Agricultural Systems 218 (2024) 103992

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Changing pasture management practices on the Greek island of Samothraki: Obstacles and opportunities

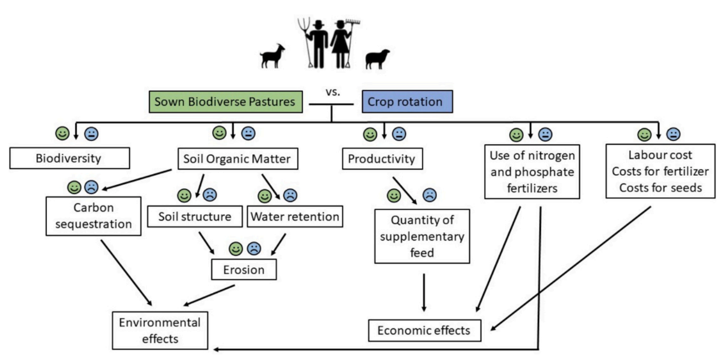
Marjan Jongen [a,*], Dominik Noll [b], Giorgos Maskalidis [c], Tiago Domingos [a,d], Marina Fischer-Kowalski [e]

[a] MARETEC - Marine, Environment and Technology Centre, LARSyS, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal
[b] Mediterranean Institute for Agriculture, Environment and Development (MED) & Global Change and Sustainability Institute (CHANGE), University of Évora, Pólo da Mitra, Ap. 94, 7006-554 Évora, Portugal
[c] Sustainable Samothraki Association, Samothraki, Greece
[d] Terraprima, Quinta da França, 6250-111 Caria BMT, Portugal
[e] Institute of Social Ecology (SEC), University of Natural Resources and Life Sciences, Vienna, Austria

HIGHLIGHTS

- Decades of overgrazing have accelerated soil erosion and ecosystem degradation on the Greek island of Samothraki.
- Sown legume-rich pastures were introduced to Samothraki, to achieve more sustainable pasture management practices.
- Productivity in the sown legume-rich pastures outperformed yield in the conventional agricultural practices.
- Successful adoption of new management practices requires close collaboration with local stakeholders.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Paul Crosson

Keywords:
Sustainable pasture management
Changing agricultural practices
Sown biodiverse pastures
Productivity
Small ruminants
Island sustainability

ABSTRACT

Context: On the Greek island of Samothraki, decades of overgrazing by the large domestic population of small ruminants accelerated soil degradation and surface erosion, with direct consequences for ecosystem functioning and the delivery of ecosystem services.
Objective: This manuscript reports on a 5-year research project to achieve more sustainable pasture management practices among small ruminant farmers on the island, through the introduction of Sown Biodiverse Pastures (SBP). This practice, based on sowing a seed mixture of legumes and grasses that increase pasture productivity, has proven to be a successful tool to overcome degradation of ruminant pastures in Portugal.
Methods: Local small ruminant farmers on Samothraki, a difficult group when it comes to the acceptance of new practices and ideas, were engaged in the transdisciplinary research process, and trained in appropriate management practices of SBP. This led to the adoption and implementation of SBP by nine farmers on 13 parcels.
Results and conclusions: Quantitative data on species composition and productivity shows that the performance and persistence of SBP on Samothraki is favourable, if soil preparation and sowing is practiced as recommended,

* Corresponding author.
E-mail address: marjan.jongen@tecnico.ulisboa.pt (M. Jongen).

https://doi.org/10.1016/j.agsy.2024.103992
Received 30 October 2023; Received in revised form 15 March 2024; Accepted 6 May 2024
Available online 10 May 2024

and relevant management practices are adopted. Comparing with conventional agricultural practices, i.e. annual crop – fallow rotation, productivity in SBP outperformed the forage quantity in fallow land, while yield in the annual crop was approximately equal as compared to SBP. The increasing forage capacity of SBP instigates several environmental and economic benefits, such as a reduction of grazing pressure in vulnerable areas, and less expenditure on supplementary feed requirements. However, lack of will and trust in these new practices and seed mixtures among local farmers resulted in discontinuation in almost half of the parcels. The adoption of new management practices by the farming community on Samothraki required continuous efforts, and the short-term framework of the research project did not favour long-term success.

Significance: It is recommended for any programs aiming at changing farming practices to engage with local stakeholders, especially farmers, and to closely collaborate with local institutional partners who can carry the work forward after scientific researchers have left.

1. Introduction

Extensive pasture-based livestock herding is of great socioeconomic and ecological importance in the Mediterranean region. Within the European Union, these systems represent the highest proportions of agricultural land in Greece (53%), Portugal (37%) and Spain (34%) (Bernués et al., 2011). As the specific environmental conditions and local traditions only allow for limited intensive and specialized farming in these regions, ruminant herding, often in combination with various forestry practices (silvopastoral farming), still prevails (Rigueiro-Rodríguez et al., 2009). These characteristic landscapes, dominated by heterogeneous plant communities of forests, shrubs and grasslands, have undergone a long co-evolutionary process which generated diverse and resilient ecosystems with high utility to society (Kizos et al., 2013). These systems have recently been affected by the two contrary processes of land abandonment or intensification through an increase of grazing animals (Jiménez-Olivencia et al., 2021; Pereira et al., 2006). Both trends in most cases lead to pasture degradation, as abandonment potentially fosters shrub encroachment and an increase in fire risk, while intensification results in environmental degradation through overgrazing and soil erosion (e.g. Caraveli, 2000; Quaranta et al., 2020). The underlying drivers for both trends are socio-environmental and require a wider knowledge of potential management adaptations and their consequences for land systems and farmers. Ways to increase the productivity of grazing areas while at the same time ensuring their long-term resilience would thus help to mitigate both socioeconomic and ecological pressures. Sown Biodiverse Permanent Pastures Rich in Legumes (SBPPRL), or in short SBP (Sown Biodiverse Pastures) hold the potential to achieve these goals. The present article presents ecological results and socioeconomic insights from a 5-year research process aimed at counteracting overgrazing and soil erosion on a Greek island through the promotion of and training in the use of SBP on overgrazed areas.

