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Role of ley pastures in tomorrow's cropping systems. A review

Guillaume Martin¹ · Jean-Louis Durand² · Michel Duru¹ · François Gastal³ · Bernadette Julier² · Isabelle Litrico² · Gaëtan Louarn² · Safia Médiène⁴ · Delphine Moreau⁵ · Muriel Valentin-Morison⁴ · Sandra Novak³ · Virginie Parnaudeau⁶ · Foteini Paschalidou⁴ · Françoise Vertès⁶ · Anne-Sophie Voisin⁵ · Pierre Cellier⁷ · Marie-Hélène Jeuffroy⁴

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Abstract

Diversification of cropping systems has been proposed as a major mechanism to move towards sustainable cropping systems. To date, a diversification option that has received little attention is introduction of ley pastures into cropping systems, but the use of ley pastures is challenged by most future-oriented scenarios aiming to feed the world sustainably. In these scenarios, ruminant livestock feed only on permanent pastures, while cropping systems focus completely on production of crop-based human food. Diversification of cropping systems with ley pastures is thus compromised by knowledge gaps and future-oriented policy options. Here, we review ecosystem services provided by introducing ley pastures into cropping systems to increase sustainability of agriculture, discuss types of ley pastures and their management liable to promote these services, and raise future challenges related to introducing ley pastures into cropping systems. We conclude that (1) ley pastures provide a large set of input (soil conservation, nutrient provision and recycling, soil water retention, biological control of pests) and output (water purification, climate regulation, habitat provision for biodiversity conservation, forage production) ecosystem services of primary importance to cropping systems and society, respectively, as long as their spatial and temporal insertion within cropping systems is well-managed; otherwise, disservices may be produced. (2) To benefit from ecosystem services provided by ley pastures in cropping systems while limiting their disservices, it appears necessary to define a safe operating space for ley pastures in cropping systems. Moving towards this space requires changing plant breeding programs towards multiservice ley pastures, producing knowledge about emerging ways of introducing ley pastures into cropping systems (e.g., living mulch, green manure) and better quantifying the bundles of ecosystem services provided by ley pastures in cropping systems.

Keywords Ley pastures · Sown grasslands · Cropping systems · Ecosystem services · Scenarios

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1 Introduction

Grain production has doubled in the past 50 years (Tilman et al. 2002) under the effect of more efficient machinery; improved varieties; and increased reliance on irrigation water, fertilizer, and pesticides. This trend has favored simplification and intensification of cropping systems (i.e., monocultures or crop sequences limited to 2 crops) (Aguilar et al. 2015; Barzman et al. 2015) and specialization of many agricultural regions. It has also led to the disappearance of ley pastures in regions where grain crops are dominant (Mignolet et al. 2012; Peyraud et al. 2014). Currently, these simplified cropping systems have stagnating yields (Brisson et al. 2010; Ray et al. 2012; Moore and Lobell 2015) and appear sensitive to global changes such as climate change (Brisson et al. 2010; Meng et al. 2016). Their strong reliance on mineral fertilizers and agrochemicals has negative impacts on the environment (e.g., pollution of air, water and soils; losses of soil quality and agroecosystem biodiversity; Sebilo et al. 2013) and human health (Kim et al. 2017). This reliance on synthetic inputs can even cause problems, such as emerging cases of resistance to agrochemicals, especially herbicides (e.g., ryegrass in wheat in Australia (Saini et al. 2015); windmill grass in soybean in Brazil (Brunharo et al. 2016)). Nonetheless, the trend of pesticide use is stable or increasing (e.g., in France; Ecophyto 2017), and agriculture continues to rely heavily on mineral fertilization (FAO 2019). To address these challenges, alternative agricultural models are increasingly needed.

Several directions have been proposed to move towards sustainable cropping systems, such as agroecology (Altieri 1989; Tomich et al. 2011), ecological intensification (Cassman 1999), ecoefficient agriculture, and sustainable intensification (Pretty and Bharucha 2014). Nearly all of these models rely on greater plant diversity in cropping systems.

