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A conceptual framework for the analysis of engineered biodiverse pastures

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Abstract

Sown biodiverse permanent pastures rich in legumes (SBPPRL) were developed in Portugal in the 1960`s and 1970’s as a strategy to increase grassland productivity by

sowing mixtures of up to 20 species/cultivars of legumes and grasses. Compared to semi-natural pastures, the resulting engineered system provides higher yields of better quality pasture, significantly increasing sustainable stocking rates, with multiple environmental co-benefits. Here, we propose a conceptual framework for the sustainability assessment of SBPPRL and apply it with existing data. Our objective is to inquire if this system is an example of sustainable intensification of livestock production, i.e. an economic and ecological win-win solution that can answer many of the causes for ecosystem degradation in semi-arid and sub-humid climate zones, such as in the Mediterranean basin. We build on experimental results from previous studies, which suggest that SBPPRL replenish soil organic matter pools and improve soil structure. The high increase in stable soil organic matter acts as a carbon sink, turning the system into an optimum tool for climate change mitigation and adaptation. Portugal made use of this fact by supporting the expansion of SBPPRL areas and abating the corresponding carbon from Kyoto Protocol emissions calculations. We resorted to the literature to evaluate other environmental effects due to the absence of data specifically for SBPPRL. Surface water runoff decreases and pirophyte shrub vegetation is eliminated or much reduced. Nitrogen accumulates in stable forms in the soil after being fixed by *Rhizobium*/legume symbiotic associations. Legumes depend on phosphorus fertilization; as such the nitrogen cycle in SBPPRL relies on a potentially non-renewable resource (required during the first years after installation of the pasture), which may be a potential limiting factor in the future. The effects on wild biodiversity are unclear. The methodology laid out in this article provides an innovative framework to assess these effects as additional experimental data becomes available.

Keywords

Pastures; Biodiversity Engineering; Sustainable Intensification; Mediterranean; Climate change; Soil organic matter.

Main/non-standard abbreviations

DM – Dry Matter; PCF – Portuguese Carbon Fund; SBPPRL – Sown Biodiverse Permanent Pastures Rich in Legumes; SNP – Semi-natural Pastures

Highlights

- SBPPRL are mixes of up to 20 species/cultivars of legumes and grasses.
- We present a framework to analyze the sustainability of SBPPRL.
- We perform a preliminary analysis using field data and a literature review.
- SBPPRL can sequester carbon in soils and restore desertified soils in arid regions.
- SBPPRL currently help Portugal to comply with the Kyoto Protocol.

1. Introduction

The system of engineered pastures henceforth designated as “Sown Biodiverse Permanent Pastures Rich in Legumes” (SBPPRL) uses biodiversity as a lever for productivity. Its development started in the second half of the 1960’s when Portuguese agronomists, namely David Crespo, began noticing that fertilization alone was insufficient to reach satisfactory levels of grass productivity and animal feed quality. After tests conducted at his family’s property “Herdade dos Esquerdos” (in Vaiamonte, Portugal, as depicted in Figure 1), Crespo advocated that the introduction of species and varieties originated from the Mediterranean either absent or in lower proportions in spontaneous grasslands (as, for example, species/varieties of legumes) establishes a functioning ecosystem with complementary ecological niches and improves production (Crespo, 1975). He created the first SBPPRL seed mixtures. According to Fertiprado (http://www.fertiprado.pt), the major Portuguese company preparing seed mixtures, 94,260 hectares of rainfed SBPPRL were installed in Portugal between 1990 and 2008. During this period, there has been evidence of Soil Organic Matter (SOM) increases in these grasslands. Since then the mechanisms for SOM accumulation and carbon sequestration in SBPPRL have been established (Teixeira et al., 2008, 2010, 2011). Teixeira (2010) estimates that 3.5 million tons of CO_2 were sequestered in SBPPRL as soil carbon between 1996 and 2008. Because of this work, Portugal was one of only two countries, alongside Denmark, to choose the "Grassland Management" activity, in the framework of the voluntary Land Use, Land Use Change and Forestry (LULUCF) activities under Article 3.4 of the Kyoto Protocol. Since 2008, The Portuguese Carbon Fund (PCF), a financial instrument created by the Portuguese Government to help the country comply with Kyoto targets, has been supporting the installation and maintenance of SBPPRL through a system of payments for carbon sequestration. Since then, the area has increased 48,491 hectares (spread between 1095 farmers) distributed as shown in Figure 1. SBPPRL now occupy an area of more than 4% of the country's agricultural land. Terraprima (http://terraprima.pt/), the company running the carbon sequestration project, estimates that SBPPRL are sequestering 1.54 million additional tons of CO_2 under PCF payment for the carbon sequestration service in the 2009-2014 timeframe.

Carbon sequestration in grassland soils has wide policy (Gerber et al., 2013, pp. 52-53, 88-89; Neely et al., 2009) and scientific (Lal, 2004) support but also many question marks regarding methodologies used for its assessment and the feasibility potential of concrete applications (Smith et al., 2007). The Grassland Carbon Working Group of the Food and Agriculture Organization of the United Nations (FAO) argues in favor of the enhancement of carbon sequestration in grasslands, as long as it meets the conditions of being a low cost mitigation option with important environmental and economic co-benefits (FAO, 2009).

SBPPRL have been presented as a an example of such win-win solutions (environmentally and economically) since they combine the private interests of farmers with the public or ecosystem services provided such as carbon sequestration through increases in SOM, which in turn may help reverse the degradation of Mediterranean ecosystems by providing positive externalities. For example, the PCF project won in 2013 the "World You Like Challenge" of the European Commission for the best solution for climate change, the initiative being deemed "a perfect example of how practical solutions for climate action can also save money and create jobs and growth" (EC, 2013). SBPPRL were also said to "help increase the soil's resilience to environmental instabilities", and their implementation "led to improved soil fertility, water retention and erosion resistance" (EC, 2013).

This land use system is no longer just relevant in Portugal – today SBPPRL also exist, to a lesser degree, in Spain, Italy and (more recently) Uruguay. Its potential of application (with modifications) may extend to similar semi-arid and sub-humid regions in the Mediterranean and elsewhere, since managed grasslands extend to larger geo-climatic reaches than other land uses (Asner et al., 2004). SBPPRL have reached a scale that justifies a study on their environmental benefits to kick-start a research agenda that can ultimately quantify their exact advantages and disadvantages. But so far, in proportion to their potential, SBPPRL are underresearched in many respects. The system as a whole has not yet been conceptualized in the scientific literature, nor has a systems-based approach been used to characterize and as much as possible quantify its sustainability. Unlike the potential of SBPPRL for sequestering carbon, other environmental and economic effects commonly attributed to the system have not yet been assessed.

In this article we propose a framework for the sustainability assessment of SBPPRL that is focused on the Portuguese case but that can also be applied to other semi-arid and sub-humid regions. We begin by describing the conceptual framework that we propose to evaluate the sustainability of SBPPRL, followed by an illustration of experimental results drawn from the literature. We also present a research outlook containing limitations in the sustainability assessment of SBPPRL.

2. Conceptual framework

Our framework involves devising a detailed conceptual causal model for SBPPRL in three steps: (1) we start by establishing the baseline system replaced by SBPPRL, (2) then we introduce the economic and environmental effects that can be expected from the land use change, and (3) finally we evaluate each proposed effect. The evaluation resorts to field data from SBPPRL in Portugal when available, and to a narrative review of the scientific literature on grassland systems with similar characteristics from similar climatic regions otherwise. Unless specifically noted, the literature cited in the sections below refers to systems similar to SBPPRL but composed of associations of a much smaller number of grass and legume species.