SBP were developed in Portugal during the last fifty years as a strategy to increase grassland productivity and combat soil erosion and land abandonment (AFJ, 2010). SBP are a system of engineered pastures using biodiversity to enhance pasture productivity (Teixeira et al., 2015). This practice involves the introduction of up to 20 self-reseeding species/cultivars of highly productive legumes and grasses originating either from Portugal or the wider Mediterranean region, with the aim of establishing a functioning ecosystem with complementary ecological niches (Teixeira et al., 2015). SBP are 'permanent' pastures, characterized by having a long lifespan. Once sown, with proper management, these pastures can be maintained for ~10 years. The diversity of plants and the balance between grasses and legumes allow a higher resistance to local and climate variability, and the selection of highly productive cultivars ensures a higher productivity as compared to natural or semi-natural pastures. To date, studies have shown a 32–147% increase in productivity in SBP, as compared to semi-natural pastures (Almeida et al., 2017; Barradas et al., 2006; Carneiro et al., 2008; Hernández-Esteban et al., 2019a; Teixeira, 2010), thereby significantly increasing sustainable stocking rates and providing animals with forage of higher nutritional value and digestibility. An additional benefit from this practice is increased soil organic matter, which translates into carbon storage and consequent sequestration from the atmosphere (Teixeira et al., 2011), and the carbon sequestration capacity of SBP is estimated at 6.5 t CO_2 ha^{-1} yr^{-1} (Teixeira, 2010). As the SBP system is self-sufficient in nitrogen, with the legumes and associated *Rhizobium* fixing atmospheric nitrogen, the need for synthetic nitrogen fertilizers is eliminated. However, SBP may require an external input of phosphorus and a correction of soil acidity, i.e. liming, for optimal legume growth. Regarding biodiversity, little information is available on the implications of the sowing practice. Comparing semi-natural pastures with SBP, Hernández-Esteban et al. (2019b) concludes that plant diversity is not compromised by the implementation of SBP, i.e. no significant differences were observed between species richness in sown versus control plots. However, if the alternative practice to SBP would be a cereal crop, plant diversity in SBP would undoubtedly be higher as the biodiversity in these crops is known to be extremely low (Andrén and Kätterer, 2008).

In Portugal, SBP have increasingly gained popularity, currently occupying an area of ~150,000 ha, which is more than 4% of the agricultural land (INE, I.P, 2016). From 2009 to 2014, the installation and maintenance of SBP in Portugal was supported by a governmental fund, the Portuguese Carbon Fund (PCF). This project was managed by Terraprima (www.terraprima.pt), a spin-off of Instituto Superior Técnico from the University of Lisbon, and it led to new developments in terms of cost-effective approaches to pasture management (Ravaioli et al., 2023). The positive experience with SBP in Portugal and Spain suggests that this practice has potential to be successfully implemented in other Mediterranean regions.

This manuscript reports on ecological feasibility as well as socioeconomic opportunities and challenges encountered during a 5-year pilot project, which aimed to change agricultural practices on the Greek island of Samothraki through implementation of SBP. This pilot project has been part of a long-term transdisciplinary research process on Samothraki, which was initiated in 2008. The goal was to foster sustainable socioeconomic development and to preserve the unique natural and cultural heritage of the island, with the scientists gradually transferring ownership of this vision to local stakeholders (Fischer-Kowalski et al., 2020; Noll et al., 2024). One of the main problems identified by the researchers was overgrazing, due to the large number of free-roaming goats, which had led to severe soil erosion and dying-out of the pristine mountain forests (Fetzel et al., 2018; Noll et al., 2020). The pilot project started in 2015, in collaboration with local farmers and Terraprima, a company having vast experience in the implementation of integrated systems for environmental services provided through best pasture management practices. The present article aims at answering the question whether seed mixtures such as SBP, that increase the resilience of grazing land and at the same time help farmers to sustain their business, can uphold their promises in different socioeconomic contexts. It further advances knowledge about the factors that promote or hinder the adaptation of farm management practices for achieving these goals. Section 2 introduces the island of Samothraki, followed by an outline of the methodological approach in section 3. Section 4 (results) exclusively focusses on the ecological feasibility of implementing SBP on Samothraki, and section 5 (discussion) reflects on the socioeconomic context, and highlights opportunities and challenges for the implementation of SBP on Samothraki.

2. Overgrazing on the island of Samothraki

Samothraki is an example of a 'marginal' mountainous Mediterranean island, located 42 km off the northern Greek coast in the Aegean Sea, covering 178 km^2. The climate is transitional Mediterranean. For the period of 2009–2018 average temperature was 17.3 °C, with daily averages ranging from 8.2 °C in January to 27.6 °C in August (http://meteosearch.meteo.gr/). Average annual precipitation was 681 mm, with 81% of the precipitation being confined to the period of September to March. The interior of the island is almost entirely occupied by the mountain range Saos, with its highest peak reaching 1611 m above sea level, and the presence of this mountain causes a drastic north-south gradient in precipitation.

The island has a population of 2596 (ELSTAT, 2021). The majority of the economically active population was until recently employed in the primary sector, mainly practising sheep and goat farming and olive cultivation. Between 2001 and 2011, the number of farmers decreased from more than 400 to 200. However, the transparency database for agricultural subsidies still registers more than 500 recipients in Samothraki in 2015, this discrepancy due to the fact that agriculture is often not the sole profession (https://transpay.opekepe.gr/).

CORINE land cover data (EEA, 2018) for Samothraki lists 14 land cover classes (Fig. 1). Agricultural land accounts for 22.2% of land cover, and includes non-irrigated arable lands, land principally used for agriculture (i.e. cropland or pastures interspersed with natural vegetation), complex cultivation patterns and olive groves. The agricultural land is mostly located in the south-western part of the island. Sclerophyllous vegetation (i.e. Mediterranean shrubland, with maquis, garigue and phrygana) and natural grasslands cover 29% of the island. Forests comprise 9.3% of the island's area. Samothraki's mountainous interior has sparse or nearly no vegetation, representing 37.8% of the island.

Samothraki is known for its relatively undisturbed nature (Skoulikidis et al., 2014) but the island's ecosystems are under pressure, primarily as a result of overgrazing (e.g. Biel and Tan, 2014; Fetzel et al., 2018). Up until 2002, supported by the agricultural policies of the EU, there had been a steep increase in the number of small ruminants (sheep and goats) on the island (Fig. 2), which graze unrestrictedly on all land types all year round (Fetzel et al., 2018). Ruminant numbers peaked in

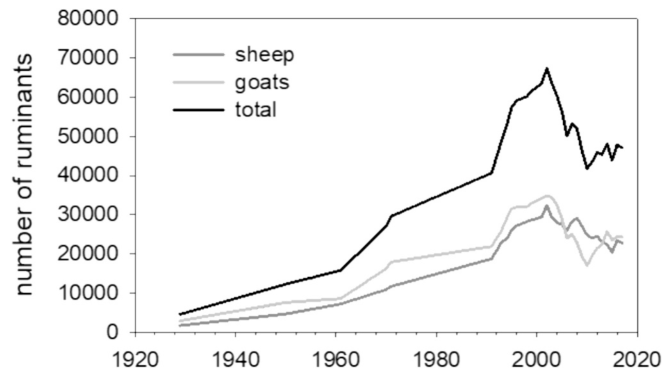


Fig. 2. Number of small ruminants on Samothraki from 1929 to 2016.

