace, where the transformation of local agriculture was identified as the major driver for ecosystem degradation and widespread soil erosion [14–16].

The importance and multiple challenges faced by SRFSs in Greece and other Mediterranean regions, calls for a comprehensive research approach, focusing on environmental, social and economic aspects simultaneously [17]. In our case study, we aim to analyze the interdependencies of environmental, economic and social factors regarding the SRFS on Samothrace. We use the conceptual framework of socio-ecological systems research, as it builds a useful link between biophysical and socio-economic processes, by describing the exchange of materials and energy between society and nature [18,19]. The utilized mixed methods approach [20], integrates data on environmental, economic and social aspects of small ruminant farming from various sources and builds upon the long-term research project on the island. The integration of monetary flows expressed in relative prices complements the socio-metabolic approach, as it directly influences biophysical flows through farmers' behavior [21]. This approach allows us to derive sustainability indicators, assess socio-economic drivers, and define possible pathways for a sustainable future for agriculture on Samothrace. The study is guided by the following research questions: What factors contribute to and represent the current sustainability crisis of the SRFS on Samothrace? What are the socio-economic drivers for the regression of sedentary extensive SRFSs in Greece? What role does the EU Common Agricultural Policy (CAP) play, in the context of the current sustainability crisis of small ruminant farming on Samothrace? What could a sustainable future of small ruminant farming in the Mediterranean look like?

In Section 2, we outline the methodological approach by introducing the study site in Section 2.1, the conceptual framework in Section 2.2, the biophysical assessment in Section 2.3, the socio-economic assessment in Section 2.4 and the evaluation of uncertainty of input data in Section 2.5. Results are provided in Section 3. The Discussion in Section 4 contains chapters about the sustainability crisis of the SRFS on Samothrace in Section 4.1, the regression of sedentary extensive SRFSs in the Mediterranean in Section 4.2, the role of EU CAP in the changes affecting the SRFSs of Samothrace in Section 4.3, and the future of small ruminant farming in the Mediterranean in Section 4.4. Conclusions are provided in Section 5.

2. Material and Methods

2.1. The Island Samothrace

Samothrace stretches over 178 km² and is one of the very few hotspots of preserved archaic wilderness among the Greek islands. Its remote location in the north-eastern Aegean Sea, the pebbly nature of most beaches and often unclear land ownership, averted economic exploitation and mass tourism on the island. The 1611 m high mountain range Σάος gives Samothrace its geomorphological character and shapes the distinct microclimates. While the northern side presents itself in lush green with old forest cover and numerous streams of drinkable water, the southern and western sides are shaped by a rather typical dry summer Mediterranean climate and vegetation. A large proportion of the island's terrestrial area is part of the Natura 2000 network, and since 2012, the island has been a UNESCO MAB ("UNESCO's Man and Biosphere (MAB) Program is an intergovernmental scientific program striving for the improvement of the relationship between people and their environment. The Biosphere Reserve concept started by a Task Force of UNESCO's Man and the Biosphere (MAB) Program in 1974, while the World Network of Biosphere Reserves (WNBR) was launched in 1976. Biosphere Reserves (BR) are terrestrial and/or marine areas that encompass valuable ecosystems and social communities that wish to combine the conservation of ecosystems with their sustainable use. They are established to promote and demonstrate a balanced relationship between humans and the biosphere" (www.sustainable-samothraki.net) candidate [14,22]. The island community of Samothrace is officially registered as 2840 people [23], but is subject to high fluctuations because many people leave the island in winter months or visit the island as tourists, seasonal workers or second homeowners. Of the 1000 economically active residents, 20% work as livestock herders and small-scale farmers. The secondary sector is relatively underrepresented at 10%, while the tertiary sector employs 60% and consists mainly of tourism services.

The development path of recent decades has led to a wide variety of environmental but also social problems which the island community currently must face. One of the major threats to local ecosystems was triggered by the transformation of the local agricultural system. Decades of overgrazing by sheep and goats resulted in biodiversity reduction and widespread soil erosion [15,16]. Since the mid-20th century, farms and farmers are declining, while the small ruminant population increased to unprecedented levels [24]. Increasing feed prices, dependence on subsidies, the lack of marketing opportunities and little cooperation among themselves, have caused local farmers to find themselves in an economic deadlock situation that now threatens the very existence of agriculture on the island.

2.2. The Conceptual Framework

For the present study, we defined the system of investigation as the small ruminant farming system (SRFS) and its most relevant socio-economic and ecological relations, shown in Figure 1. The green circle represents the natural, and the blue circle, the cultural sphere of causation, with the livestock and human population in the overlapping part. The SRFS is defined as the small ruminant population (sheep and goats), its metabolic requirements, its material output in terms of products, the small ruminant farmers and their monetary economy. Terrestrial ecosystems provide the net primary production (NPP) consumed by small ruminants. The SRFS exchanges goods and money with the

local population, including visitors. The political, legal and cultural framework is represented by rules and regulations of the Greek state, and the EU and local traditions. The EU provides agricultural subsidies through the Common Agricultural Policy (CAP), and the Greek state pays pensions to retired farmers. The local and visitor population receive money from external markets and through income from external sources (e.g., work or pensions). Wastes are not explicitly assessed in this study, but they are a relevant factor, especially regarding slaughtering residues and emissions.