Diversified cropping systems (Kremen et al. 2012) relying on agroecological principles should be more sustainable, as suggested by theoretical ecology studies (Isbell et al. 2011), cropping system experiments (Davis et al. 2012), and on-farm assessments (Carlisle 2014). A fine-tuned combination of functional complementarities of a variety of species provides a wide range of ecosystem services to sustain crop production through biological processes, with relatively low negative environmental impacts (Kremen and Miles 2012; Kremen et al. 2012). At the field level, several options exist to diversify cropping systems, such as mixing varieties, intercropping species, introducing cover crops, and increasing the diversity of crops in the crop sequences. These options have received frequent attention from the scientific community (e.g., Schipanski et al. 2014; Ponisio et al. 2015; Finney et al. 2017), but another option has received much less: introducing ley pastures into cropping systems (Fig. 1). Ley pastures are defined as temporary pastures that are integrated in crop sequences (Allen et al. 2011). They are composed of grasses, legumes, and/or other forbs and are grown from several months to 5 years at most (according to European Union (EU) regulations). Currently, they are located mainly in low-land agricultural regions dominated by ruminant livestock production to produce forage by haying, grazing, or both

Most future-oriented scenarios aiming to feed the increasing world population while improving the sustainability of agriculture converge towards a reduction of animal protein in human diets in developed countries (Westhoek et al. 2014; Schader et al. 2015; Rööös et al. 2017; Muller et al. 2017). Along with this change in human diets, all but one scenario (Poux and Aubert 2018) suggest a shift in livestock's primary role in the food system from producing animal protein to extracting value from land unsuitable for food production (e.g., semi-natural pastures, wetlands), which cover two-third of worldwide agricultural area, through ruminant livestock grazing (Schader et al. 2015). This implies that livestock be located in areas less suitable for arable crop production and consume no feed supplements except food byproducts (e.g., meals, pulps). Accordingly, these scenarios assume that the land devoted to permanent pastures remains constant, as a "sustainable" way to feed ruminant livestock. However, if arable land is less or no longer used to produce ruminant livestock feed (including forage), ley pastures should appear less frequently in cropping systems devoted mainly to food production.

Diversification of agricultural systems and especially of cropping systems is thus confronted with future-oriented policy options designed to feed the world's human population more sustainably. We argue that potential benefits offered by introduction of ley pastures into cropping systems are currently underestimated. In this context, there is a need to clarify the bundles of ecosystem services provided by ley pastures introduced to improve sustainability of cropping systems,



Fig. 1 Examples of cropping system situations including ley pastures. (Photo credits: Sandra Novak for **a**, **b**, **d**, and **e**, SOERE ACBB for **c**)

depending on their management. In this review, we (i) present a theoretical framework suited to analyze introduction of ley pastures into cropping systems, (ii) synthesize their potential benefits to improve sustainability of agriculture, (iii) discuss the types of ley pastures liable to promote these benefits, and (iv) raise future challenges related to introducing ley pastures into specialized cropping systems or mixed systems of crops and ruminant livestock.

2 Theoretical framework

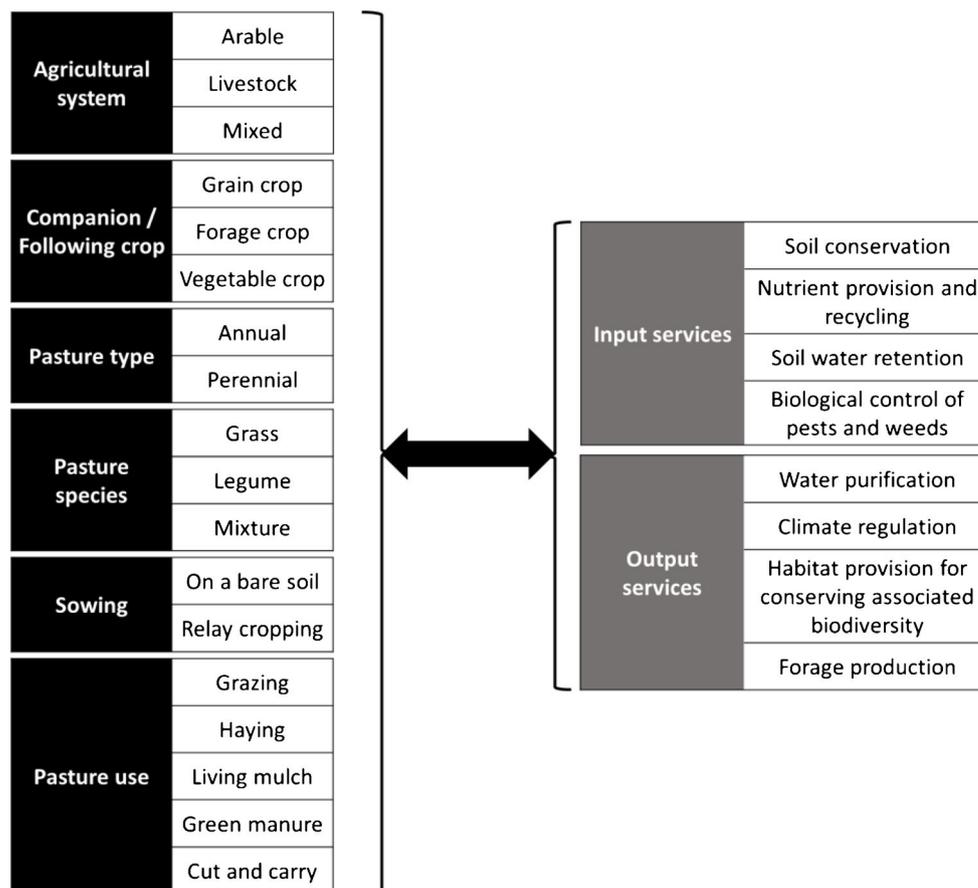
2.1 Characterizing management options for introducing ley pastures into cropping systems