2002 at approx. 70,000 individuals. Although numbers subsequently declined, with current estimates giving approx. 50,000 individuals, this still exceeds the island's carrying capacity (Noll et al., 2020). Overgrazing, coupled with the steep topography, has led to dramatic levels of soil degradation and erosion. Indeed, analysis combining remote sensing and ground truthing detected areas with significant vegetation degradation over the last three decades (Fischer-Kowalski et al., 2020). This erosion not only poses a major threat to the island's ecosystem and conservation efforts but has also resulted in severe floods with considerable damage to local infrastructure (Noll et al., 2019). Model estimations of erosion vulnerability, incorporating different grazing management scenarios, indicated that combining decreasing stocking rates with a reduced grazing period was favourable from an environmental and socioeconomic point of view (Panagopoulos et al., 2019), and this highlights the urgency to change agricultural management practices for erosion abatement actions. The present study reports on an example of these actions, aiming to change agricultural practices on Samothraki by introducing legume-rich seed mixtures that improve soil quality and pasture productivity.

3. Material and methods

The methodological approach consisted of the implementation of an experiment with SBP on the island of Samothraki and its evaluation in a three-stage process. Section 3.1 describes the main aspects of the

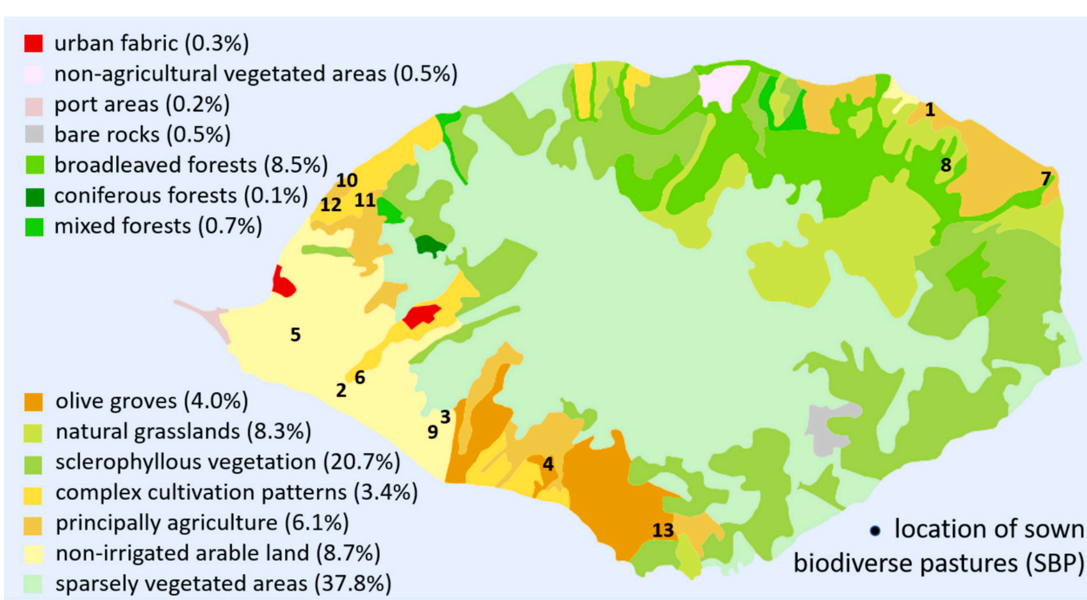


Fig. 1. Land cover map for Samothraki based on CORINE land cover data (EEA, 2018).

initiation of the SBP project on Samothraki, from the selection of participating farmers to their training. Section 3.2 provides details about the preparation of the parcels and application of SBP. Section 3.3 describes the methodologies applied for an evaluation of the environmental and social parameters for the application of SBP on Samothraki. In order to evaluate the farmers' reasons for maintaining or discontinuing the SBP, six expert interviews with participating farmers were conducted. Results of these interviews are integrated in the discussion in section 5.3.

3.1. Selection of farmers for the experiment

Farmers' participation and direct farmers' engagement was fundamental and crucial for successful implementation of SBP. A resident of Samothraki, a forester by education, was enlisted to recruit farmers on the island that showed interest in the project. This resident was also actively involved in 'Sustainable Samothraki', an association of local residents addressing the current socioeconomic and environmental problems on the island (Noll et al., 2024). Initially, in 2015, three farmers expressed interest. In October 2015 a technical consultant of Terraprima visited Samothraki, to provide technical recommendations and knowledge transfer to stakeholders regarding the SBP practice. In the following years, this practice was adopted by nine farmers on 13 parcels.

3.2. Soil sampling and selection of seed mixtures

In the selected parcels, soil sampling took place to determine soil texture and pH. Three tailored seed mixtures were used, for acidic, alkaline or neutral soils. Seed mixtures, provided by Fertiprado (Vaiamonte, Portugal), contained different proportions of the legumes *Trifolium subterraneum* (several varieties, differing in hardseededness, pH adaptability, maturity and resistance to grazing), *Trifolium vesiculosum*, *Trifolium resupinatum*, *Trifolium incarnatum*, *Trifolium isthmocarpum*, *Trifolium michelianum*, *Medicago truncatula, Ornithopus sativus*, *Onobrychis viciifolia* and *Hedysarum coronarium*, and the grasses *Lolium multiflorum* and *Dactylis glomerata*. The two most prominent species in the seed mixture are *Trifolium subterraneum* and *Lolium multiflorum*, constituting about 60% of the seed weight. The majority of the species in the seed mixtures are autochthonous species, and all species are native to the Mediterranean basin. Some of the species are exotic to Samothraki, i.e. *Trifolium incarnatum*, *Trifolium isthmocarpum*, *Ornithopus sativus*, *Onobrychis viciifolia* and *Hedysarum coronarium* (based on Biel and Tan, 2014; Dimopoulos et al., 2013).

3.3. Assessment of the success of the implementation of SBP on Samothraki

Two different approaches were used to evaluate the implementation of SBP on the island of Samothraki. First, the success of the established SBP was assessed directly, using collected field data on species composition and productivity, and if appropriate, comparing the data from SBP with relevant control plots (CP). Second, interviews were conducted with farmers who implemented SBP on their farm to determine their impressions and opinions.