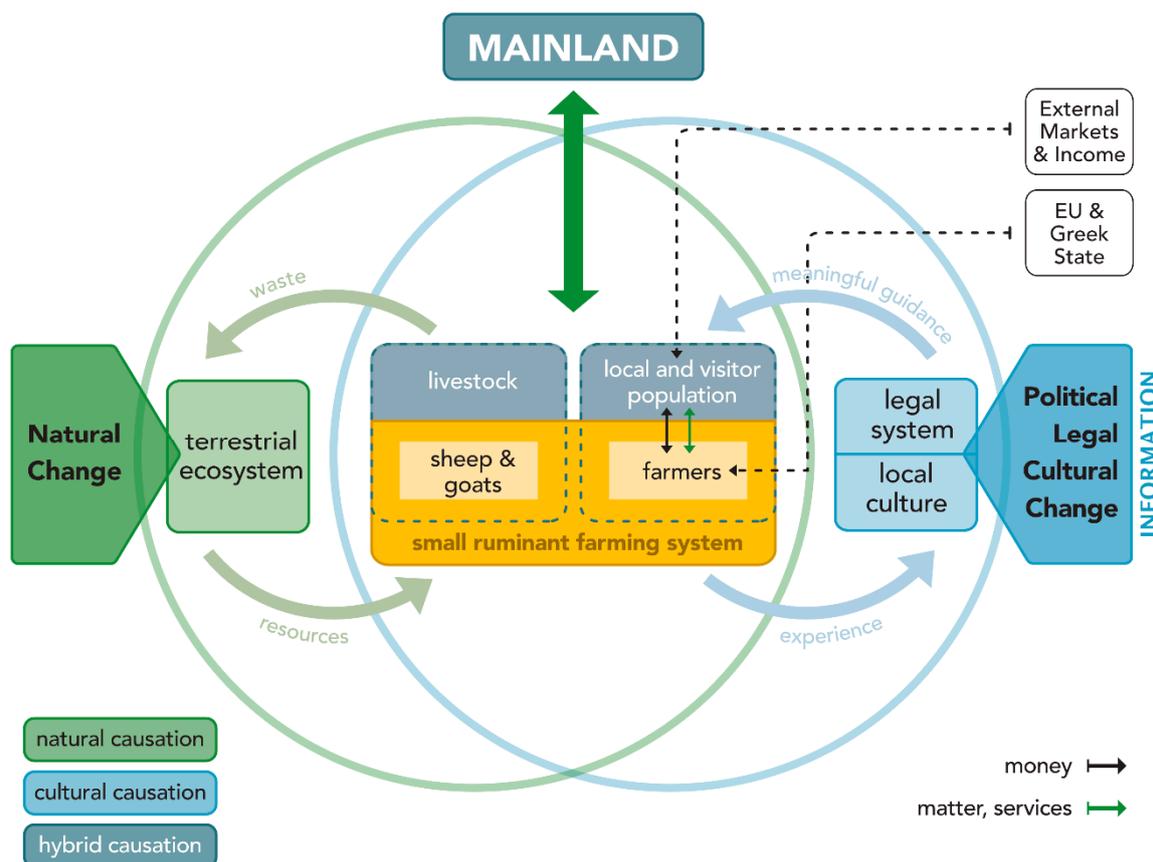


Figure 1. Schematic representation of the studied system and important influential factors. Figure adapted from Petridis et al. and Fischer-Kowalski et al. [25,26].

The present study is part of a long-term research project on Samothrace, beginning in 2008. Thus, we were able to build upon previous research efforts and use data from various sources. The aim of covering environmental, social and economic factors resulted in the need to utilize a mixed methods approach [20]. As indicated by the grey boxes shown in Figure 2, we integrate quantitative and qualitative data from a survey with 23 small ruminant farmers, qualitative data from 12 expert interviews, public statistical data, and data from previous research on land cover dynamics [24,27]. For the assessment of biophysical flows, we utilize a bottom-up or stock-driven approach, to assess the biomass consumption of the SRFS on the island. Detailed documentation can be found in the Supplementary Data (SD) and Information (SI) file.

The Material and Methods section is divided into the biophysical, in Section 2.3, and socio-economic, in Section 2.4, assessment of the SRFS system. The utilization of the metabolic small ruminant model in combination with various data sources requires a systematic assessment of uncertainty of the model and exogenous data [28]. For this reason, we conducted a sensitivity analysis in combination with a qualitative description, and when applicable, an uncertainty range of key input parameters in Section 2.5.

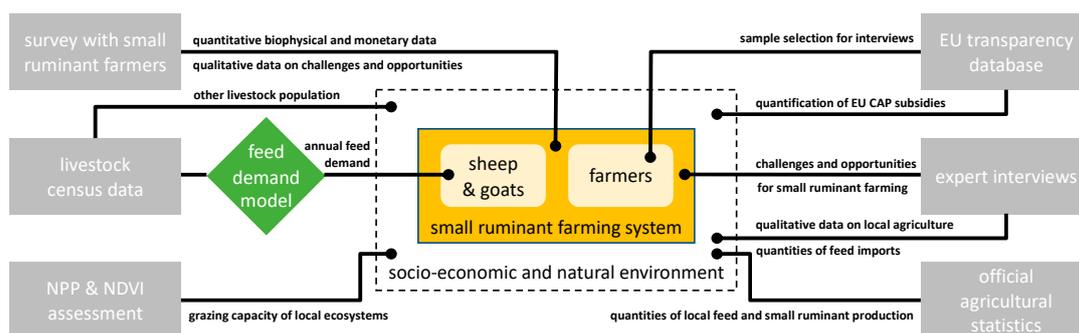


Figure 2. Mixed methods approach as applied to the SRFS (small ruminant farming system) and its socio-economic and natural environment.

2.3. Biophysical Assessment of the Livestock System

The assessment of biophysical conditions is based on the conceptual framework of socio-ecological systems research [18,19], and utilizes the methodological approaches of material and energy flow accounting (MEFA), and principles of human appropriation of net primary production (HANPP) on a local island level. The assessment was conducted in three ways:

1. Livestock units for all livestock species are reconstructed through official livestock census data from 1929 to 2016 [29] and the application of feed requirement factors. Factors for all species, except sheep and goats, were derived from Krausmann et al. [30].
2. For the assessment of feed intake of sheep and goats on Samothrace, we set up the herd and feed rations modules of GLEAM (Global Livestock Environmental Assessment Model) in Excel (For a detailed description of GLEAM, its components and equations, refer to <http://www.fao.org/gleam/en/>. For a detailed description of equations used for the present study see Supplementary Information: Section 4 and Supplementary Data: Tables S1–S4.) [31]. For the description of this model in Section 2.3.1, we follow the ODD (Overview, Design Concepts, Details) protocol that has been widely used to describe simulation models in multiple disciplines [32,33].
3. For the estimation of the grazing capacity of the island's ecosystems (Section 2.3.2), we used net primary production (NPP) data derived from Fetzel et al. [24], and the Normalized Difference Vegetation Index (NDVI) derived from Löw [27].

2.3.1. Calculation of Metabolic Requirements of Small Ruminants Based on GLEAM

The ODD (Overview, Design Concepts, Details) protocol is structured around *overview*, *design concepts* and *details* sections. Sections *overview* and *design concepts* are provided in Table 1. The *details* section is outlined below and includes the description of the *initial state* of the model and *model input* and *output data*.

Table 1. Overview and design concepts of the utilized modelling approach following the ODD (overview, design concepts and details) protocol.

Overview and Design Concepts of the Utilized Modelling Approach		
Overview	purpose	Assess feed requirements of the local SRFS, based on population dynamics and the potential output of livestock products in regard to the availability of feeding resources on the island
	materials	Grazed biomass and locally produced and imported feed in tons per year
	processes spatial and temporal scale	Population dynamics and energy requirements of sheep and goats, translated into biomass consumption The island of Samothrace from 1993 to 2016
	system overview	Provided in GLEAM model description (see Supplementary Information: Figure S5)
Design Concepts	basic principles	Retrospective, dynamic and bottom-up or stock driven material flow analysis (MFA)
	modelling approaches	Dynamic modelling approach based on the Global Livestock Environment Assessment Model (GLEAM) [31]
	dissipation	Not explicitly modelled
	spatial dimension	A spatially explicit assessment was not conducted
	uncertainty	Systematic uncertainty assessment of all model input parameters based on the framework by Laner et al. [28], as well as systematic sensitivity testing

The **initial state** of the utilized modelling approach is set by the official annual numbers of sheep and goats and their energy requirements, expressed in tons of dry matter and carbon content of biomass. The assessment of the feed intake of sheep and goats on Samothrace is based on GLEAM, which generally follows an LCA approach with the goal of assessing emissions of livestock production systems. GLEAM includes a method to derive feed inputs of small ruminants based on their energy demand, and production output through the utilization of the herd and feed ration modules (Supplementary Information: Figures S6 and S7). These modules were built in Excel by using the equations provided by the FAO in the GLEAM model description.