“Cropping system” refers to a crop sequence and management techniques consistently planned, adapted, and implemented by a farmer on a particular field over a period of years according to available resources (e.g., workforce, machinery) (Sebillotte 1990; Reckling et al. 2016). It describes systems of annual crops such as grains, forages (e.g., silage maize), and vegetables where ley pastures are a key component of the crop sequence (Amossé et al. 2013a, b; Weißhuhn et al. 2017), while in perennial woody-crop systems such as orchards and vineyards, pastures are usually restricted to areas next to the perennial crop of interest (Miglécz et al. 2015). Consequently,

this review focuses on the former. Analysis of the introduction of ley pastures into cropping systems should consider the agricultural system in which the introduction takes place, the companion annual crop and/or the crop sequence, and the management techniques applied.

“Agricultural system” refers to the type of production system on the farm, i.e., arable, livestock, or mixed including crop, pastures, and livestock. “Crop sequence” refers to a sequence of plant species grown on the same piece of land (Dury et al. 2012). Knowledge of the position of ley pastures and the other crops (i.e., grain, forage or vegetable crops) in the crop sequence is required to understand effects of ley pastures on following crops. Beyond interactions among crop and pasture species, there are a variety of management techniques to consider when analyzing impacts of introducing ley pastures into cropping systems (Fig. 2). The first is the type of ley pasture (i.e., annual or perennial) and the species sown (i.e., grasses, legumes, or a mixture of both that may include other forbs). The second option is how the ley pasture is sown, usually on bare soil, but increasingly within a cash crop as “relay intercropping” (planting a second crop before the first crop is mature; McCormick et al. 2014). The third option is how the pasture is used. Traditionally, pastures were grazed and/or hayed. Other emerging uses of pastures include “living mulch” (partially killed before sowing using a power harrow or moderate herbicide spraying) to sow a crop in the ley pasture (Turlin 2017),

Fig. 2 Overview of the theoretical framework developed to analyze introduction of ley pastures into cropping systems. Management options (on the left) for growing ley pastures within cropping systems affect bundles of services (on the right) provided by ley pastures in cropping systems



“green manure” (killed by crushing, e.g., with a power harrow, herbicide spraying or frost) for mulching or incorporating residues before sowing a crop (Fisk et al. 2001) and “cut and carry” by using legumes (fresh or dried) as sources of fertilizer on arable land (van der Burgt et al. 2013).

2.2 Characterizing bundles of services provided by ley pastures in cropping systems

Analyzing potential benefits offered by introducing ley pastures into cropping systems may rely on the concept of ecosystem service bundles (Raudsepp-Hearne et al. 2010). Bundles exist when provision of one service leads to changes in others or when the same factor drives changes in multiple services. Bundles thus describe interactions among services under the influence of the companion crop of ley pastures or the crop sequences in which ley pastures are integrated, as well as the techniques used to manage them. They can even reveal disservices, such as when introducing a ley pasture into a cropping system results in an outcome worse than not doing so (Finney et al. 2016).