3.3.1. Assessment of ecological parameters

In June 2016, May 2017, May 2018 and June 2019, quantitative data relating to species composition and productivity in the existing SBP was collected in each parcel. Species composition was determined by means of individual species observations along 200–400 m line transects, using the step-point method (at intervals of 1 m), giving data on relative abundance and cover for each species, enabling calculation of diversity indices (Shannon index, Simpson index, Evenness). Aboveground productivity and standing biomass were determined by harvesting all plant material in four 30 × 30 cm or 40 × 40 cm quadrats. Harvested plant material was sorted into three functional groups (grasses, legumes, forbs) and prominent individual species. All plant material was oven-dried at 60 °C for 72 h and weighed. In November 2017, three or four exclosure cages (1 × 1 m) were installed in parcels 3, 4, 7 and 8, to exclude the presence of livestock. Within each of the cages, all plant material in two 30 × 30 cm quadrats was harvested, sorted and subsequently oven-dried.

Thus, even in parcels subjected to grazing, quadrat cuttings from inside the cages enabled calculation of aboveground productivity. In addition, quadrat cuttings were made outside the cages, to estimate forage intake through grazing.

However, not all of the activities outlined above could be performed in all existing SBP. In several cases the parcel had been heavily grazed, or the vegetation was in an advanced senescent state, making accurate pinpoint analysis impossible. In addition, productivity assessment was not possible in those parcels that had undergone intensive grazing (unless, of course, exclosure cages were present). In addition to the quantitative data collected in SBP, measurements for productivity were done in several control plots by harvesting all plant material in four 30 × 30 cm or 40 × 40 cm quadrats. Control plots consisted of parcels in the vicinity of SBP, and they were either annual crops or fallow land.

3.3.2. Assessment of social parameters

Qualitative semi-structured expert interviews were conducted (Appendix A1) with six participating farmers, asking them about personal experiences and perceptions, with some quantitative questions for generating background information. The survey contained 10 questions that were adjusted and/or extended depending on the answers and on the level of the farmers' involvement in the program. Data evaluation was conducted by assigning the answers to one of four categories (level of satisfaction, obstacles, opportunities and recommendations), which allowed deductions regarding the farmers' perceptions of the SBP program (Table A2). Results of the interviews are incorporated in the discussion but must be considered carefully as they only represent two thirds of the participating farmers. Thus, opinions about the SBP program only refer to those individual farmers with whom interviews were conducted, and only enable conclusions derived from these individual cases in the context of the long-term research process on Samothraki.

4. Results: ecological performance of SBP in the experimental parcels on Samothraki

In parcel SBP1, field data indicated successful establishment of the sown pasture, with a high productivity (6930 kg ha^{-1}) and a relative abundance of SBP species of 75.1% (Tables A3 and A4). Moreover, productivity in this parcel exceeded the productivity in the adjoining CP1 (barley crop) by 30% (Fig. 3a).

No field data is available for parcel SBP2 as the parcel was harvested by the farmer at the end of May, prior to the field data collection. Photos taken in January, March and May 2015 looked promising, and indicated excellent installation of this sown pasture.

Both parcels SBP3 and SBP4 were sown in November 2016, the latter pasture in the understorey of an olive grove. Establishment of these sown pastures was successful, as revealed by the high relative abundance for the SBP species in May 2017, i.e. 70.5 and 80.2% in SBP3 and SBP4, respectively (Table A4). Moreover, in May 2017, productivity in these pastures, being 4578 and 4719 kg ha^{-1} in SBP3 and SBP4, respectively, was equivalent or higher as compared to relevant controls (Fig. 3b and c, Table A4). Productivity in SBP3 in subsequent years was extremely high: 9147 kg ha^{-1} in May 2018 and 10,565 kg ha^{-1} in June 2019 (Fig. 3b). These productivity values are much higher as compared to the adjoining fallow land (CP3–4), but lower than those in the barley crop (CP3–3) (Table A5). In May 2018 and June 2019, productivity in SBP4 was moderate to high: 5000 kg ha^{-1} in May 2018 and 6841 kg ha^{-1} in June 2019 (Fig. 3c).

SBP5 and SBP6 did not do well (Tables A3 and A4). In SBP5, the

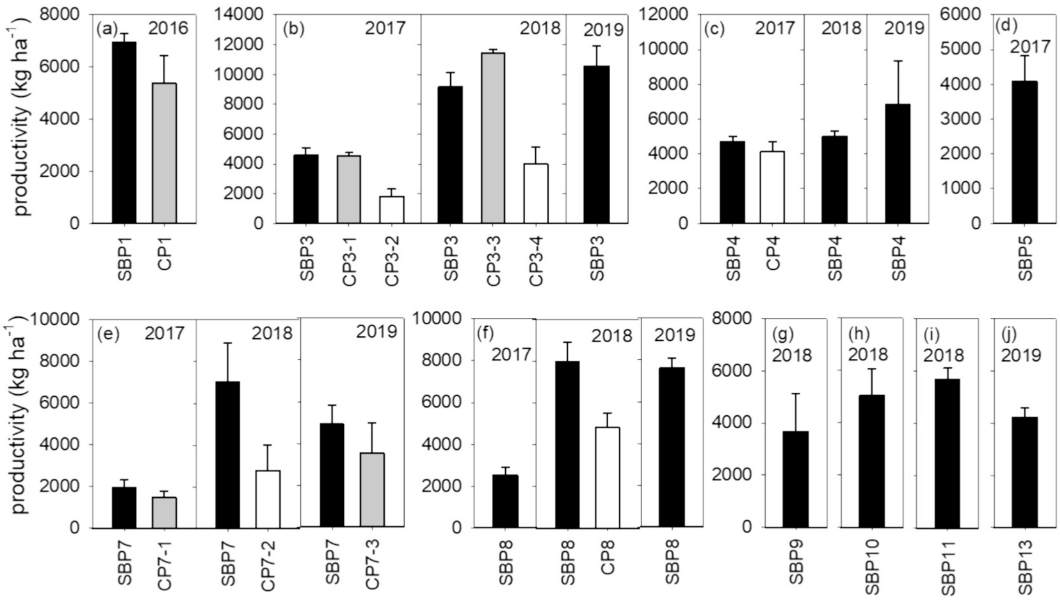


Fig. 3. Aboveground productivity (kg ha^{-1}) in SBP (■) and relevant CP (■ = barley, □ = fallow). Year of monitoring is indicated in graph. Data represent mean ± SE, n = 4–8.

species from the seed mixture only accounted for 41.7% of biomass, having a relative abundance of 29.5%. No field data is available for SBP6, as this parcel was heavily grazed in the initial months after sowing, rendering accurate monitoring impossible. In the following year, SBP practice in both these parcels was aborted and they were sown with an annual crop.