Model input data was derived from official statistics, survey data, literature and GLEAM model parameters. The herd module requires annual input data for the number of animals, live weights and ratios of cohorts, death, fertility and replacement rates, lambing/kidding intervals and litter size. The feed ration module requires input data for the daily milk production, annual production of fiber, feed rations and their average digestibility and gross energy content. A survey with 23 local livestock farmers was conducted in 2017–2018 to collect data on 176 parameters regarding flock characteristics, production, processing, grazing, feeding, land management, revenue and costs. Modelling of biophysical flows, live weights of animal cohorts, proportion of dairy animals, male to female ratio, lambing or kidding intervals, litter size and daily milk production were derived from survey data (for a detailed description of the selection process and sample see Supplementary Information Section 3). Death and replacement rates, average daily weight gains, average digestibility of feed ration and average gross energy content of feed ration were derived from region specific FAO data provided in the GLEAM model description. Total annual numbers of animals at the end of each year from 1993 to 2016 and their fertility rates were derived from official statistical data. The calculation of feed rations is based on the energy demand of animals in relation to the available amount of feed. Local feed production was derived from official statistical data on annual primary production [29]. Crop residues were calculated based on areas used agriculturally for crop cultivation and factors derived from literature [34]. Data from local traders was used to estimate annual external feed supply through imports. FAO data was used for the share of leaves in the diet. Total available feed was integrated to calculate the feeding ration of small ruminants in which the remaining feeding gap was assumed to be filled by grazing (Supplementary Data: Tables S3 and S4).

Model output data is generated for total feed demand for small ruminants in fresh grass, hay, crop residues, leaves and grains from 1993 to 2016, in tons of dry mass per year (tDM/year) and tons of carbon per year (tC/year). The model further calculates the share of feed demand that was covered

by imported feed, locally produced feed and grazed biomass from 1993 to 2016. By multiplying the number of milked animals by the duration of the milking season and the daily production potential, it was possible to estimate the potential annual milk production of all sheep and goats. Standard deviation values for average daily milk production (sheep: $\pm 12\%$; goats: $\pm 25\%$) were generated through integration of data from different sources (Supplementary Information: Section 4). The herd module of GLEAM also allows for the calculation of the share of animals that is available for meat production in each cohort. A standard deviation of $\pm 15\%$ was defined. The modelled increase in production of milk and meat would cause a higher feed demand which is not considered in the results.

2.3.2. Estimation of the Grazing Capacity of Local Ecosystems

For the assessment of the potential overutilization of grazing resources through sheep and goats from 1993 to 2016, we provide estimates for local net primary production (NPP), in combination with a trend derived from the assessment of the Normalized Difference Vegetation Index (NDVI). Data on total available biomass for grazing was derived from Fetzel et al. [24], who utilized MODIS Net Primary Production (NPP) data for 9 CORINE land cover classes identified for Samothrace [35]. These land cover classes were grouped into 3 major land-cover types: “arable land”, “natural forests”, and “principally agricultural land with significant natural vegetation”. For each land-cover type, the authors defined maximum biomass off-take levels to ensure that the feed supply estimates from local ecosystems are realistic and would not degrade essential resources. These net primary production (NPP) levels do not represent total aboveground biomass (NPP_{act}) but refer only to the amount that can be grazed without continuous degradation of local ecosystems. For simplification, we refer to this level of net primary production as NPP in this study. The Normalized Difference Vegetation Index (NDVI) trend applied to NPP values is based on previous research. The NDVI for Samothrace was calculated based on LANDSAT-datasets and their spatially discrete land-cover classifications in combination with a time-series analysis of continuous field data on biophysical ecosystem properties [27]. The NDVI trend for the years 1993 to 2016 was applied to the average NPP for the years 2000 to 2004 in order to derive annual NPP values for the covered period. As this approach is prone to relatively high uncertainties, we applied an NPP range of $\pm 27\%$ with regard to an uncertainty assessment for MODIS and NDVI data sources, derived from Jia et al. [36].

2.4. Social and Monetary Assessment of the Local Small Ruminant Farming System

Qualitative and quantitative surveys were conducted in order to integrate information about constraints and opportunities for agriculture on the island and data on the monetary economy of the small ruminant system. 12 qualitative expert interviews with 6 farmers (Expert 1–6), the dairy owner (Expert 7), 2 traders (Expert 8 and 9), 1 municipal employee (Expert 10), 1 local agricultural consultant (Expert 11) and 1 former vice mayor (Expert 12), were conducted between 2012 and 2018. A content analysis in regard to the past, present and future situation of small ruminant farming on the island was also conducted. Qualitative data from the survey with 23 small ruminant farmers was used to describe the sample (Supplementary Information: Section 3). Results of both qualitative analyses have been integrated into the discussion section. For the monetary assessment, retail prices for milk, cheese and meat, meat processing costs and feed costs for hay and grain, were asked for in the survey (Supplementary Information: Table S1 and Figure S1) and multiplied by the actual purchased or sold quantities of products to estimate annual expenses and revenue. Land, transport and farm utility costs were assessed in the survey per farmer, and average values applied to all small ruminant farmers on the island. For 2016, total revenues from milk, dairy products, meat, wool and subsidies are contrasted with total costs for feed, labor, land, transport, farm utility, processing, and the veterinarian. Total income or loss for the entire small ruminant production system and the average farmer was calculated.

2.5. Validation and Uncertainty of the Utilized Model and Data

The sensitivity analysis was applied to biophysical and monetary parameters. 23 input parameters were tested with a freely chosen $\pm 10\%$ factor and their effect on the 6 output variables, total feed demand [tC/year], sustainable grazed biomass [t/year], revenue [€/year], costs [€/year], income [€/year], potential milk production [kg/year], and potential meat production [kg/year] evaluated. Figure 3 shows the deviation of output variables with higher values than $\pm 1.5\%$. The different colors represent the 6 different output variables in regard to the $\pm 10\%$ deviation of the input variables. The left side represents minus 10%, the right side plus 10% deviation of input variables. Transparent colors indicate a minus deviation, and full color bars represent a plus deviation of output variables. For a detailed description of the uncertainty evaluation of model input parameters see Supplementary Information: Section 6.