Ley pastures may provide multiple ecosystem services (Fig. 2). When applying the ecosystem services framework to agriculture, it is common to distinguish services flowing

to agriculture (input services) from those flowing from agriculture (output services), thus highlighting that agroecosystems both depend on and contribute to provision of ecosystem services (Zhang et al. 2007). Among input services, we considered the following, at various levels:

- Soil conservation (field level) by preserving its stability and controlling erosion. The former refers to the ability of soil aggregates to resist environmental stress (e.g., wet-dry cycles) without breaking, while the latter refers to preventing loss of soil particles due to wind, rain, or water flow.
- Nutrient provision and cycling (cropping system level). Nutrient provision refers to uptake and supply of nutrients to the following crop. Nutrient cycling refers to deposition, uptake, and decomposition of litter and animal manure in the soil, which allow recycling to occur.
- Soil water retention (field level), i.e., retaining soil water and providing it to the following crop.
- Biological control of pests and weeds (cropping system level), i.e., reducing or eliminating their populations by influencing their ecology.

Among output services, we considered the following, at various levels:

- Water purification (watershed level), i.e., removing undesirable chemicals, contaminants, suspended solids, and gases from water.
- Climate regulation (global level), i.e., decreasing greenhouse gas emissions or increasing carbon (C) storage in the soil.
- Habitat provision for wildlife conservation (landscape level), i.e., providing high-quality functional and structural habitats for a wide range of animal and plant species.
- Production of forage for livestock (in both quantity and quality) or biomass to produce energy (Rösch et al. 2009).

Although knowledge is available about each service in ley pastures individually, services have rarely been quantified or considered together for ley pastures. In the following sections, we review these services to provide an integrated view of bundles of services provided by ley pastures in cropping systems.

3 Input services provided by ley pastures in cropping systems

3.1 Soil conservation

Soil structure directly impacts several aspects of soil functioning: water, solutes, fine particles, and gas transfers within the soil; development and activity of root systems; and biological activity (Bronick and Lal 2005). Stability of soil structure, often assessed by the degree of soil aggregation, strongly determines a soil's ability to resist and recover from disturbances (e.g., tillage, erosion). Soil aggregation and stability are generally positively related to soil organic matter (SOM) content (Bronick and Lal 2005). They are generally lower under annual crop sequences but higher under permanent pastures or during the ley pasture period of crop sequences (Haynes 1999; Diaz-Zorita et al. 2002; Franzluebbers and Stuedemann 2008; Puerta et al. 2018). Puerta et al. (2018) report increases in the proportion of large macroaggregates in the range 47–65% (depending on management: organic vs. conventional) after a ley period following a 4-year arable crop rotation. Thus, whatever the type of agricultural system, decreasing soil disturbance with practices like relay cropping and increasing C input by developing multiannual or short-duration (i.e., several months) ley pastures within sequences based on annual crops, regardless of their use, can greatly improve soil structure and, more generally, soil health (Fig. 3) and even more if associated with inputs of crop residues and animal manure (Franzluebbers and Gastal 2018).

Multiannual ley pastures also protect soil from water and wind erosion (Franzluebbers 2008; Franzluebbers et al. 2014). This is also the case when introducing short-duration ley pastures into arable cropping systems (e.g., as living mulch)

during the fallow period instead of leaving soil bare (Panagosa et al. 2015) and when implementing practices decreasing soil disturbance like relay cropping (Fig. 3). Several factors explain the decreased erosion observed under vegetation cover (Zuazo and Pleguezuelo 2009):

- Rain interception by the canopy and by plant litter on the soil surface protects the soil physically.
- Development of permanent root systems in shallow and deeper soil layers helps maintain soil stability and decrease particle losses.
- Higher SOM content in the topsoil increases soil aggregate stability.
- Higher soil porosity, related to the higher SOM content and biological activity (particularly earthworms; Lamande et al. 2003) below pastures, increases soil water infiltration, thus reducing water runoff (Carroll and Tucker 2000).
- Canopy roughness decreases detachment and transfer of soil particles by the wind.