SBP7 and SBP8 are located in the north-eastern part of the island, and both these parcels were sown in March 2017. Assessment in May 2017 indicated a successful establishment of these pastures, as revealed by the high relative abundance of the SBP species, i.e. 67.6 and 83.0% in SBP7 and SBP8, respectively (Table A4). However, productivity in these pastures in May 2017 (Fig. 3e and f) was relatively low (1953 and 2510 kg ha^{-1}, in SBP7 and SBP8, respectively), probably due to the late sowing. In subsequent years productivity was very high in both parcels, always outperforming relevant controls. Unfortunately, in SBP7, the practice was discontinued, with the sowing of a barley crop in 2019.[1]

SBP9 was sown in March 2018, and assessment in June 2018 did not look promising, with the species from the seed mixture only accounting for 43.2% of biomass, and having a relative abundance of 38.9% (Tables A3 and A4). *Vicia sativa*, a legume species that is not present in the seed mixture, was the prominent species in 2018, left-over from previous management practices. Although the SBP practice was not discontinued, no quantitative data for SBP9 is available for 2019. However, visual assessment indicated high productivity, with little evidence of the presence of *Vicia sativa* while the legume species from the seed mixture were abundant. This is promising, and data collection in spring 2020 and/or 2021 would have given valuable additional information, but due to COVID19 restrictions this was not possible.

SBP10, SBP11 and SBP12 are in close proximity, and these pastures were sown late in the season i.e. in March 2018. In May 2018, the relative abundance of SBP species was low, ranging from 36.5 to 48.6% (Table A4). Nevertheless, productivity was moderate to high, i.e. 5036 and 5671 kg ha^{-1} in SBP10 and SBP11, respectively (Table A3). In 2019, practice was discontinued in SBP10 and SBP11 and these parcels were sown with a barley crop.

No quantitative data on productivity is available for SBP12. Visual assessment of this parcel in June 2019 showed a high productivity, although the high abundance of thistles was worrying. Legume abundance was high, with ample evidence of seeds and seedpods from the legume species from the seed mixture.

SBP13 was successfully established in the autumn of 2018, in the understorey of an olive grove. Productivity in June 2019 was moderate to high (4231 kg ha^{-1}), and SBP species accounted for 75.4% of biomass, and had a relative abundance of 64.3% (Tables A3 and A4). This is promising, and data collection in spring 2020 and/or 2021 would have given valuable additional information, but due to COVID19 restrictions this was not possible.

Diversity indices in SBP ranged from 2.08 to 3.34 for the Shannon index, from 5.90 to 14.86 for the Simpson index, and from 0.66 to 0.82 for Evenness (Table A4). Plant cover in SBP was high with percentage of bare soil ranging from 0 to 6.5%. No data is available on plant biodiversity and cover in the control plots. However, regarding plant biodiversity in the control plots, values are expected to be low with the majority of control plots consisting of annual crops, i.e. cereal monocultures.

5. Discussion

5.1. Ecological performance and suitability of SBP on Samothraki

Results of the evaluation of ecological parameters clearly show that SBP could present great sustainability potentials for Samothraki. Field trials indicated that if care is taken during soil preparation and sowing, and relevant management practices are adopted, the performance and persistence of these pastures is favourable. Implementation of SBP in three parcels (i.e. SBP 3, 4, 8) was highly successful. In these parcels, SBP species had a relative abundance of ~70% and SBP species accounted for ~70% of biomass. *Trifolium subterraneam*, the key species behind the rationale of SBP, thrived well in all parcels. Moreover, productivity was very high, ranging from 6841 to 10,565 kg ha^{-1} in the third year. In Portugal and Spain, forage production in SBP varies, depending on soil type, fertility and climatic factors (Almeida et al., 2017; Barradas et al., 2006; Carneiro et al., 2008; Hernández-Esteban et al., 2019a; Teixeira, 2010). For example, Morais et al. (2024) reported values between 3300

[1] This parcel was sown with barley in 2019. However, the exclosure cages and their immediate surroundings were not affected by this, and biomass sampling in SBP7 still took place in 2019. This also presented the opportunity for a direct comparison of productivity between the SBP and the control plot.

and 8500 kg ha^{-1}, with this study assessing productivity in five farms for four consecutive years. Thus, productivity in Samothraki exceeds yield in SBP in the Iberian Peninsula, probably reflecting the favourable soil characteristics on the island (Table A6), with average values for available nitrogen and phosphorus (3.9 and 98 mg kg^{-1}, respectively), and soil organic matter (1.7%) in Samothraki being higher than those found in Iberian SBP (e.g. Hernández-Esteban et al., 2019a). Especially the high values for available phosphorus are relevant for SBP efficacy. Legumes, with a mutual symbiotic relationship with *Rhizobium* bacteria in soil, can improve nitrogen fertility through biological N-fixation. But to maximize such functions, legumes need more phosphorus as it is required for energy transformation in nodules (Oliveira et al., 2002; Rotaru and Sinclair, 2009). Indeed, there is considerable evidence that nodulated legumes require more phosphorus than nonsymbiotic plants grown solely on a mineral nitrogen source (Rotaru and Sinclair, 2009; Sulieman and Schulze, 2010).

In Samothraki, the benefits from SBP are thus obvious from the increased productivity, which increases fodder quantity. However, the quality of the produced fodder is of equal importance. The nutritive value of a forage feed is a measure of proximate composition and digestibility, which are important to maintain or promote growth, milk production, pregnancy or other physiological functions in the animals. In both SBP and CP forage quality was determined, with the analysis of plant material from the control plots including the kernels of the annual crops, these parts being known to have a high nutritive value (e.g. Biel et al., 2020). Nevertheless, results indicated slightly higher values for mineral, protein or crude fibre content in SBP (9.38%, 8.53% and 28.15% respectively), as compared to CP (7.51%, 8.24% and 27.86% respectively). However, these differences were not statistically significant. Nevertheless, it can be concluded that feed value in SBP was maintained as compared to the products of conventional agricultural practices.