2.1. Establishing a baseline system

2.1.1. The Mediterranean context

The Mediterranean Basin is a human-shaped, rich and diverse mosaic of landscapes and an important biodiversity hotspot. Anthropic disturbances, such as fire, clearing of shrubs and reduction in forest density, have been shaping Mediterranean ecosystems for millennia (Perevolotsky and Seligman, 1998). Primarily these changes were employed to maintain or reverse the process of vegetation succession and permit grazing (Bugalho et al., 2011). One of the human-engineered grazed landscapes that resulted was the *montado/dehesa*, a savanna-like forest dominated by cork and/or holm oaks (Bugalho et al., 2011).

Today, the ecosystem services provided by these Mediterranean ecosystems display signs of degradation (Bugalho et al., 2011). Grazed ecosystems occupy vast areas where soils are shallow, stony, gently sloped, and low in organic matter and nutrients, namely phosphorus. For instance, 57% of Portuguese soils have low or very low SOM concentrations (0.5-2.0%) (Van-Camp et al., 2004). The annual soil erosion risk by water in Europe is highest in the Mediterranean Basin, reaching 10 tons of soil per hectare per year (Van-Camp et al., 2004).

The factors that led to this state of affairs are multiple and location-dependent. In some Mediterranean European countries , intensification of animal production through the use of subsidized concentrate feed led to overexploitation (Crespo, 2006b; Detsis, 2010) and amplified deleterious effects of grazing, such as overgrazing and trampling (Bugalho et al., 2011). Alternatively or concurrently in other Mediterranean European countries, the degradation of ecosystem functions is linked to the opposite driver: rural abandonment

(Weissteiner et al., 2011; García-Ruiz and Lana-Renault, 2011), which may take the form of cessation of agricultural activities or extreme extensification by conversion to minimum labor- and capital-intensive systems. This latter factor has been identified as a main driver for degradation of ecosystem services in Portugal (Pereira et al., 2006; Pereira et al., 2009; Teixeira, 2010), Spain (Cammeraat et al., 2007; Dunjó et al., 2003; Lesschen et al., 2007; Ruecker et al., 1999), Italy (Bathurst et al., 2003; d'Angeloa et al., 2000; Geeson et al., 2002; Salvati and Zitti, 2011), Greece (Juntti and Wilson, 2003) and France (Aronson et al., 2009). To establish a baseline for the future of ecosystem services from grazed landscapes, and depict the main drivers of change in the present, we use the Portuguese case.

2.1.2. Baseline in Portugal

Portugal was the object of an in-depth sub-global assessment (Pereira et al., 2009) within the Millennium Ecosystem Assessment (MA, 2005), a United Nations-sponsored initiative established to determine the state of ecosystem services from local scales to the national scale. The main contemporary drivers of change in ecosystem services identified for Portugal are presented in igure 2 (Pereira et al., 2004; 2009). Economic growth in the second half of the twentieth century led to an increase in labor costs in agriculture. The European Common Market and global trade agreements led to a drop in agricultural prices, which was only partially compensated by subsidies. Two effects now ensue: (1) pure land abandonment, with farmers ceasing activities and leaving fields unmanaged, and (2) abandonment of previous agricultural activities and conversion to extensive livestock production. The number of farms with pastures decreased (from effect 1 above), while the total area of pastures more than doubled since 1989 (from effect 2) and is now close to 2 million hectares in Continental Portugal (Teixeira, 2010).

Extensive animal production is less demanding in terms of labor and capital investment than the alternatives, but spontaneous grassland productivity is also low, strongly limiting feed nutritional quality. The consequence is a dependence on purchased crop forages or commercially mixed feeds, which are expensive and further contribute to the decrease in agricultural profits (Ramsey et al., 2005). Ruminants (cattle, sheep, goats) are selective while grazing, leading to imbalances in botanical composition (Chapman et al., 2007) and defoliated patches in plots (Pavlů et al., 2009). Lower pasture productivity and less farm activity induce a cycle of ecological succession that leads to the increase in abundance and dominance of shrub cover (Koulouri and Giourga, 2007). If abandoned or insufficiently managed/grazed, the system will evolve, creating continuous areas of woody encroachment (Asner et al., 2004). Growth of native shrubs in grasslands may promote increases in soil carbon (Gómez-Rey et al., 2013), for example in encroached holm oak woodlands (Simões et al., 2009) , and habitat for fauna by promoting landscape heterogeneity (Sirami et al., 2007); however, in the Mediterranean, struck by dry and hot seasons, fire risk and severity are highly increased by accumulating woody biomass (Moreira and Russo, 2007; van Wilgen et al., 2010). The incidence of wildfires is particularly high in the Mediterranean (Rodrigo et al., 2004), with direct consequences on soil structure loss for soil water holding capability and biodiversity. Decades of continued extensification and natural re-vegetation of ecosystems, following abandonment, have not reversed past degradation caused by human activities and have in some cases continued a downward spiral in degradation, as grasslands supported progressively lower stocking rates with increasing inter and intraannual dry matter (DM) production variability and lower feed quality. In the long run, those effects also translate to issues of food security and rural sustainability (López-Bermúdez and García-Gómez, 2006). The main drivers of ecosystem failure attributed to grazing – soil desertification, shrub encroachment and deforestation (Asner et al, 2004) – thus coincide in this region.

Shrub control decreases fire risk by removing flammable woody materials from the ecosystem, but in degraded semi-natural grasslands it requires active management (Castro and Freitas, 2009), which is usually carried out using methods that inflict soil degradation (Pinto-Correia and Mascarenhas, 1999). Tillage destroys soil structure and mineralizes active SOM pools (Pereira et al., 2009), which are similar effects to those from wildfire. This is the baseline land use in areas where SBPPRL are commonly installed (Teixeira, 2010), and will be henceforth designated as "semi-natural pastures" (SNP) in this article, following the European grasslands classification system developed by Peeters et al. (2014). SNP are defined as any grazing land exhibiting only spontaneous vegetation and with no other mechanical operation besides tillage.

2.2. SBPPRL as an alternative to the baseline

2.2.1. Definition of the SBPPRL system

Bugalho et al. (2011) show that some level of human management is required to maximize ecological and economic returns in Mediterranean cork oak *montados* – meaning that spontaneous re-vegetation is an economically inefficient and ecologically insufficient strategy to improve the state of ecosystem services. In historically grazed sites in the Mediterranean, increased grazing may be an efficient land use strategy (Perevolotsky and Seligman, 1998) to maximize ecological benefits such as soil carbon accumulation and plant cover (Neely et al., 2009; Pavlů et al., 2009; Reeder et al., 2002), because grazing guarantees a level of disturbance that promotes, among other effects, habitat diversity and stimulates primary production. Worldwide, the highest greenhouse gas (GHG) emissions per animal from animal production systems are found in semi-arid lands with low animal productivity due to the use of low-quality feeds or feed scarcity (Herrero et al., 2013). Stocking rate increases must be accompanied by an increase in the carrying capacity of grasslands (Duru et al., 2012) – typically obtained only through some level of intensification – which can be achieved by active restoration through sowing of palatable plant species (Török et al., 2011). SBPPRL are one example of intensification with claimed environmental co-benefits.

The SBPPRL system consists of diverse seed mixtures, each adapted to particular soil, climate and use conditions, and containing between six and twenty different species or varieties of mostly legumes and grasses. What distinguishes SBPPRL from simpler types of sown annual pastures is the number of species/cultivares in the mixture, as well as the fact that the species/cultivars are selected for high DM productivity. This process of ecological engineering can be referred to as “biodiversity engineering”, since it makes use of species diversification and richness to improve pasture persistence, herbage productivity and quality.