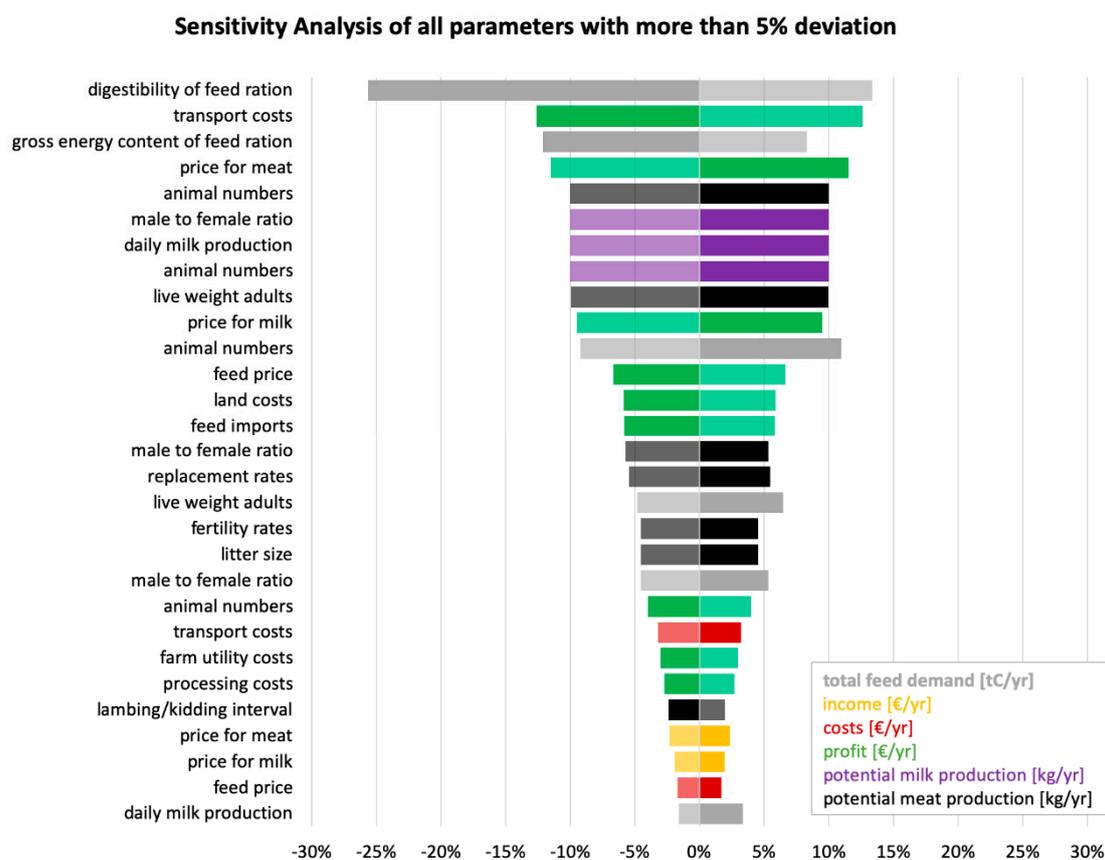


Figure 3. Results from a systematic sensitivity analysis, where each model input parameter was varied by $\pm 10\%$ and the effects on the main indicator are then plotted.

3. Results

Results contained the development of all livestock units (LSU) from 1929 to 2016 in Section 3.1, the feed demand of the small ruminant population in Section 3.2, the grazing demand in comparison to the grazing capacity from 1993 to 2013 in Section 3.3, an analysis of production potentials in Section 3.4, and the assessment of the monetary economy of the small ruminant farming system (SRFS) in Section 3.5.

3.1. Development of the Total Livestock Units on Samothrace 1929–2016

Figure 4 shows the increasing significance of small ruminants in relation to other livestock species on the island from 1929 to 2016. Total livestock is expressed in livestock units (LSU), which express

the nutritional requirements of each species. In 1929, the island had 490 [LSU] cows, 430 [LSU] pigs, 1250 [LSU] Equidae (horses, mules and donkeys), 3026 [LSU] poultry, 1672 [LSU] sheep and 2892 [LSU] goats. Small ruminants represented only 21% of all [LSU] in 1929, compared to cows (22%), pigs (10%), Equidae (45%) and poultry (2%). In 2016, small ruminants represented 93% of all LSU (2276 [LSU] sheep; 2428 [LSU] goats), while cows are reduced to 0%, pigs to 5% (277 [LSU]), Equidae to 1% (56 [LSU]) and poultry remained at 2% (77 [LSU]). Total [LSU] for small ruminants increased from 456 in 1929 to 4478 in 1992 before reaching their peak at 6735 in 2002, declining to values between 4100 and 4800 thereafter. For annual population numbers and [LSU] refer to Supplementary Data: Figure S4.

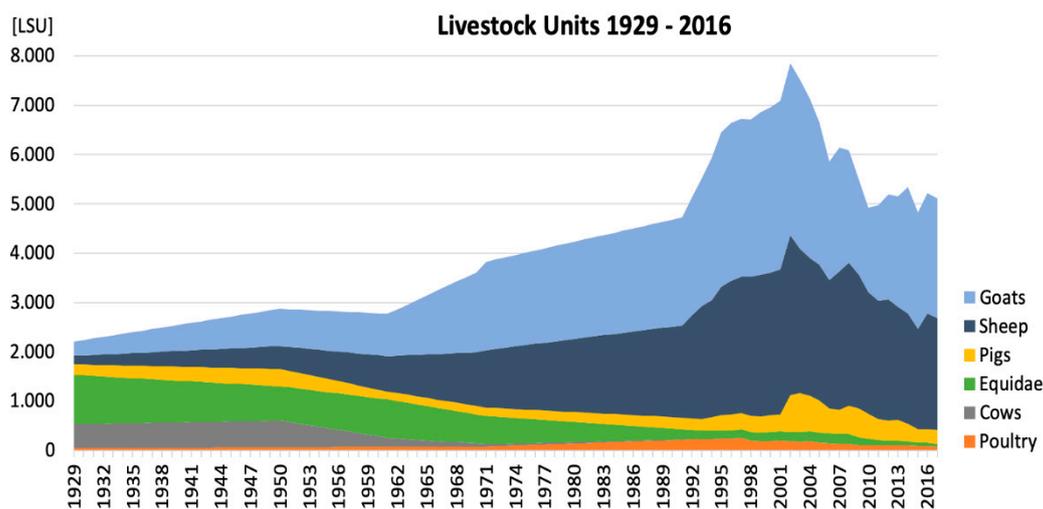


Figure 4. Development of total livestock units [LSU] on Samothrace from 1929 to 2016.

3.2. The Metabolism of the Small Ruminant Population of Samothrace 1993–2016

Figure 5 shows the annual feed demand of the small ruminant population in 5 categories: imported feed (orange), locally produced feed (dark yellow), crop residues (yellow), leaves (dark green) and fresh grass (green). Total feed demand was 23,000 tDM/year in 1993, increased to 31,600 tDM/year in 2001, and declined to values between 19,000 and 21,000 tDM/year thereafter. Annual values are provided in Supplementary Data: Figure S5.