For these reasons, soil erosion decreases exponentially with increasing plant cover (Gyssels et al. 2005) and decreased soil disturbance, which is promoted over time by integrating ley pastures into arable and mixed systems, regardless of pasture use as long as overgrazing and trampling are avoided (Fig. 3). In England, Fullen (1998) found that under developed ley pastures, erosion rates were limited to 0.1–0.5 t/ha/year against 11.3 t/ha/year for bare arable soils. In the Chinese Loess plateau, which is highly susceptible to soil erosion, runoff on fields planted with alfalfa (*Medicago sativa*) and Caomuxi (*Melilotus suaveolens* Ledeb, a biennial forage) was limited to 13.0 mm against 81.0 mm for cropland leading to sediment losses by 4.6 and 40.6 t/ha/year, respectively (Jun et al. 2010). This trend was confirmed on sloppy (> 25°) croplands of the Loess plateau converted into forests and pastures leading to an estimated decrease of soil erosion from 85 to 55 t/ha/year although the latter remains extremely high (Fu et al. 2011). A decrease in soil erosion decreases loss of soil nutrients, particularly nitrogen (N) and phosphorus (P) (Franzluebbers 2008), thereby decreasing crop productivity losses and damage to the environment (e.g., eutrophication).

3.2 Nutrient provision and recycling

Soil microorganisms control a large part of C, N, and P cycles in arable and pasture soils (Recous et al. 2017). Their biodiversity and activity are higher in soils with less disturbance (van Eekeren et al. 2008), such as those under ley pastures especially if sown with relay cropping, than in soils with frequent tillage, such as those under annual crops sown on bare soils (Fig. 3). Moreover, introduction of ley pastures into

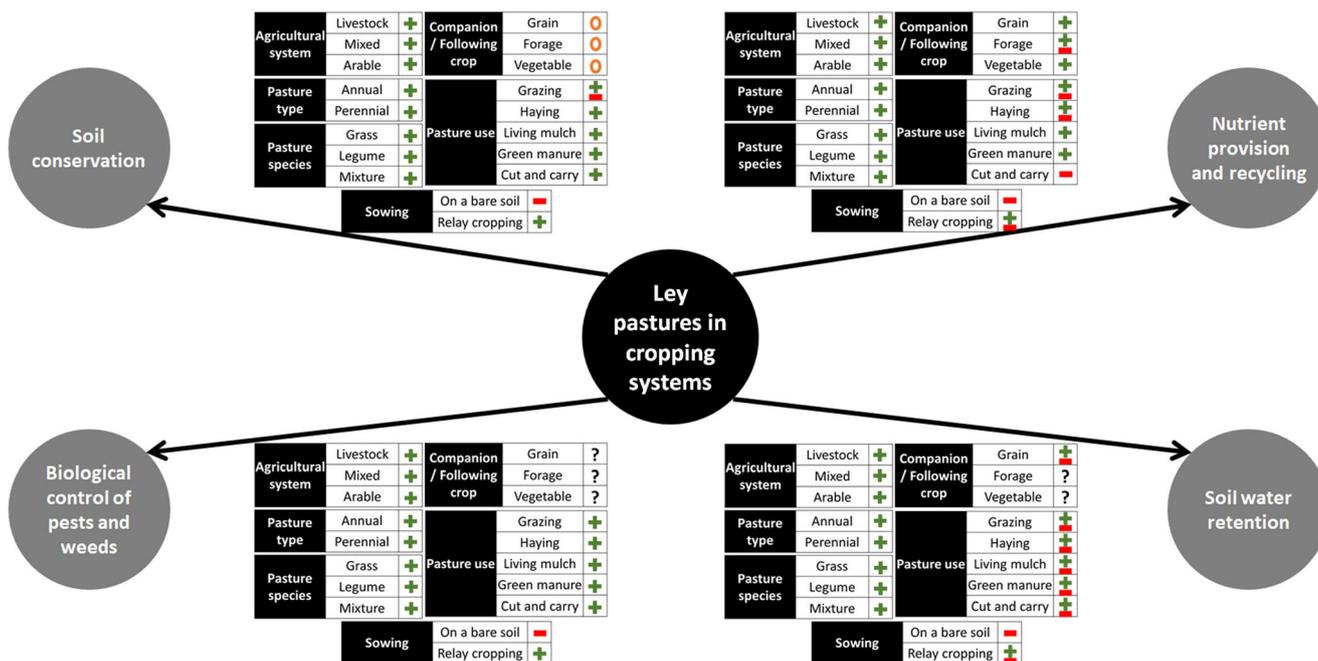


Fig. 3 Synthesis of the effects of introducing ley pastures in cropping systems on input ecosystems services according to the management options considered in this review. Symbols have the following meaning: known positive effects (plus sign), known negative effects