Some common sown species in rainfed SBPPRL mixtures are self-reseeding annual legumes (with hard seeds) such as *Trifolium subterraneum (ssp. subterraneum, ssp. brachycalycinum and ssp. yanninicum*), *T. michelianum, T. resupinatum, T. vesiculosum, Ornithopus spp. (e.g. O. sativus, O. compressus*), *Biserrula pelecinus,* annual *Medicago spp. (M. polymorpha, M. scutellata, M. truncatula, M. rugosa, M. litorallis*). In certain soil conditions some drought resistant perennials (with deep root systems) are also used, such as *T. fragiferum, Onobrychis viciifolia, Hedysarum coronarium* and *Medicago sativa*. The most common companion annual grasses are *Lolium multiflorum*, *L. rigidum*, and drought resistant perennials are also used in the mixture, such as summer dormant types of *Dactylis glomerata*, *Phalaris aquatica*, *Festuca arundinacea* and *Lolium perenne*. The composition of SBPPRL may also be enriched with seeds from spontaneous plants such as *Plantago spp*., *Cichorium intybus*, *Vulpia spp.* and *Bromus spp* (Carneiro et al., 2005). Within each annual sown species there are various cultivars with different phenological traits and different lengths of the vegetative cycle and, among the perennials, cultivars with more or less drought resistance may also be chosen. We show as an example one specific mixture in Table 1. The species and varieties included in the mixture are typically native to Portugal or the Mediterranean region.

Mixtures are different for each typical combination of soil and climate conditions, and may be specifically tailored to particular locations, after soil sampling and analysis of physical and chemical characteristics, as well as an analysis of local climate conditions. The creation of a biodiverse mixture well adapted to geodiversity requires good knowledge of the characteristics of adaptation of every species and cultivar, of the soil (pH, texture, depth, drainage, fertility, etc.), and climate (rainfall and its distribution, temperature patterns, particularly frost occurrence and its intensity). The ability of each species/cultivar to combine with other species/cultivars is also equated. If the mixture is well chosen and the pasture properly managed, the seed bank established in the first year grants SBPPRL great persistence. For instance, some plots at Herdade dos Esquerdos were sown 35 years ago and have not been re-sown since.

2.2.2. The role of legumes in SBPPRL

Active biodiversity restoration in grasslands, when nitrogen (N) is not a limiting factor, increases the rate of carbon and N accumulation due to increased SOM level (which is the most important effect in SBPPRL), improved soil structure and reduced ecosystem respiration (de Deyn et al., 2011). In SBPPRL the seeds of legumes are pre-inoculated with specific bacteria of the genus *Rhizobium* to enhance N fixation. These bacteria form N-fixing nodules in the roots of legumes and are able to fix considerable amounts of atmospheric N. The amount fixed depends on the cultivars and percentage of legumes in the pasture composition and on the efficiency of the symbiotic process. *Trifolium subterraneum*, for example, can fixate between 21-238 kg N per hectare per year depending on location (Peoples et al., 2001), a range that typically contains the potential for N fixation by most cultivars in legume/grass systems (Ledgard and Steele, 1992). This translates into a range of 0-31 kg of total shoot N per ton of DM in most legume cropping and/or grassland systems, depending on the system and location (Peoples et al., 2001), with the best estimate lying between 20-25 kg N (Peoples and Baldock, 2001).

Plants in SBPPRL use the fixed atmospheric N to grow – making the system self-sufficient in terms of N. Nevertheless, Mediterranean soils are typically poor in phosphorus, which causes SBPPRL to require a generous application of phosphate for optimum legume growth and N-fixation (Spehn et al., 2002). Eventually other missing macro and micro-nutrients in the soil may be required, such as potassium, magnesium, sulphur, boron, molybdenum, zinc or copper. Limestone is applied if soil pH is lower than 5.3, decreasing acidity to optimum levels for legumes. Most or all of these inputs, as well as sowing of the pasture itself, are not commonly used in SNP, implying that SBPPRL are more intensive in terms of operations.

Legumes cover more than 50% of first-year SBPPRL (Carneiro et al., 2005), and may increase in the second and third year of implementation (Carneiro et al., 2009). As the age of the pasture increases (settlement progresses), grass cover tends to dominate. The percentage of legumes in the plant cover of a mature SBPPRL (more than 5 years) tends to stabilize around 25-30% (Rodrigues, 2009). In the life cycle of the pasture the fraction of legumes is within the range typically considered optimal (30-50%) to maximize N symbiotic fixation, increase net primary production, improve nutritive value, create conditions for high voluntary intakes of food by livestock, minimize the risk of N losses and promote SOM increases, relative to fertilized and unfertilized SNP (Lüscheret al., 2013; Soussana et al., 2004; Soussana and Lemaire, 2014). In SBPPRL, it is estimated that at least 30 kg of N are fixed symbiotically per ton of legume shoot dry mass (Carneiro et al., 2005), assuming a negligible amount of residual N contributing to shoot N since SBPPRL are commonly installed in unfertilized, N-depleted soils.

2.2.3. Management in SBPPRL

The settlement of SBPPRL and the output in terms of DM produced and available N is crucially dependent on keeping the correct ratio of legumes to grasses, which in turn is achieved with correct management practices (Soussana and Lemaire, 2014). Fertilization, as described above, is one such practice, but there are also recommendations regarding grazing management (Frame and Newbould, 1986). During the first year of establishment, farmers should ensure the formation of an abundant seed bank by excluding grazing from the beginning of flowering to the end of the seed maturing period. In subsequent years, overgrazing should also be avoided during the flowering and maturation stages of legume seeds. Conversely, SBPPRL should be heavily grazed during the summer to assure that there is no excess of dry vegetation at the beginning of the first autumn rains, which otherwise would reduce hard seed break down and germination. Apart from these key periods, grazing should always be fine-tuned to match plant production. If farmers notice that legumes are very scarce with grasses becoming dominant , heavy grazing is recommended during the winter/early spring to reduce shading of legumes by grasses. If grass domination is extreme, it is also possible to use rotational or intermittent (heavy) grazing to quickly remove grasses before or during flowering, and thus diminish the production of grass seeds.

2.2.4. Proposed ecological and economic effects of SBPPRL

Our method involves two parts. First, we use a review of specific studies on SBPPRL and apply the conceptual analysis of the Millennium Ecosystem Assessment regarding the baseline drivers of change in Portuguese ecosystems to obtain the expected ecological and economic effects of SBPPRL and SNP. Then, the effects that have not yet been measured are obtained using a literature review of studies with similar properties in comparable bio-climatic regions. In practice, each of these approaches was used for each effect represented in Figure 3, which can be read as follows.

The first systematic experiment set up in Portugal to assess the effects of SBPPRL gathered data from rainfed pastures in eight farms from 2001 to 2005 (Carneiro et al., 2005). Most studies regarding grassland diversity effects on ecosystems functions are usually conducted on small-scale test plots but these issues require observational studies under farm conditions (Aguiar et al., 2011). This experiment with SBPPRL used plot areas ranging from 5 to 15 hectares. They were located in private land currently used by farmers for animal production. Prior to the beginning of the projects, plots were used in a system of long cereal/fallow rotations (Teixeira, 2010) – one year of crop production followed by five to seven years of grazed fallow (i.e. SNP). Each plot's soil and landscape type was approximately homogeneous, in terms of soil and previous use (for more detail on farm locations and characteristics see Teixeira et al., 2011). The project broke down plots in three differently managed systems: SNP with (1) and without (2) fertilization, and SBPPRL (3). This allowed for differences-in-differences tests to be conducted – i.e. assessing differences in productivity, stocking rate, SOM and soil N between systems in the same farm and between farms for one system.