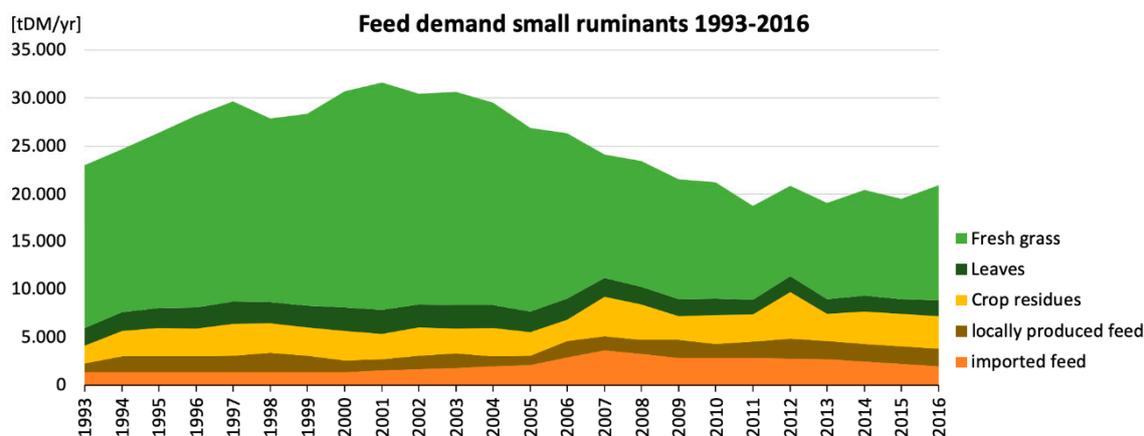


Figure 5. Annual feed demand of the small ruminant population in tons of dry mass (DM) from 1993 to 2016.

3.3. Utilization of Grazing Resources by the Small Ruminant Population

Grazing in local ecosystems accounts for the feed demand categories of fresh grass, leaves and crop residues (Figure 6). In 1993, the grazing demand of the small ruminant population was 9900 tC/year, increasing to 13,700 tC/year in 2001, and declining to values between 7000 and 8000 tC/year thereafter. Herein, we use two boundaries of the net primary production of biomass available for grazing (NPP) to assess the potential overgrazing and therefore, degradation of local ecosystems (see Section 2.3.2). We found that the upper grazing boundary was exceeded for at least 10 years between 1995 and 2005, while the lower boundary was exceeded for almost the entire period.

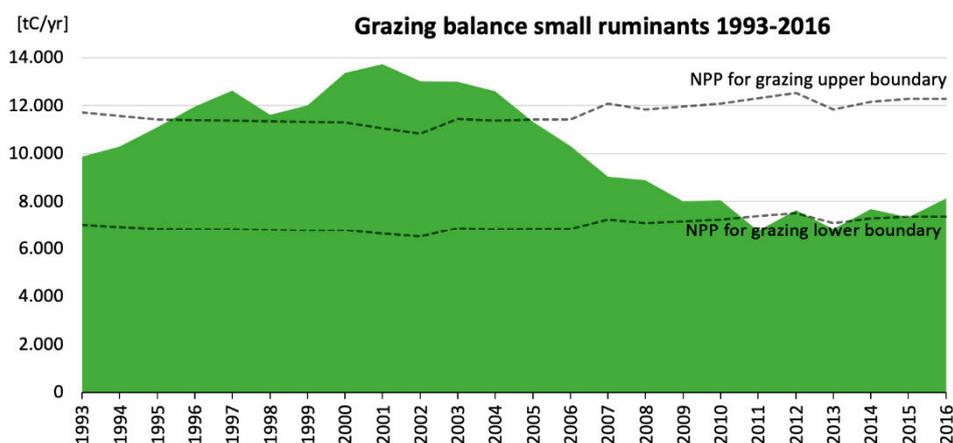


Figure 6. Grazing balance for the small ruminant population in annual tons of carbon (C) from 1993 to 2016. Annual values are provided in Supplementary Data: Figure S5.

3.4. The (Under-)Utilization of Production Potentials

Figure 7 shows the difference between modelled potential and official production numbers between 1993 and 2016, derived from statistical data. Official production of milk (blue solid line) and meat (red solid line) are far below the potential production (dashed lines and standard deviation bars of same color) for the entire period. For the entire period, farmers produced 74% (milk) and 61% (meat) below the modelled production potentials. While potential milk production increases with the population increase from 4800 t/year in 1993 to 6600 t/year in 2002, official production declines from 1330 t/year to 806 t/year. The increase of the official milk production after 2003 can most likely be attributed to the reopening of the local dairy. Annual values are provided in Supplementary Data: Figure S7.

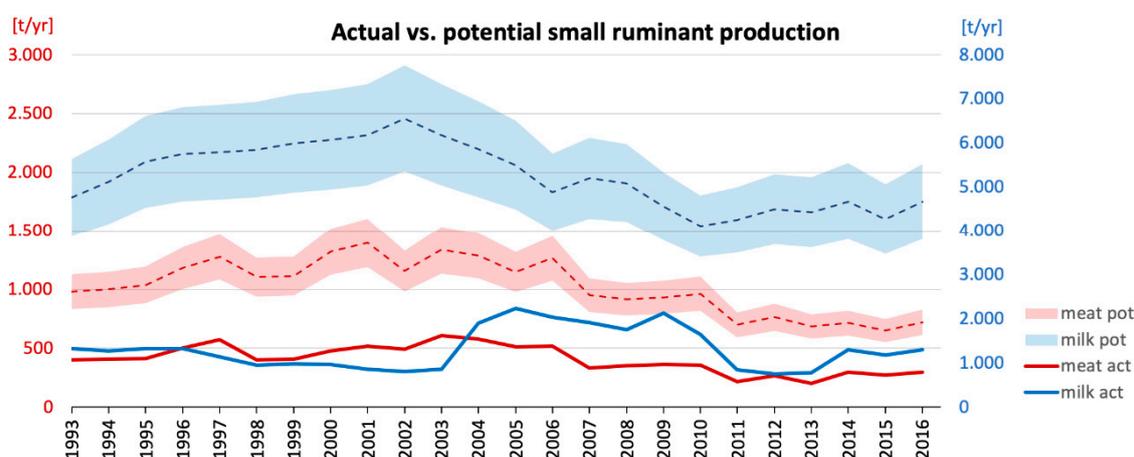


Figure 7. Actual vs. potential production of milk and meat from 1993 to 2016.

3.5. The Monetary Economy of the Small Ruminant Farming System in 2016

Figure 8 plots revenue against cost to estimate the annual income for the entire small ruminant farming system (SRFS) and the average farmer. 171 small ruminant farmers generated a revenue of 4.2 million €/year through milk and milk products, meat and subsidies in 2016. Costs for farm utility, processing, transport, land and animal maintenance were 3.4 million €/year, resulting in a net income of 860,000 €/year. For the single average farmer, this meant a revenue of 25,000 €/year, costs of 20,000 €/year and a net income of 5000 €/year. Values for categories are provided in Supplementary Data: Figure S8.