5.2. Environmental and economic benefits of SBP on Samothraki

Fig. 4 integrates and compares the environmental and economic effects of SBP versus crop rotation, i.e. a comparison with the conventional agricultural practices of an annual crop – fallow rotation. Productivity in SBP outperformed the forage quantity in fallow land, while crop yield (barley or oat) was approximately equal. Thus, in Samothraki, the benefits from SBP can be evaluated primarily by their increased productivity. Implementation of SBP in the south-western part of the island, dominated by agricultural land cover, did increase available fodder quantity. This would, if SBP were applied on a larger scale and provided as feed to small ruminants, allow for a reduction in grazing pressure in other parts of the island, especially areas with steep slopes, thus reducing the risk of soil erosion. Moreover, as the feed provision from grazing land in Samothraki is insufficient to cover the feed demand, the increased productivity in SBP would reduce the quantity of supplementary feed used on the island. On average, small ruminant farmers on Samothraki need to dedicate €3350 or 20% of their annual expenses to supplementary feed, which mostly needs to be imported from the mainland (Noll et al., 2020). This shows that SBP offer great potential for establishing a domestic market for animal feed that would relieve degraded pastures and at the same time relieve local small ruminant farmers from some of their financial burden. Additional substantial economic benefits can be achieved with SBP, as they are 'permanent' pastures, characterized by having a long lifespan. Once sown, with proper management, these pastures can be maintained for ~10 years. The alternative practice, i.e. annual crops, has higher costs for seeds and nitrogen fertilizer, and increased labour related to the sowing and harvesting. As the SBP system is self-sufficient in nitrogen, there is no need for nitrogen fertilization. Moreover, phosphorus fertilization, which is often required in SBP in Portugal, is not required on Samothraki, with ample phosphorus present in the soil.

Olive groves, as well as vineyards and fruit orchards on the island, can also benefit from the application of SBP. The maintenance of a herbaceous cover, provided by SBP, in the understorey of these permanent cultures is fundamental to minimize the erosion risk. This is more so, as the majority of the olive groves are located in areas with steep slopes. The increased plant cover will not only protect the soil against erosion and improve its physical and chemical properties, but it will also lead to a gradual increase in the soil organic matter. This will result in an increase in fertility, infiltration and water retention capacity. The produced plant cover should be left on the ground in order to protect the soil, not only reducing the impact of erosion (rain, wind, etc.), but also avoiding water loss through evaporation. The current agricultural practice, i.e. annual crop – fallow rotation, involves excessive soil tillage which leads to a greater risk of soil loss due to erosion.

5.3. Challenges faced for the implementation of best management practices

For the successful implementation of SBP a number of best management practices are recommended. Among these is soil preparation, which includes disking to a minimum depth of 10 cm, followed by cross disking, which breaks up clods and surface crusts, thereby improving soil granulation and surface uniformity. If necessary, soil correction and fertilization should take place, with special attention given to phosphorus, potassium, magnesium and soil pH. The best time for sowing is

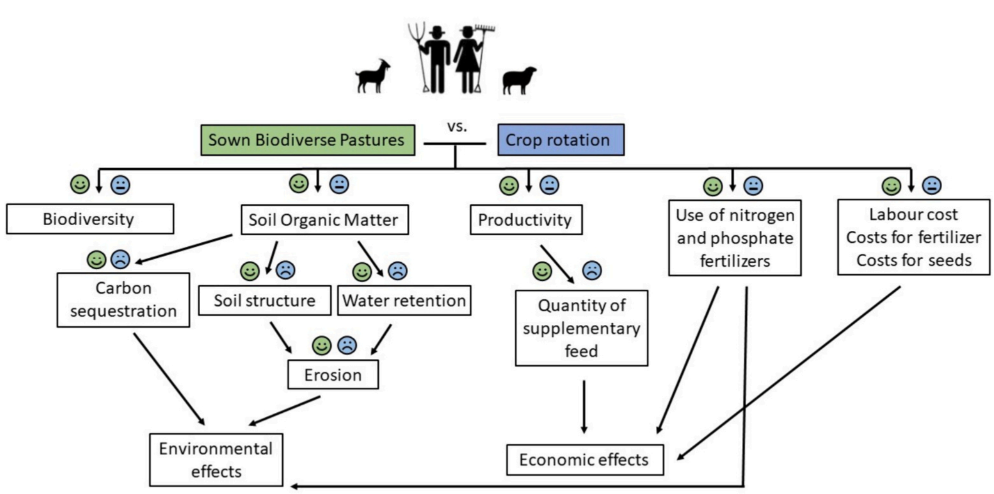


Fig. 4. Overview of environmental and economic effects of SBP versus crop rotation.

in October, using in-line sowing, or a seed launcher. Sowing should be followed by rolling to a maximum depth of 1 cm and packing with the roller, to flatten and firm the seedbed for a more uniform emergence. After the appearance of the first flowers, usually around the end of February, the pasture should not be grazed until the vegetation is senescent, for a good seed bank production. Subsequently in late spring and summer, deep grazing should take place to consume all the accumulated dry matter. After the autumn precipitation, natural generation will take its due course. In subsequent years, grazing may take place all year round. With good management practices, SBP may be effective for approx. 10 years, without any interferences or actions from the farmers, bar the occasional phosphorus fertilization in autumn, if necessary. Overgrazing is detrimental to the persistence of SBP. Moreover, grazing in the first year during seed production and dispersal interferes with adequate seed bank provisioning. The latter implies that SBP should only be established in parcels that are fenced off, to avoid grazing in specific phenological periods. With little fencing in Samothraki, this poses a limitation to the practice of SBP.

On Samothraki, SBP were discontinued within the first year of implementation in six parcels, i.e. SBP 1, 2, 5, 6, 10 and 11. The reasons for discontinuing the practice vary. In relation to SBP1 and SBP5, the farmer made a deliberate decision to cease the practice, being dissatisfied with the performance of the pasture. Indeed, SBP5 did not thrive, which may have been due to the late sowing. However, in SBP1, field data indicated successful establishment of SBP, with productivity in SBP1 being high, and exceeding the productivity in the adjoining barley crop by 30%.

Farmers' interviews highlighted that overall satisfaction with the project is mixed. Two thirds of the interviewed farmers were satisfied and one third was not satisfied at all. Farmers who claimed high dissatisfaction with the program had low productivity in their sown parcels. This low productivity was due to the fact that these farmers were not adopting the recommended management practices, especially in relation to the timing of sowing and the advised deep grazing in late spring and summer. Insufficient grazing in late spring and summer leads to an accumulation of dry matter in autumn, with this dry matter 'smothering' the seeds which subsequently hinders seed germination. Farmers who were in favour of the program mentioned the low cost, extensive labour and high productivity as the main advantages. These farmers acknowledged that under optimal weather and management conditions, SBP would be highly suitable on Samothraki. In general, farmers were positive of the SBP practice, but only if the weather conditions were favouring pasture development, and they perceived that the predominant obstacle for a successful SBP was lack of precipitation leading to low productivity. Hence, all farmers recommend irrigation for a better performance of SBP on Samothraki.