Results from this project demonstrated and explained how sowing mixtures rich in legumes can increase productivity – the original driving force behind the development of SBPPRL. High productivity in SBPPRL is achieved due to the selection of hard seeds and high-production cultivars. In addition to this effect, plant diversity has a potentially positive effect on productivity (Cardinale et al., 2012). This effect is observed not only in SBPPRL (section 3.1 of this article) but also in simpler sown annual pastures. For example, Finn et al. (2013) report data from 3 years of monitoring functionally diverse pastures in 31 sites (mostly in continental Europe); the associations of just four different functional types were sufficient to show increased productivity and decreased invasion by exotic species (confirming an independent study with only 2-3 species by Török et al., 2010). A different study in 17 European countries testing a mix of two species of grasses and two species of legumes found higher yields in these diverse grasslands than in mono-species grasslands (Suter et al., 2013). The main reason behind this effect is the ecological complementarity between functional traits in pasture species. The species-genotypes (i.e., species and their varieties) diversity in SBPPRL is able to track and tune to soil attributes (Aguiar et al., 2012). As a result, in SBPPRL there are fewer gaps in plant cover throughout the plots, since species variability ensures that the species most suited for each specific condition will thrive (Teixeira, 2010), thus promoting stability in ecosystem functioning. This counteracts the inherent variability in SNP yields (Martiniello, 1999). Sown biodiverse mixtures are thus expected to increase productivity (Schipanski and Drinkwater, 2012) even if the initial SOM level is low (Kardol et al., 2008). Increased diversity affects production by increasing the density (rather than the size) of plants (Marquard et al, 2009a; 2009b).

Increased productivity in SBPPRL allows a sustainable increase in animal carrying capacity. Animals graze the plants, which have an annual life cycle. High plant productivity implies increased atmospheric carbon capture through photosynthesis. Part of the biomass produced is stored in soils due to the high density of yearly-renewed roots. Storage occurs in several forms of soil organic carbon (SOC), which is part of the SOM pools (Rees et al., 2005). On average, SOM is composed by the stoichiometric percentage of 58% of carbon (Pribyl, 2010). SOM pools are also increased by leaves' senescence, and by animals returning undigested fiber to the soil. The stability of SOC pools established in SBPPRL depends on landscape factors (Pérez-Bejarano et al., 2010). Non-labile fractions (lower decomposition rates) are higher when the pasture is installed in forested areas (Ramachandran Nair et al., 2009). While SBPPRL may stimulate microbial activity regardless of tree cover (Rodrigues et al., 2014), Gómez-Rey et al. (2012; 2013) report that soil quality amelioration and SOC accumulation in SBPPRL is higher beneath tree crowns. Typically treeless pastures store less carbon (Gómez-Rey et al., 2013; Ramachandran Nair et al., 2009). The mineralization rate in SBPPRL may be similar to SNP (Gómez-Rey et al., 2012) or higher (Almeida, 2011) but SOM inputs are higher in SBPPRL. Even labile fractions of SOM in SBPPRL contribute to the accumulation of soil carbon unless land use change (involving tillage) takes place. This threat of SOC loss due to land use change is minimized by the economic incentives for farmers to maintain the system.

Other effects may follow but there is no data specific for SBPPRL. We use published literature to show, for example, that SOM increase improves soil nutrient availability and water holding capacity, thus increasing plant productivity and reducing surface runoff of water, which in turn decreases sediment loss and soil erosion (EEA, 2004). Decreasing water runoff and soil erosion have positive effects even outside the plot. Sediments, nutrients and organic matter carried in water contribute to silting, eutrophication and contamination of surface waters (EEA, 2004). These effects are known, but their true costs are still hard to estimate. N fixation by legumes eliminates the need for synthetic N fertilizers, whose production is highly energy demanding, and therefore responsible for high greenhouse gas emissions (Soussana and Lemaire, 2014). Finally, both increased livestock feed produced on-farm and reduced fertilizer use increase the economic viability of the farms.

3. Results and Discussion

3.1. Productivity and nitrogen leaching in SBPPRL

Farmers originally adopted SBPPRL because they are more productive than SNP (Crespo, 2006a; 2006b). Primarily this is because SBPPRL contain highly productive species and cultivars with hard seeds that configure a persistent seed bank and increase the likelihood of pasture persistence.

DM productivity results vary with the location of the farm between 2-6 tons DM per hectare (increasing every year), but are systematically 50 to 100% higher for SBPPRL (Carneiro et al., 2005; Rodrigues, 2009; Teixeira, 2010). The relative increase in yield is lower when soil fertility prior to sowing is higher (Barradas et al., 2006). Measurements in Algeria after the installation of similar (albeit simplified) mixtures of seeds confirm this improvement. In one test site, DM in sown pastures was double that of natural fallows (Abbas et al., 2008a). In another experiment, DM increased from 1.3 to 8.2 tons per hectare in the first year and increased diversified plant cover with legumes from 19 to 30% (Abbas et al., 2008b).

Increased DM productivity directly implies more fodder available for livestock. This fact is evidenced by experimental results. Average stocking rate between 2001 and 2004 was 1.0 cattle unit (CU - One CU is the equivalent of one adult cow) per hectare in SBPPRL and 0.43 CU per year in fertilized and unfertilized SNP. 2004–2005 figures were much lower because of a severe drought, but still higher for SBPPRL (0.36 against 0.14 CU per hectare for SNP). There is also a qualitative difference between the amounts produced – spoiled DM is greater in SNP since SBPPRL produce more usable forage of higher quality, as SNP are characterized by spontaneous species of low preference and nutritional value (Frankow-Lindberg et al., 2009).

The lower estimate in the DM ranges above corresponded to one year of severe drought. The fact that SBPPRL showed resilience to withstand environmental pressure and maintained higher levels of DM production than SNP supports the hypothesis that niche complementarity in SBPPRL may positively affect the stability of the grassland system (Neely et al., 2009) and thus provide adaptation to global changes and extreme conditions. The floristic structure of semi-natural Mediterranean grasslands is remarkably sensitive to annual rainfall fluctuations (Figueroa and Davy, 1991), which affects the stability of human activities. Grassland soils with well-established and diverse banks of seeds possess more genetic variability and so are quicker to respond to changing environmental conditions.

Plant diversity in grasslands promotes productivity and the stability of nutrient retention in soils (Schläpfer and Schmid, 1999), by promoting the storage of carbon and N in soils (de Deyn et al., 2009). This limits soil nutrient concentration variability in space and time, thus being particularly important in chemically and minerally heterogeneous Mediterranean soils (Yaalon, 1997). SBPPRL have also been observed to enhance N-pools (Gómez-Rey et al., 2012). Legumes guarantee the amount of N adequate for grass growth and grazing pressure. *Trifolium* are particularly efficient at fixing N (Spehn et al., 2002). Legume persistence and the number of plant species with diverse functions contribute to higher yields (Fornara and Tilman, 2009). The risk of decline in net biome productivity due to N limitation, common in extensive systems (Allard et al., 2007), is thus reduced. N fixation from legumes is a stable nutrient source for grasses, and the complementarity of functional roles minimizes dumping of free nutrients – accentuating an effect that also occurs in SNP (Otieno et al., 2011; Schipanski and Drinkwater, 2012). Rodrigues et al. (2010) monitored soil inorganic-N levels in SBPPRL and SNP for one year showing that the risk of N loss is practically non-existent since there is a balance between fixed-N (by legumes) and consumed-N (by legumes and grasses). The losses of N from the system are thus in the form of N_2O (discussed below) and animal harvest, namely one steer removed from the pasture each year. The removal of the steer is not significant in the N balance of the pasture (Teixeira, 2010). There is some evidence that SBPPRL are approximately balanced in terms of N (Carneiro et al., 2010), but longer time series are needed to assess the impact of possible thus far uncovered N imbalances on long term productivity.