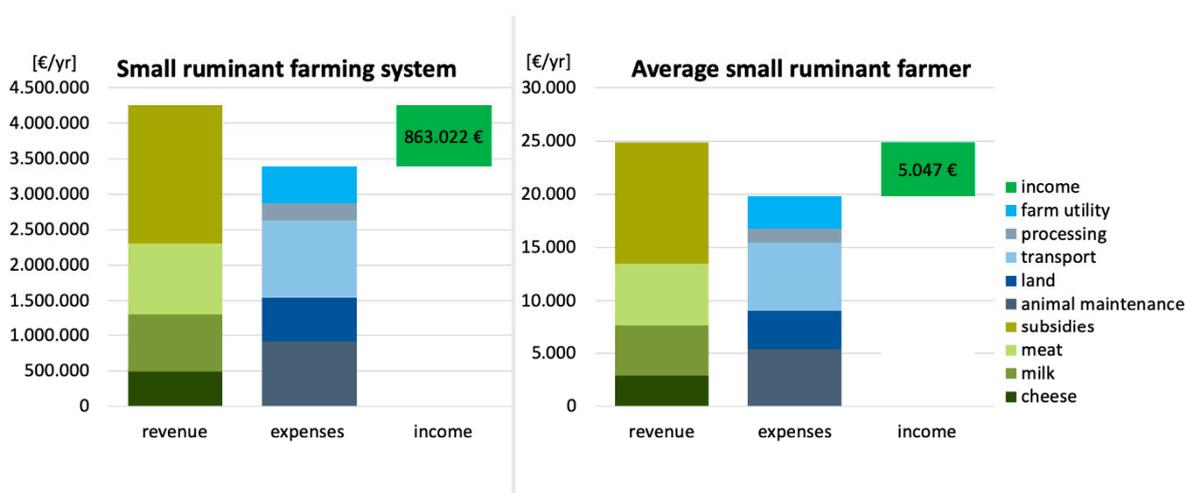


Figure 8. Annual monetary economy of the small ruminant farming system (left) and the average small ruminant farmer (right) in 2016.

4. Discussion

The integration of biophysical, monetary and qualitative data, in combination with results from previous studies analyzing changes in local ecosystems, enables us to comprehensively describe the current sustainability crisis of the system, its socio-economic drivers and potential ways forward. Consequently, we integrated the quantitative insights gained in the previous sections with qualitative insights from 12 expert interviews and additional literature.

4.1. The Sustainability Crisis of the Small Ruminant Farming System on Samothrace

We found that the small ruminant farming system (SRFS) of Samothrace was highly dependent on local grazing resources throughout the period covered (Figure 5). Thus, a continuous overutilization of local grazing resources undermines the very existence of the system (Figure 6). While both the abandonment and intensification of grazing represent challenges for Mediterranean ecosystems [12], Samothrace is clearly affected by the latter. This, in combination with a social and economic crisis indicated by the low average income of small ruminant farmers (Figure 8) and confirmed in qualitative interviews, threatens the very basis of farming on the island.

Biel and Tan [15] reported, in their extensive survey about the flora of Samothrace, that intense grazing and repeated “slash-and-burn” practices for obtaining pastureland, contributed to fundamental ecosystem changes and threats. A study conducted on the mountainous oak forests in 2017 assessed a sample of 940 trees and found no tree with a younger cambial age than 47 years. The authors concluded that 86% of the island’s forests are currently threatened by overgrazing and have *high regeneration priority* [37]. An analysis of the Normalized Difference Vegetation Index (NDVI) based on satellite images from 1984 to 2015 revealed a 40% reduction of large parts of Samothrace’s land cover up until 2002, and only a partial recovery in the decade after [26,27]. This development perfectly matches the increase of the small ruminant population prior to 2002 (Figure 4). The reconstruction of the annual

herd dynamic and metabolic requirements of all sheep and goats, allows for a reconstruction of the feed demand from 1993 to 2016. From 1993 to 2005, the supplemented feed only represented 10% of the total feed demand, increasing to 20% thereafter (Figure 5). Samothrace, therefore, represents a rather untypical Greek island, as grazing on Greek islands was usually reported to cover below 30% of nutritional needs of small ruminants [8]. Grazing demand surpassed the upper boundary of the estimated NPP between 1995 and 2005, and the lower boundary from the 1980s until today (Figure 6). Thus, the small ruminant population seems to have over-utilized grazing resources for at least a decade, or otherwise, animals were severely undernourished. In reality, it was most likely a combination of both. A reduction of animal numbers is inevitable if local ecosystems are to fully recover. The degradation of pastures is also the most plausible reason for the decline of the small ruminant population after 2002. The reproduction rate of small ruminants was stable at 0.87 from 1993 to 2006 and showed a decline to 0.5 in 2016 (for a more detailed analysis see [24]). Goats were more affected by the population decline between 2002 and 2010 (50%) than sheep (24%). As farmers cannot manage the reproduction of the mostly free roaming goat herds, inadequate feed supply is likely to have played an important role in their declining reproduction rate. This hypothesis is supported by local farmers (Supplementary Information: Section 3) and the fact that farmers started providing more feed only in the years following 2005, when animal numbers were already declining (Figure 5).

The social and economic crisis of the system is reflected in multiple aspects. Of the 23 farmers interviewed for the farm economy survey, 22 have said that they see no future in farming on Samothrace and they advise their children to leave the island. The main reasons given were the increase in prices for feed, high taxes, reduction of subsidies and the declining market prices for products (Supplementary Information: Section 3). For farmers in the north-east of the island, the only local dairy is too far away, so they produce only small quantities of dairy products for their own consumption or, in some cases, their restaurants. Milking is largely done by hand and as prices are so low, it is not profitable for most farmers (Expert Interview 4, 6). The dairy can only process milk between April and July/August and 80% of their production is exported. According to the owner, in recent years they have needed to shut down the production in the middle of July as they cannot sustain their business over the summer (Expert interview 7). In Mediterranean regions, many dairies stop taking milk during summer, as during the later stage of lactation, the coagulating properties of milk deteriorate, which has negative effects on yogurt and cheese production [7]. Many of the farmers interviewed claimed that the low capacity of the dairy is the main reason why they cannot generate any income from milk. Lambs are mainly slaughtered around Easter and kids in the middle of August. Animals are often exported alive as they are purchased by external traders who take care of the transport and the slaughtering. If slaughtered locally, it can legally only be done in the slaughtering house. For many farmers, use of the slaughtering house is inconvenient and too expensive, so they slaughter by themselves and distribute the meat informally or may sell it in their own restaurants. The selling price per kilo is usually lower if the animals are sold alive for export (Expert interview 1, 3, 4, 11). These difficulties are reflected in the current financial situation of local small ruminant farmers (Figure 8). Almost half of their revenue is generated through subsidies, and main expenses are for transport and animal feed. This leaves the average small ruminant farmer with about 5000 € income per year, too little to sustain their business and family.