Nevertheless, while the adoption of recommended management practices is key to appropriate implementation of SBP, favourable weather conditions are pivotal for their success. Although irrigation could be applied to some parcels, making it a condition for SBP would rule out the use of SBP for regreening overgrazed and eroded steep slopes, as irrigating these areas is difficult. However, on the other hand, it could help farmers to increase their forage production on selected parcels and thus relieve erosion prone areas from grazing pressure. This being said, good management practices, especially in relation to time of sowing and grazing, already posed challenges for some of the farmers. Adding to this appropriate irrigation management would not only be costly, but also time-consuming. Moreover, our results show that SBP thrive very well under rainfed circumstances on Samothraki.

6. Conclusions

Our research underscores the potential of SBP as a suitable tool for addressing ecological and socioeconomic sustainability challenges. The outcome of the 5-year pilot study on the Greek island of Samothraki hinged not only on ecological factors but was rooted within the ability of the local farmer population to adopt new management practices. The long-term transdisciplinary research process this pilot study was embedded in proved initially to be conducive for its initiation, providing beneficial framework conditions (Noll et al., 2024).

Nevertheless, achieving meaningful socioecological impact demands the convergence of several key elements. First, initiating such a pilot study necessitates engaged researchers with secured funding, and local institutional partners facilitating knowledge exchange between researchers and farmers. In addition, expertise on the proposed pasture management practice is essential, whether from a dedicated company or from involved scientists. Most important, farmers need to be interested and committed to this kind of long-term collaboration. This transdisciplinary approach facilitates communication among stakeholders, ensures the continuous provision of expert advice, and helps to recruit additional farmers to engage in the new management practice. This in turn will contribute to data that enables the assessment of ecological and socioeconomic impacts.

From an ecological point of view, Samothraki provides excellent conditions for the installation of SBP. However, sustained use of SBP to mitigate overgrazing demands deeper engagement with local stakeholders, particularly farmers. Such a program can in our understanding only be successful if all farmers are satisfied with the outcome and if regional farm advisors would facilitate the implementation of such programs beyond the horizon of research projects. Short-term funding of scientific research projects does not favour these long-term processes, as the adoption of new management practices by farming communities requires continuous efforts, with results often only visible after many years. Thus, it is imperative for programs aiming at transforming farming practices to closely collaborate with local institutional partners capable of sustaining efforts post researchers' departure.

CRediT authorship contribution statement

Marjan Jongen: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Dominik Noll:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Giorgos Maskalidis:** Conceptualization, Investigation. **Tiago Domingos:** Conceptualization, Funding acquisition, Supervision. **Marina Fischer-Kowalski:** Conceptualization, Funding acquisition, Investigation, Supervision.

Declaration of competing interest

The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report. We certify that the submission is original work and is not under review at any other publication.

Data availability

Data will be made available on request.

Acknowledgements

This work would not have been possible without the consultancy work of António Martelo of Terraprima, who visited the island several times to advice the farmers regarding the installation of the SBP. We wish to thank the initiators of Sustainable Samothraki, especially Carlota Marañon and Jacqueline Kirby, and current president of the association, Stelios Valmas. We also thank Efstathios Apostolopoulos, Bastian Bertsch-Hoermann, Paula Bethge and Joachim Raich, for conducting the interviews during the Samothraki summer school in 2019. Dominik Noll was funded by the research contract (2022.05039.CEECIND) through the Portuguese Foundation for Science and Technology (FCT).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2024.103992.

References

AFJ, 2010. Species diversity: David Crespo takes C3 pastures the next step to boost soil carbon. Aust. Farm. J. 20, 44–47.

Almeida, J.P.F., Canavarro, C., Alberto, D., Rebello-Andrade, C., Rodrigues, A.M., 2017. Optimization of Mediterranean rainfed pasture systems in Portuguese conditions, based on a linear programing model. Ann. Agric. Crop. Sci. 2, 1028.

Andrén, O., Kätterer, T., 2008. Agriculture systems. In: Jørgensen, S.E., Fath, B.D. (Eds.), Encyclopedia of Ecology, vol. 1. Academic Press, Oxford, UK, pp. 96–101. https://doi.org/10.1016/B978-008045405-4.00313-X.

Barradas, A., Carneiro, J.P., Amante, H., Simões, A.M., Olea, L., Almeida, J.P., 2006. Does the response of natural pastures to improvement techniques depend on soil fertility level? Grassl. Sci. Eur. 11, 101–103.

Bernués, A., Ruiz, R., Olaizola, A., Villalba, D., Casasús, I., 2011. Sustainability of pasture-based livestock farming systems in the European Mediterranean context: synergies and trade-offs. Livest. Sci. 139, 44–57. https://doi.org/10.1016/j.livsci.2011.03.018.

Biel, B., Tan, K., 2014. Flora of Samothraki. The Goulandris Natural History Museum, Militos.

Biel, W., Kazimierska, K., Bashutska, U., 2020. Nutritional value of wheat, triticale, barley and oat grains. Acta Sci. Pol. Zootechn. 19, 19–28. https://doi.org/10.21005/asp.2020.19.2.03.

Caraveli, H., 2000. A comparative analysis on intensification and extensification in mediterranean agriculture: dilemmas for LFAs policy. J. Rural. Stud. 16 (2), 231–242. https://doi.org/10.1016/S0743-0167(99)00050-9.

Carneiro, J.P., Simões, N., Maçãs, I.D., Tavares de Sousa, M.M., 2008. Pasture improvement in montado extensive farming systems. Options Méditérr. A-79, 193–197. http://om.ciheam.org/om/pdf/a79/00800644.pdf.

Dimopoulos, P., Raus, T., Bergmeier, E., Constantinidis, T., Iatrou, G., Kokkini, S., Strid, A., Tzampidalos, D., 2013. Flora of Greece Web, Vascular Plants of Greece: an annotated checklist. Berlin: Botanic Garden and Botanical Museum Berlin-Dahlem; Athens: Hellenic Botanical Society. Available online. https://portal.cybertaxonomy.org/flora-greece/. accessed on 26 February 2024.

EEA, 2018. Corine Land Cover (CLC) 2018, European Environment Agency, European Union. available at: https://land.copernicus.eu/pan-european/corine-land-cover/clc2018 (accessed on 5 December 2019).

ELSTAT, 2021. Census Results of Population and Housing. Hellenic Statistical Authority (ELSTAT). available at: https://elstat-outsourcers.statistics.gr/census_results_2022_en.pdf (accessed on 25 February 2024).

Fetzel, T., Petridis, P., Noll, D.A., Singh, S.J., Fischer-Kowalski, M., 2018. Reaching a socio-ecological tipping point: overgrazing on the Greek island of Samothraki and the role of European agricultural policies. Land Use Policy 76, 21–28. https://doi.org/10.1016/j.landusepol.2018.04.042.