3.2.SOM balance

Between 2001-2005 SOM concentrations where determined using data from the same plots where productivity and nutritional quality were previously assessed (for sample collection and analysis protocol see Teixeira et al., 2011). Teixeira et al. (2011) combined measurement and modeling (as recommended by Conant et al., 2011) in a statistical model controlling for spatial heterogeneity. The model was calibrated to determine, for average conditions, the mean SOM increase. The resulting model is a negative (i.e. saturating) exponential. Changes in management, such as fertilization or sowing, create a transient state during which SOM accumulates due to the high plant productivity (i.e. more individual plants). The high percentage of legumes guarantees a steady flow of N into the system, thus increasing productivity and SOM accumulation. Ammann et al. (2007) used an eddy covariance technique to show positive effects of management intensity in the carbon budget of grasslands. As the pasture ages, soil respiration, the process through which the SOM pool is being mineralized, increases and eventually the two effects (SOM accumulation and soil respiration) are balanced (Trumbore and Czimczik, 2008). and a new, higher, steady-state SOM concentration is reached (Teixeira et al., 2011).

Teixeira et al. (2011) showed that SBPPRL soils increase SOM concentration on average by 0.21 percent points (pp) each year during the first 10 years, starting from an initial SOM concentration of 0.87%. This result is consistent with previous measurements made at Herdade dos Esquerdos, where SOM concentrations were 0.7%-1.2% when the first SBPPRL were sown in 1973 and were 3.0%-5.5% in the same plots in 2010 (AFJ, 2010). This increase is also more than double that verified in fertilized and unfertilized semi-natural plots (0.08 pp per year).

3.3. Carbon balance of SBPPRL

SOM increases while the balance between soil carbon assimilation and soil respiration is positive (Teixeira et al., 2011). SBPPRL are active carbon sinks during that period.

The 0.21 pp increase in SOM is equivalent to an average sequestration of 6.5 tons of CO_2 per hectare per year in the first 10 cm of topsoil and during 10 years after installation (Teixeira, 2010). Although these results were obtained using soil sampling and modeling, there is evidence from SNP that flux measurements would point in the same direction, as these numbers are similar to those obtained for SNP using soil sampling (Teixeira et al., 2011). For example, Aires et al. (2008) measured carbon fluxes in one SNP in Southern Portugal and found that, in 2004–2005 (drought year), 0.49 t C per hectare were emitted, while in 2005–2006 (normal precipitation year) 1.91 t C were sequestered per hectare.

To calculate the overall plot-level GHG balance, other contributions must be assessed. Application of limestone in SBPPRL results in GHG emissions (IPCC, 2003). N_2O is emitted as co-product of bacterial nitrification/denitrification cycle in SBPPRL legumes nodes (IPCC, 2006) and is known to be higher in semi-intensive systems (Flechard et al., 2007) and capable of significantly offsetting the gains from C sequestration (Conant et al., 2005).CH_4 is emitted from manure and enteric fermentation from livestock. Subtracting these three effects, SBPPRL are still a carbon sink of 1.55-2.13 tons CO_2 per hectare per year (Teixeira, 2010).

The difference between SBPPRL and SNP may underestimate the real balance because calculations assume that: (1) farmers use the bump in production to import livestock instead of replacing concentrated feeds and maintaining the stocking rate; and (2) legumes cover over 50% of the area. Assumption (1) is unlikely due to the EU's quota scheme for subsidies that in practice limits the total cattle stock in Portugal (Teixeira et al., 2008), and also because recent projections indicate that in the near future increases in meat production will likely be due to monogastric livestock (pork and poultry) rather than ruminants (particularly beef cattle) (Herrero and Thornton, 2013). Assumption (2) is only valid in first-year settlements, since surface cover of legumes decreases as C:N ratios decrease in grasslands (Rodrigues et al., 2010).

3.4. Life-cycle consequences of increasing productivity

The increase in the stocking rate that can be sustained by DM production in SBPPRL may translate in two possible effects: (1) more animals grazing, and so more impacts from grazing livestock (such as methane emissions) or (2) less need for concentrated feeds than in SNP (Teixeira, 2010). In both cases the increase in sustainable stocking rate, in an agricultural sense, is always economically advantageous (Teixeira 2010). The environmental sustainability of these two effects deserves a deeper analysis.

In case (1), it could be argued that if the effective stocking rate increases, there are adverse effects to wild biodiversity. More livestock could clutter the ecosystem and prevent functional ecological groups from establishing in the area due to resource limitation (Curry et al., 2008). High stocking rates also imply that animals control shrubs either by stomping or by using them in their feed (since shrubs are rich in fiber, to compensate for excess protein from the consumption of legumes) (Teixeira, 2010).

The need for operations dedicated to controlling shrubs, such as tillage, is thus eliminated.

In case (2), environmental life cycle effects benefit SBPPRL. Life Cycle Assessment (LCA) has been carried out (Teixeira, 2010) for SNP, to assess impacts of tillage and concentrated feed, and for SBPPRL, to assess the impact of management operations, production and transportation (and application, when relevant) of seeds, phosphate fertilizer, limestone and concentrated feed. Teixeira (2010) assumed that the excess in production is used to replace concentrated feeds. The study compares one hectare of SNP and one hectare with mixed composition: 0-20% of the area is SBPPRL (area of SBPPRL required to completely replace concentrated feeds in the farm), and the remainder SNP. The carbon balance of SNP, when CH_4 emission from off-site digestion of feedstock by animals is added, is likely to be neutral (Soussana et al., 2007), but results for SBPPRL show that the substitution of the feed, which has high impacts due to the production of feed ingredients, and increased carbon sequestration are enough to more than compensate the higher emissions from inputs and operations in SBPPRL for all LCA indicators studied and indicate that the system as a whole may be a net carbon sink (Teixeira 2010).

3.5. Ecosystem functioning, soil quality and water management

Experiences with clover/grass sown pastures in other semi-arid regions are abundant (Ledgard et al., 2009; Finn et al., 2013; Marquard et al, 2009). It has been established that high species diversity often improves ecosystem functioning (Spehn et al., 2005; White et al., 2004) because diverse communities contain key species of crucial influence, and due to efficiency gains from differences in functional traits among organisms (Cardinale et al., 2012). This aspect of functional diversity in particular has the most effect on ecosystem processes (Díaz and Cabido, 2001; Wardle et al., 2000).