While the 1990s were, in general, beneficial for small ruminant farming in Greece, as milk prices were high, pastures were lush and farmers received good subsidies, the situation on Samothrace gradually became worse in the last two decades. After 2000, the milk prices started falling and feed prices increased [8]. In the last five years, meat prices on Samothrace have dropped by 40% as traders agreed on a price among themselves before negotiating with individual farmers. Traders benefit from the lack of farming cooperatives on the island that would allow a joint price policy on the part of the farmers (Expert interview 1, 3, 4, 11). The partially coupled subsidy payments, or as stated by local experts, at least the perception that there is a strong correlation, continuously prevent farmers from minimizing their herds (Expert interview 11; Supplementary Information: Section 3). Farmers

increased their feed imports slightly after 2005. However, this had more effect on their financial expenses than on the relief of local pastures. The island is disadvantaged in free market competition as transport costs are high, processing facilities are lacking, and the market is flooded with cheap products, mainly from New Zealand and Australia (Expert interview 7, 12). As stated by most interviewed farmers and local experts, without additional income it is not possible to live from small ruminant production on Samothrace today (Expert interview 1, 2, 3, 4, 6, 11).

4.2. The Regression of Sedentary Extensive Small Ruminant Farming Systems

Sedentary extensive small ruminant farming systems (SRFSs) have been regressing at a fast pace over the last decades throughout the Mediterranean [9]. The present case study describes this process on a local island level, contributing to a better understanding of the effects of industrialization on agriculturally-shaped, remote regions within the EU.

Samothrace's socio-metabolic profile was, up until the 1960s, in most aspects, pre-industrial. The first diesel engines for electricity production were installed around 1960, as were the first paved roads, and a port that allowed for larger ships to dock [38]. Samothrace lost 40% of its population between 1951 and 1981 [23], due to a combination of push and pull factors regarding employment opportunities abroad and the fundamental changes affecting the agricultural system of the island. The transformation of local agriculture becomes evident in the changing composition of livestock species shown in ure 4. In 1929, the livestock system had only 2000 livestock units [LSU], was relatively diverse and dominated by Equidae (horses, mules and donkeys). The growth to almost 8000 [LSU] in 2002 occurred almost exclusively in the small ruminant population. While the number of animals has been reduced since then to approximately 5000 [LSU], the livestock system today is still dominated by sheep and goats. The reduction of Equidae and cows documents clearly the loss of one of the central features of livestock in pre-industrial land-use systems, their use as draft animals [39]. Expert interviews confirm the shift in the local livestock system. Up until the 1960s, sheep and goat herders had a special position on the island. People who produced meat and had meat in abundance were considered rich by the community. Back then, nobody possessed more than 100 animals and everything from the animals like meat, milk, wool and skins, was processed and used. Herds of goats grazed in the mountains in the summer and were chased down to the lowlands in winter and for slaughtering (Expert interview 3, 4, 10). With the provision of supplementary feed starting in the 1960s, initially only locally produced, later also imported, the relationship between the herders and the animals changed. While in former times herders chased their animals, following them on foot even over mountainous terrain, animals today come close to the numerous newly built mountain roads when they hear the sound of the farmer's car (Expert interview 4, 10). This reduces the labor efforts of herders but increases their transport costs substantially (Figure 8; Expert interview 6). In the past, animal numbers were kept below the carrying capacity of the island's ecosystems, as there were no feed imports. The introduction of cars, fossil fuels and supplementary feed lowered the labor input but increased monetary costs, and in combination with agricultural subsidies, enabled an increase in animal numbers. Apart from these aspects, the SRFS on Samothrace today is still determined by fairly high labor input, low access to markets, lack of cooperatives and a low level of technological advances. Technological innovation played, therefore, only a minor role in the onset of the transformation of the local livestock system, leaving structural changes in land management and regional markets as more important factors [40].

Despite the lack of statistical data on land use before 1993, the results of the present study clearly indicate that the land use system of Samothrace must have experienced a similar shift, as described by Kizos et al., for the island of Lesbos. In their case study, the authors showed how since the 1960s "complex and multifunctional agrosilvopastoral land use systems were simplified to a pure livestock raising system" [3]. As evident from statistical data and confirmed by local experts, Samothrace's crop production is almost exclusively used for livestock feed today, while this was not the case prior to 1960. The Treaty of Lausanne in 1923 set the beginning of structural land use changes which shaped Greece in the 20th century. Due to population increase and compulsory expropriations, grazing areas were

transformed into cultivated land and animals were increasingly kept in enclosures and supplemented with harvested feed [10]. This marked the end of traditional nomadic small ruminant herding in many regions in Greece. At the beginning of the 1930s, agriculture on Samothrace was characterized by small intensive farm holdings in combination with transhumant practices in small ruminant farming. In the decades following 1945, most traditional transhumant or small intensive systems in Greece were then transformed into sedentary extensive systems, in which farmers have only a few ha of land, use communal grazing lands and need to buy supplementary feed [9]. This transition is a good example for the whole of Mediterranean Europe [41], and marked the end of subsistence-based forms of peasantry, also on Samothrace. These changes are reflected in the decline of people employed in the primary sector and the disintegration of half of the island's traditional farm houses between 1971 and 2016 [38]. The allocation of fundamental land use rights to single farmers and the transfer of grazing rights for communal land to the municipal level, changed the situation in the country fundamentally and are of high relevance with regard to current EU CAP (Common Agricultural Policy) regulations.

4.3. The European Common Agricultural Policy (CAP) as a Socio-Economic Driver for Changes Affecting the Small Ruminant Farming System on Samothrace

Subsidy payments, initially by the Greek state and later by EU CAP, represent an important socio-economic driver for changes in local agriculture. This is reflected in the high contribution (50%) of subsidies to local livestock farmers' income (Figure 8). This does not reflect the general situation in Greece, where subsidies usually comprise only a small fraction of farmers' income [42]. Local farmers and agricultural administrators benefitted from sheep and goat farming through specifically-targeted subsidy schemes. More recently, the implementation of the "headage payment" in the early 1990s enabled farmers to increase the size of their herds substantially (Figure 4). One effect of the subsidy payments was that farmers neglected the need for a functioning farming business model. The regular payments simply covered their losses and created a situation in which subsidies became a substantial source of income. Farmers were never educated on how to use these payments in order to create a sustainable business strategy (Expert interview 10, 11). The main achievement of the 2003 reform was the implementation of decoupling of direct payments to farmers from their production numbers in order to reduce farmers' dependence on subsidies and produce according to market demand [43]. This is a process that is still ongoing. This policy was, however, much more directed towards stopping abandonment, as farmers were encouraged to maintain their grazing levels with a cross-compliance maximum of 1.4 heads/ha for degraded semi-mountainous or mountainous pastures, or continue to breed at least 50% of their herds if they graze on communal land [10].