Fischer-Kowalski, M., Löw, M., Noll, D., Petridis, P., Skoulikidis, N., 2020. Samothraki in transition: a report on a real-world lab to promote the sustainability of a Greek island. Sustainability 12 (5), 1932. https://doi.org/10.3390/su12051932.

Hernández-Esteban, A., López-Díaz, M.L., Cáceres, Y., Moreno, G., 2019a. Are sown legume-rich pastures effective allies for the profitability and sustainability of Mediterranean dehesas? Agrofor. Syst. 93, 2047–2065. https://doi.org/10.1007/s10457-018-0307-6.

Hernández-Esteban, A., Rolo, V., López-Díaz, M.L., Moreno, G., 2019b. Long-term implications of sowing legume-rich mixtures for plant diversity of Mediterranean wood pastures. Agric. Ecosyst. Environ. 286, 106686 https://doi.org/10.1016/j.agee.2019.106686.

INE, I.P, 2016. Estatísticas Agrícolas, p. 2015.

Jiménez-Olivencia, Y., Ibáñez-Jiménez, Á., Porcel-Rodríguez, L., Zimmerer, K., 2021. Land use change dynamics in euro-mediterranean mountain regions: driving forces and consequences for the landscape. Land Use Policy 109, 105721. https://doi.org/10.1016/j.landusepol.2021.105721.

Kizos, T., Plieninger, T., Schaich, H., 2013. 'Instead of 40 sheep there are 400': traditional grazing practices and landscape change in Western Lesvos, Greece. Landsc. Res. 38 (4), 476–498. https://doi.org/10.1080/01426397.2013.783905.

Noll, D., Wiedenhofer, D., Miatto, A., Singh, S.J., 2019. The expansion of the built environment, waste generation and EU recycling targets on Samothraki, Greece: an island's dilemma. Resour. Conserv. Recycl. 150, 104405 https://doi.org/10.1016/j.resconrec.2019.104405.

Morais, T.G., Jongen, M., Tufik, C., Rodrigues, N.R., Gama, I., Serrano, S., Domingos, T., Teixeira, R.F.M., 2024. Estimation of annual productivity of sown rainfed grasslands using machine learning. Grass Forage Sci. (in press).

Noll, D., Lauk, C., Gaube, V., Wiedenhofer, D., 2020. Caught in a deadlock: small ruminant farming on the Greek island of Samothrace: the importance of regional contexts for effective EU agricultural policies. Sustainability 12 (3), 762. https://doi.org/10.3390/su12030762.

Noll, D., Petridis, P., Gingrich, S., Skoulikidis, N., Singh, S.J., Jongen, M., Papaioannou, G., 2024. Fischer-Kowalski M (2024) insights into 15 years of transdisciplinary research on a small Greek island. GAIA 33 (S1), 35–43.

Oliveira, A.L.M., Urquiaga, S., Dobereiner, J., Baldani, J.I., 2002. The effect of inoculating endophytic N_2-fixing bacteria on micropropagated sugarcane plants. Plant Soil 242, 205–215. https://doi.org/10.1023/A:1016249704336.

Panagopoulos, Y., Dimitriou, E., Skoulikidis, N., 2019. Vulnerability of a Northeast Mediterranean island to soil loss: can grazing management mitigate erosion? Water 11, 1491. https://doi.org/10.3390/w11071491.

Pereira, H.M., Domingos, T., Vicente, L., 2006. Assessing ecosystem services at different scales in the Portugal millennium ecosystem assessment. In: Reid, W.V., Berkes, F., Wilbanks, T., Capistrano, C. (Eds.), Bridging Scales and Knowledge Systems: Concepts and Applications in Ecosystem Assessment. Island Press, Washington, pp. 59–79. https://api.semanticscholar.org/CorpusID:938104.

Quaranta, G., Salvia, R., Salvati, L., De Paola, V., Coluzzi, R., Imbrenda, V., Simoniello, T., 2020. Long-term impacts of grazing management on land degradation in a rural community of southern Italy: depopulation matters. Land Degrad. Dev. 31 (16), 2379–2394. https://doi.org/10.1002/ldr.3583.

Ravaioli, G., Domingos, T., Teixeira, R.F.M., 2023. Data-driven agent-based modelling of incentives for carbon sequestration: the case of sown biodiverse pastures in Portugal. J. Environ. Manag. 338, 117834 https://doi.org/10.1016/j.jenvman.2023.117834.

Rigueiro-Rodríguez, A., Fernández-Núñez, E., González-Hernández, P., McAdam, J.H., Mosquera-Losada, M.R., 2009. Agroforestry systems in Europe: Productive, ecological and social perspectives. In: Rigueiro-Rodróguez, A., McAdam, J., Mosquera-Losada, M.R. (Eds.), Agroforestry in Europe. Advances in Agroforestry, vol. 6. Springer, Dordrecht, pp. 43–65. https://doi.org/10.1007/978-1-4020-8272-6_3.

Rotaru, V., Sinclair, T.R., 2009. Interactive influence of phosphorus and iron on nitrogen fixation by soybean. Environ. Exp. Bot. 66 (1), 94–99. https://doi.org/10.1016/j.envexpbot.2008.12.001.

Skoulikidis, N., Lampou, A., Karaouzas, I., Gritzalis, K., Lazaridou, M., Zogaris, S., 2014. Stream ecological assessment on an Aegean island: insights from an exploratory application on Samothraki (Greece). Fresenius Environ. Bull. 23, 1173–1182.

Sulieman, S., Schulze, J., 2010. Efficiency of nitrogen fixation of the model legume *Medicago truncatula* (Jemalong A17) is low compared to *Medicago sativa*. J. Plant Physiol. 167, 683–692. https://doi.org/10.1016/j.jplph.2009.12.016.

Teixeira, R.F.M., 2010. Sustainable Land Uses and Carbon Sequestration: The Case of Sown Biodiverse Permanent Pastures Rich in Legumes. PhD dissertation,. Technical University of Lisbon, Lisbon.

Teixeira, R.F.M., Domingos, T., Costa, A.P.S.V., Oliveira, R., Farropas, L., Calouro, F., Barradas, A.M., Carneiro, J.P.B.G., 2011. Soil organic matter dynamics in Portuguese natural and sown rainfed grasslands. Ecol. Model. 222, 993–1001. https://doi.org/10.1016/j.ecolmodel.2010.11.013.

Teixeira, R.F.M., Proença, V., Crespo, D., Valada, T., Domingos, T., 2015. A conceptual framework for the analysis of engineered biodiverse pastures. Ecol. Eng. 77, 85–97. https://doi.org/10.1016/j.ecoleng.2015.01.002.