Ecosystem services such as maintenance of soil fertility and structure and water regulation have not yet been measured in SBPPRL, but according to our conceptual framework they are likely to occur. SOM quantity influences soil quality (capacity of soils to gather, retain and filter water, nutrients and energy) and resilience (capacity of soils to revert to the initial state after disturbance), since SOM contributes to soil's physical and chemical proprieties (Neely et al., 2009). SOM confers structure, stability and nutrients to soils (Bot and Benites, 2005), thus increasing plant productivity (Trumbore and Czimczik, 2008). Humus, the main component of SOM, is essential to keep soils stable; it influences the texture of soil by promoting aggregation of particles, and increasing soils' cation exchange capacity. High SOM thus decreases erosion and counteracts desertification (Conant et al., 2011). SOM also influences factors leading to soil compactibility (Soane, 1990). Erosion is also controlled by to the reduction in superficial water runoff during high precipitation events due to the increase in plant cover and avoided frequent soil mobilizations through tillage, which is a common operation in SNP. Decreased erosion causes a feedback increase in SOM content, since in semi-arid Mediterranean environments erosion is one of the main causes of soil degradation and SOM loss (Sinoga et al., 2012). SOM regulates the water cycle by retaining water and improving its quality before making it available for plants, thus regulating the outflow (Bot and Benites, 2005). Soils with increased fertility and capacity to hold water will be more adaptable to a future with larger temperature and precipitation extremes (Tilman, 2006). Grazing can lead to an increase in soil bulk density, since livestock stomping compacts the upper layer of SBPPRL soils, but this is typically not observed in the Mediterranean. SBPPRL soils beneath tree canopy, where SOM storage is maximum, have lower soil bunk densities than SNP soils (Gómez-Rey et al., 2012). The underlying mechanism may be that biological activity in high SOM, no-tilled soils creates canals for water infiltration and nutrient uptake by plants that decrease the need for resetting density (Sasal et al., 2006). No-tilled SOM-rich soils sustain productivity avoiding underground soil disruption, which enhances the aggregation and structure of soils (Bronick and Lal, 2005)..

3.6. Rural development and meat quality

Since the maintenance of ecosystem services in cultural landscapes is crucially dependent on sustainable agricultural practices (Bugalho et al., 2011), land use management should aim at producing quality goods that guarantee farmers' revenue without depleting or degrading natural resources. Environmentally, meat products are among those causing highest GHG emissions (Teixeira, 2014) and have limited possibilities for abatement (Golub et al., 2013), which poses a particularly difficult challenge for producers to adapt to climate policies.

The profitability of SBPPRL installation and maintenance depends on farm size, stocking rate and fluctuations in meat prices (Teixeira, 2010). Smaller farms are usually at a disadvantage, since they do not benefit from scale effects. For that reason, they were targeted by the Portuguese Rural Development Program from 2009 onwards for supporting the installation of SBPPRL. These farms also benefited from the PCF project on payments for carbon sequestration mentioned in the Introduction. In spite of the importance of payments for environmental services, farmers rely above all on market prices. Different studies have probed the preferences and willingness to pay for meat products of Portuguese consumers (Marta-Pedroso, 2008). Some sensory characteristics differ between meat from pasture-fed and concentrate-fed livestock such as color and taste (Wood et al., 2008). Meat from pastoral systems is usually darker and has an intense taste (Priolo et al., 2001). These facts were explained to surveyed consumers so that acceptability was not harmed. In one survey, 83% of inquired consumers claimed to be willing to pay more (about 1.5 € per kilogram on average) for meat of an animal that is not stabled after weaning (Marta-Pedroso, 2010). The main reason pointed is perceived meat quality and not animal well-being.

Nutritional quality is generally higher in pastoral meat, compared to meat from animals fed with concentrated feeds. When the animal is fed partially on pastures the ratio of *n*-6/*n*-3 (Omega) fatty acids is typically lower, and the contents in other important fatty acids such as oleic (C18:1) and palmitic (C16:0) acid is commonly higher. These effects have been measured in meat from bullocks (Alfaia et al., 2006), veal (Alfaia et al., 2007a, 2007b), lamb (Bessa et al., 2008; Díaz et al., 2002), cows (Gama et al., 2013), bulls (Nuernberg et al., 2005; Huuskonen et al., 2010) and pigs (Raes et al., 2004). It is unknown if SBPPRL have a specific effect apart from these generic effects of pasture feeding. There are, however, some indications that meat from livestock fed in SBPPRL is richer in saturated fatty acids than SNP-fed meat (Ralha et al., 2008). .

3.7. Research outlook

Our conceptual model provides a research framework to develop a robust knowledge base about multidimensional components, environmental and economic effects of SBPPRL. The literature overview we present results in Figure 4, which shows and assesses the most likely consequences of replacing SNP with SBPPRL. The main negative issues with SBPPRL are increased GHG emissions and increased used of phosphate fertilizer. Even when causal links could be established, our assessment of the effects of this system was currently limited by data availability. We relied mostly on literature review of systems that, like SBPPRL, make use of the complementarity between grasses and legumes, but with the difference that SBPPRL relies more strongly on genetic and species diversity. Other causal links remain unknown. In the future, in addition to the quantification of other ecosystem functions of SBPPRL, the time series used for SOM measurements should be extended in time and geographic reach to assess the permanence of effects in longer time frames and other regions/countries. Work related to the PCF project is underway to increase the geographic coverage of monitoring efforts and correlate performance with geodiversity. There is also no information about wild biodiversity, consumer valuation of products from cattle raised in SBPPRL, and the importance of phosphorus fertilizer prices to the economic sustainability of the system.

We recommend that the following topics should be addressed in the coming years:

- *Collect field data to accurately determine the precise effects of every causal link over longer time periods*. Establishing a monitoring grid to quantify the economic and environmental effects of SBPPRL and the baseline system should be high on priorities. As key issues, this process should monitor the response of wild fauna and other indicator taxa (an issue thus far overlooked), as well as determine the total species diversity in sown and biodiverse plots. SBPPRL mixes are biodiverse, but the evidence available (Carneiro et al., 2005) is insufficient to discern whether as a whole sown plots are more species-diverse (measured using number of species and Shannon-Wiener index) than semi-natural plots. The time series for SOM should be expanded to measure long-term effects and broken down to understand SOM intra-year dynamics. C and N balances should be explicitly calculated over longer periods and any possible imbalances related to changes in DM productivity.

- *Explore main threats to the functioning of SBPPRL*. SBPPRL require more inputs and operations to run, and as such are subjected to risk and uncertainty regarding prices and availability of materials. For example, phosphorus is a non-renewable resource with no known substitutes for plant nutrition (Cordell et al., 2009). For that reason, managing the phosphorus cycle is crucial for the sustainability of agricultural production, and SBPPRL in particular, even if there is only moderate risk of phosphorus shortage by 2100 (Van Vuuren et al., 2010). The main immediate risk is economic, due to galloping prices of phosphorus in recent years (Cordell et al., 2009), and as such alternatives and improvements in fertilization practices (such as described by Cordell et al., 2011) and strategies to enhance N and P uptake by plants (Vance, 2001) should be tested. Deriving optimum effects from SBPPRL also depends crucially on correct management practices. Further work should target the results of fluctuations in the composition of the pasture, such as a decrease in legumes, on productivity, end-product nutritional quality and environmental effects.

- *Establish the potential of SBPPRL in other semi-arid and sub-humid regions*. SBPPRL were first introduced in Portugal, and as such we define the baseline according to specific Portuguese conditions. To assess the implementation in other regions other baselines occur and effects will vary according to the bioclimatic region (Asner et al., 2004). However, the analysis framework defined in this article can be used in future assessments for other countries of semi-arid and sub-humid bio-climatic conditions.

4. Conclusions

Available research suggests that SBPPRL are a sustainable semi-intensive system for meat production in Portugal that maximize the bundle of services provided by grasslands, and counteract most degradation drivers identified in igure 2 due to the mechanisms shown in Figure 5. SBPPRL score higher in most environmental performance indicators available, when compared to their baseline (SNP). The main drivers for ecosystem degradation are economic. SBPPRL produce more and better quality meat products, as well as the ecosystem service of carbon sequestration remunerated by the PCF. While increasing SOM, SBPPRL sequester atmospheric CO_2.