During this reform, it was also made clear by some EU member states that full decoupling could lead to "several risks such as the abandonment of production, the lack of raw material supply for processing industries, or to social and environmental problems in areas with few economic alternatives" [44]. As the sheep and goat sector was considered as one of the sensitive sectors within the EU, member states could continue to couple 50% of payments in this sector [45]. Greece decided to implement this policy in the course of the "health check" of the 2003 reform [46]. The 2013 reform was used to partially reverse the decoupling process that started in 2003, by giving member states the opportunity to "provide coupled support to a wide range of sectors, covering virtually all agricultural production" [47]. Greece further implemented a scheme after the 2013 reform that was created to enable member states to "split the country into several regions in which the reform implementation can differ" [48]. As reported by the interviewed experts, the cross-compliance maximum was circumvented. This was done firstly by farmers declaring communal grazing land multiple times, and later, when this was discovered in 2015, by the regional agricultural administration by simply allocating grazing land on the mainland to local farmers (Expert interview 5, 10, 11). For a region like Samothrace, it is indispensable that the coupling of animal numbers and subsidies can only continue if environmental standards are implemented and enforced. Political clientelism, and stabilizing large livestock numbers, must be overcome. The perception that subsidies directly depend on animal numbers is shared among

many farmers and must change. Indeed, farmers who apply environmentally friendly management practices should receive much stronger economic support. The new European CAP regulations, currently under negotiations, should respond to these environmentally and socially threatening discrepancies between European regulations and their local interpretations and implementations.

4.4. *The Future of Small Ruminant Farming in the Mediterranean*

Sedentary extensive small ruminant farming systems (SRFSs) in the Mediterranean could represent an environmentally sustainable form of livestock production. Due to their resistance to climate extremes, they could also play an important role in the future regarding climate change adaptation [7]. The precondition for this is that the animals feed mainly on biomass not suitable for human consumption, and that the population density is kept so low that ecosystems are not degraded. This, however, would imply that these systems become largely independent from external feed supply, as industrialized feed production connects them with the industrial grain-oilseed-livestock complex [49]. Under these conditions, sedentary extensive SRFSs would contribute to biodiversity and landscape level conservation, minimize environmental hazards, increase the resilience of mixed farming systems, sustain high genetic diversity of small ruminants, and produce high quality products with relatively low monetary and biophysical inputs [50]. Thus, strategies for sustainable development must focus more on the provision of social and economic long-term perspectives for sedentary extensive SRFSs in remote regions.

Currently, there are 23,000 sheep and 24,000 goats on Samothrace, translating into 4700 livestock units (Figure 4). Fetzl et al. [24] defined three major land-cover types suitable for grazing: arable land (32.2 km²), natural forests (7.9 km²) and principally agricultural land with significant natural vegetation, natural grasslands and shrublands (134.6 km²). The cross-compliance maximum of 1.4 heads/ha, implemented by the EU CAP in 2003, would therefore translate into 23,500 animals or a 50% reduction of current animal numbers, if grazing would be abandoned from forests. Defining sustainable numbers of grazing animals for different land-cover classes poses a scientific challenge that cannot be easily overcome. Our data does not allow for a precise definition of a sustainable number of livestock. Spatial and temporal flock distribution, additional feeding, other management practices and natural factors are also highly relevant for sustainable development of grazing-based farming systems. A successful strategy must, therefore, focus on the improvement of sustainable economic, land and livestock management practices in order to relieve pastures and enable farmers to gain sufficient income. Continuous under-utilization of animals (Figure 7) would allow for some increase in production output per animal, without aiming for an intensification equivalent to industrialized systems. At the same time, if the demographic trend continues, the number of people employed in the primary sector will further decline over the next decades. In this context, it is of great importance that retired farmers eventually also lose their grazing rights and give up their herds. These factors could result in a decline of the total number of animals, while young farmers could keep their animals and moderately increase their production output per animal. Although, they will still face problems due to difficult market conditions for agricultural products regarding prices and legal regulation for on-farm sales. These difficulties can only be overcome with a higher level of cooperation. The current lack of cooperation is rooted in the historical background of farmers' cooperatives in Greece. In the 1980s and 1990s, cooperatives often became political battlegrounds as they were managed by political representatives or people closely affiliated with political parties who often used these cooperatives for their personal benefit [51]. The experience of most local farmers with these forms of cooperatives was so bad that it shapes cooperation among farmers and their trust of people in general until today (Expert interview 1). It will be a long-term and maybe tiring process but there is no alternative to overcoming doubts and mistrust and finding new ways for a closer collaboration among local farmers. This could eventually lead to a local farmers' cooperative engaging in designing a local brand that stands for high quality and maybe even organic production, which, in turn, can have great advantages for less favored regions in the Mediterranean [52]. In this way, much better prices for their products on

regional markets and beyond could be achieved. A cooperative would enable local farmers to, for instance, invest in a mobile alternative to the slaughtering house and in a mobile milking unit, and install cooling facilities for milk collection and storage in regions too far away from a dairy. Currently, first attempts at a new form of cooperation are in progress and it seems like a new momentum for change has been created.

5. Conclusions

This study shows vividly that the effects of industrialization and national or EU agricultural policies on remote regions require special attention. The socio-ecological transformation of recent decades pushed the island community into a dilemma between economic development and preservation needs. Agriculture plays a key role in this process, as the increase of the small ruminant population triggered environmental and social problems which pose threats to the entire island community. The reasons for this development are manifold but are strongly associated with structural land use changes, global industrialization of agriculture and the agricultural market and finally, the regional implementation of the EU Common Agricultural Policy (CAP). To enable a recovery of the local ecosystems, animal numbers must decline substantially. Local socio-economic contexts must be much better taken into account for a new CAP legislation after 2020. Direct payments should reach those who implement measures for sustainable livestock production. The flexibility on a national or regional level should be adapted in a way that a situation, such as that reported in the present study, can be prevented.

Herrero et al. point out that many ideas look great on paper but are only implemented by 10–20% of farmers, for a wide range of reasons. The authors further state that the understanding of environmental implications of livestock systems and factors that need to change has progressed substantially, while little is known of how to practically implement these changes [2]. Transdisciplinary science can play a crucial role in facilitating this process on a local level, by engaging farmers in the scientific process and fostering collaboration among and between farmers and experts from various fields. The long-term research project to which this study contributes, combines analytical and management approaches towards sustainability transitions [53]. Since 2008, researchers have been engaged in a process that tries to achieve scientific progress with a practical outcome. It started with focus group interviews with farmers, which led to a study about the local farming system [54]. Results were used to develop a decision support app (www.happygoats.eu) that was further used to approach local small ruminant farmers. In collaboration with *Terraprima* (www.terraprima.pt), sown biodiverse pastures (SBPs) were applied on 13 plots (SBPs were developed by the Portuguese university spin off *Terraprima* and are based on sowing up to 20 species/varieties of legumes and grasses that are self-maintained for at least 10 years. The legumes, being ‘natural factories’ of nitrogen, minimize the need for synthetic fertilizers. SBP result in, on average 30%, higher biomass production and higher grazing resistance). A growing number of farmers have become interested in the research project, which will hopefully yield stronger collaboration among farmers and between farmers and researchers in the near future. The response of socio-ecological systems to science interventions only becomes visible after long time intervals. Thus, a systematic evaluation of the impact on the local small ruminant farming system is only possible after a certain period and marks an important next step in this project.

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