These conclusions were driven mostly by literature review related to similar systems of grass/legume consociations, so in the future it is important to establish field monitoring programs that touch upon all items referred in this article. Our work presents a "proof of concept" framework of analysis that can be used to study the applicability of this system with regional adaptations to the Mediterranean basin and elsewhere with similar climatic conditions, as more data becomes available. If the system proves to be geographically robust, it could become an efficient policy against desertification or climate change.

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Table 1 – Seed mix for the Sown Biodiverse Permanent Pasture Rich in Legumes installed at Herdade da Defesa de Cima[a].

Type	Species	Sub-species	Variety(ies)
Legumes[b]	*Trifolium subterraneum*	*ssp. Subterraneum*	*cv. Dalkeith, Losa, Seaton, Park, Woogenellup, Campeda*
	Trifolium subterraneum	*ssp. Yanninicum*	*cv. Gosse, Napier*
	Trifolium subterraneum	*ssp. Brachycalycinum*	*cv. Antas*
	Trifolium balansae		*cv. Frontier, Paradana*
	Trifolium resupinatum		*cv. Prolific*
	Trifolium vesiculosum		*cv. Cefalu*
	Trifolium incarnatus		*cv. Contea*
	Biserrula pelecinus		*cv. Mauro, Casbah*
	Ornithopus sativus		*cv. Cádiz, Erica, Margurita*
	Ornithopus compressus		*cv. Charano*
Grasses	*Lolium multiflorum*		*Pollanum, Litoro*
	Dactylis glomerata		*Currie*

[a] Source: António Martelo, personal communication. Location of farm is shown in Figure 1. [b] Legumes make up to 50-60% of the seed mix in mass.

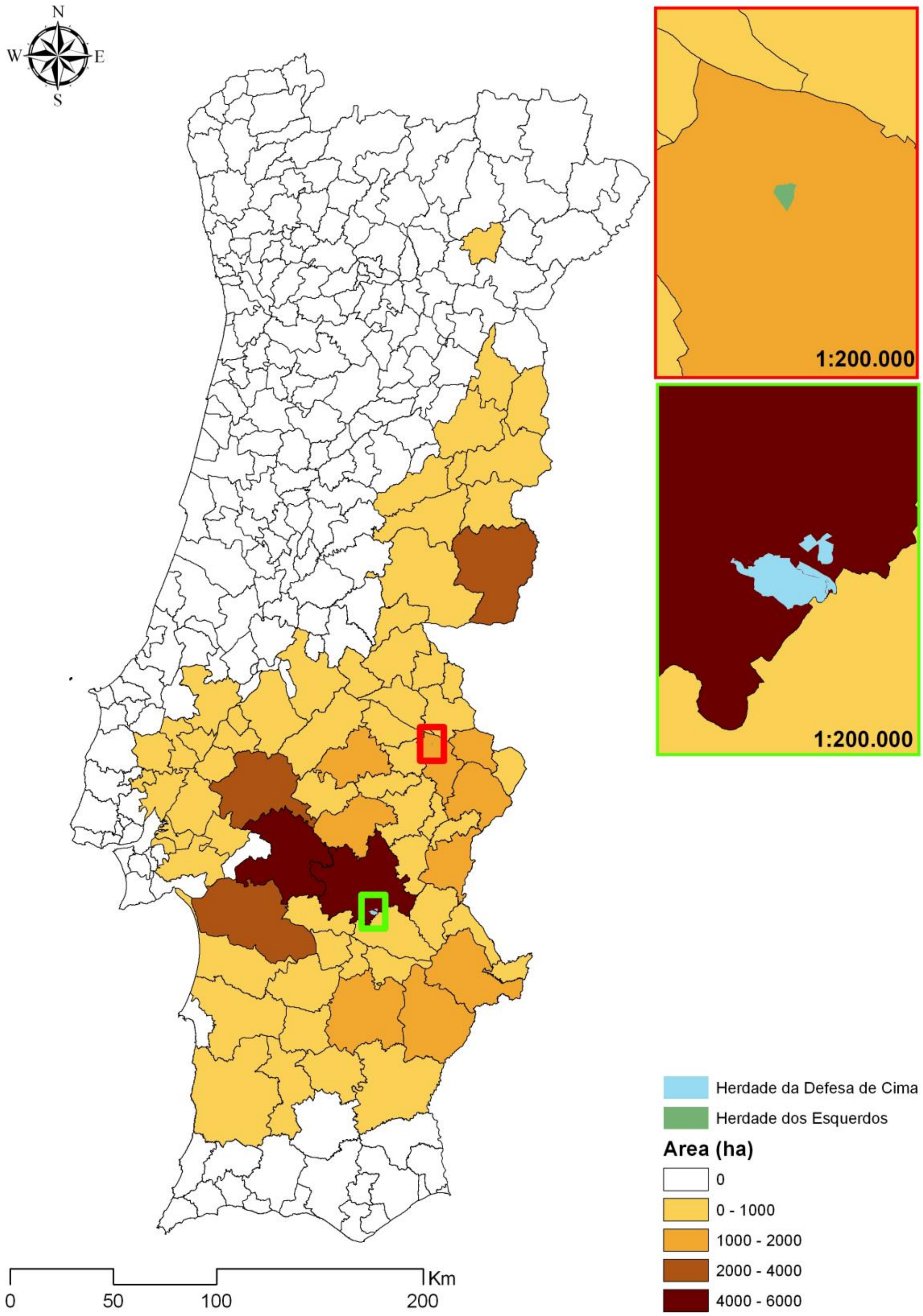

Figure 1 – Distribution of the area of sown biodiverse pastures rich in legumes sown in Portugal under support from the Portuguese Carbon Fund (2009-2013). The farm "Herdade dos Esquerdos" is shown in the upper right corner, and the farm "Herdade Defesa de Cima" immediately below.

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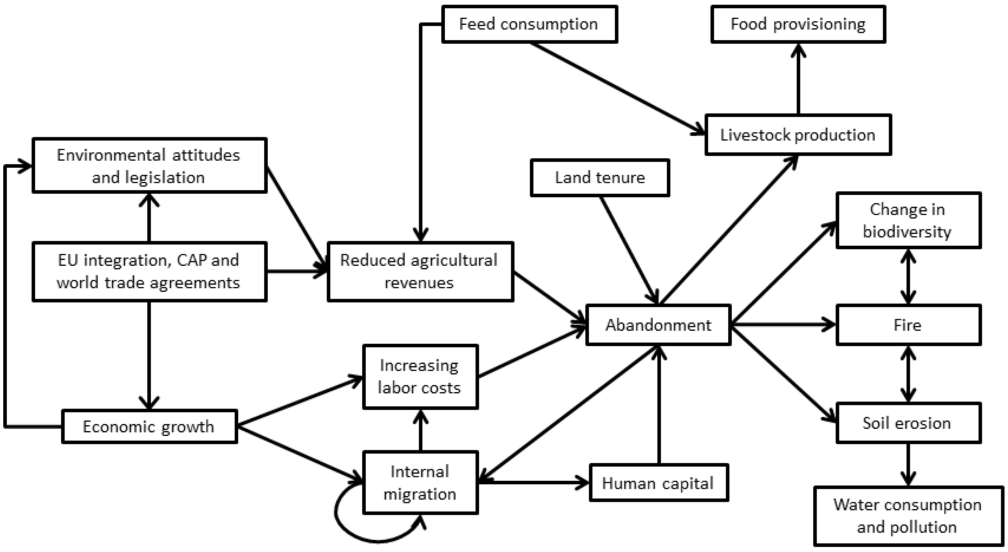

Figure 2 - Main drivers of change in Portuguese ecosystems regarding abandonment (adapted from Pereira et al., 2004, Chapter 4, page 24).
EU – European Union; CAP – Common Agricultural Policy.

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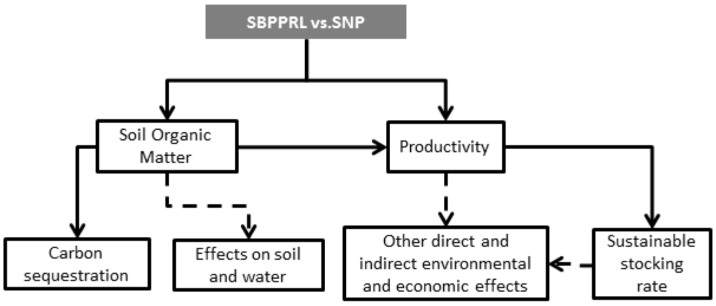

Figure 3 – Simplified scheme for the analysis of ecological and economic effects of Sown Biodiverse Permanent Pastures Rich in Legumes (SBPPRL) compared to semi-natural pastures (SNP) as the baseline. Solid lines – links established using a review of studies focused specifically on the comparison of SBPPRL and SNP; dashed lines – links established using a literature review for systems related with SBPPRL.

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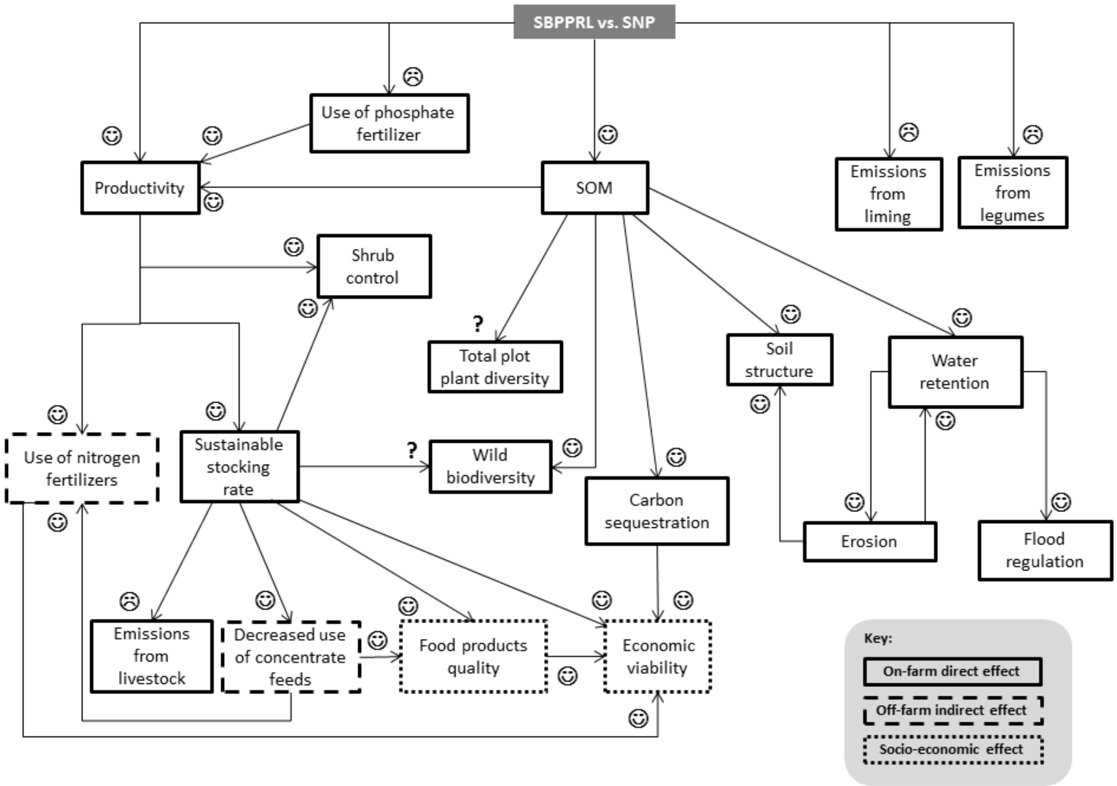

Figure 4 – Ecological and economic effects of Sown Biodiverse Permanent Pastures Rich in Legumes (SBPPRL) and semi-natural pastures (SNP).
Arrows indicate causal relation. Emoticons associated with each arrow are the likely effects of SBPPRL relative to SNP. Boxes in solid line are direct effects (at the farm), while dashed lines are indirect effects or have indirect consequences off-farm. Boxes with dotted lines are socio-economic effects. SOM – Soil Organic Matter.

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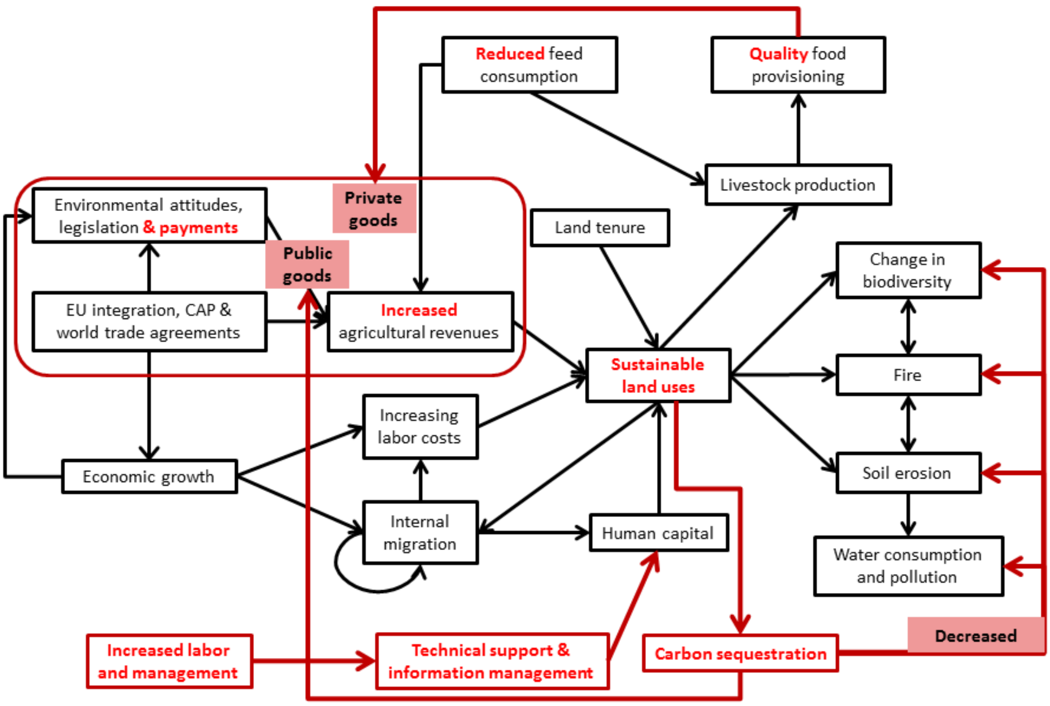

Figure 5 - Responses to improve ecosystem services in Portuguese Ecosystems regarding abandonment, using Sown Biodiverse Permanent Pastures Rich in Legumes (adapted from Pereira et al., 2004, Chapter 4, page 24). EU – European Union; CAP – Common Agricultural Policy.