(minus sign), known as a non-key factor (0), unknown effect (question mark), and positive or negative effect depending on management (plus-minus sign)

cropping systems of arable and mixed farms can increase provision of soil nutrients via three main mechanisms:

- Higher N inputs due to symbiotic N₂ fixation by legume species sown in pastures, which promotes the cropping system’s self-sufficiency in N and provides high-quality animal feed (Peyraud et al. 2014): N fixation varies from 30 to 40 kg N/ha/year in short-duration ley pastures up to more than 300 kg N/ha/year for well-established alfalfa (*Medicago sativa*) and clover (*Trifolium pratense*) stands (Anglade 2015; Rasmussen et al. 2012).
- Greater root development than that under annual crops (corresponding to ca. 30–40% of C inputs), secretion of more root exudates, and greater development of soil microorganisms including fungi, which desorb P and potassium (K) (Recous et al. 2017).
- Large C inputs by grasses and increased decomposition through earthworm, insect, and microorganisms activity, which helps improve soil structure (see section 3.1), recycle urine patches and spread dung and its nutrients (Rumpel and Chabbi 2018; Vertès et al. 2018).

In pastures, organic matter from dead plant organs, both above- and belowground, as well as urine and dung patches if animals grazed in mixed and livestock farms, result in high C and N inputs to soils (Rumpel and Chabbi 2018). Some of these inputs are organized as stable organic matter (mean C storage of 770 kg C/ha/year, ca. 80 kg N/ha/year; Klumpp and Fornara

2018) or remain particulate organic matter. Pellerin et al. (2019) highlight the uncertainties and variability in C storage under pastures reported in the literature. The longer the duration of ley pasture within a crop sequence, the greater is its influence on soil organic C (SOC) storage and mitigation of N losses to the environment. Direct recycling of N, P, and K accumulated in pastures is high with grazing, since herbivores do not convert nutrients into protein or animal products efficiently. A grazing dairy cow excretes 34% of C intake and 62% P intake, mainly through dung, and 70% of N intake and 93% of K intake, mainly through urine (Vertès et al. 2018). However, animal excretion also depends on pasture management, especially livestock stocking rate during grazing. As stocking rate increases, C–N decoupling by animals can progressively offset the C–N coupling capacity of the soil-plant system, leading to losses through nitrate (NO₃) leaching (contributing to eutrophication) and nitrous oxide (N₂O) emissions (contributing to climate change) depending on the season and soil conditions (Decau et al. 2003; Leterme et al. 2003; Vertès et al. 2008). The same trade-off may apply with haying according to the N fertilization level (Fig. 3).

Impacts of emerging uses of ley pastures on nutrient provision and cycling have not been much studied to date and require further research; nonetheless, they impact these processes greatly. Using ley pastures in “cut and carry” systems or to produce bioenergy compromises on-field recycling of nutrients since the nutrients are exported (Fig. 3). Undersowing wheat in living mulches of red fescue (*Festuca rubra*), sheep’s fescue (*Festuca ovina*), alfalfa (*Medicago*

sativa), bird's-foot trefoil (*Lotus corniculatus*), black medic (*Medicago lupulina*), and white clover (*Trifolium repens*) can increase competition for N (Carof et al. 2007b), thereby affecting nutrient provision but promoting internal recycling. In contrast, a living mulch of alfalfa can be the main source of N for cereals in low-input cropping systems, as practiced by some farmers in France. Amossé et al. (2013a) showed that none of four relay-intercropped legumes (*black medic/Medicago lupulina*, *alfalfa/Medicago sativa*, *red clover/Trifolium pratense* and *white clover/Trifolium repens*) affected N uptake of an associated winter wheat. Instead, the legume increased N uptake of the following crop (i.e., maize or spring wheat) and induced a 30% increase in grain yield.

When pastures are killed, much of the SOM is mineralized, leading to high C losses (as carbon dioxide (CO₂)) and release of mineral N in soils (Vertès et al. 2007; Necpalova et al. 2014). In addition to basal SOM mineralization, the additive (due to pasture destruction) amount of soil mineral N available for the following crop varies from 20 to more than 120 kg N/ha (COMIFER 2011) depending on the species sown, pasture use and pasture age when killed (the older the pasture, the more mineral N available; Vertès et al. 2007; van Eekeren et al. 2008). However, this high N mineralization can generate large N losses as leached NO₃ and denitrified N₂O (Vertès et al. 2007; Crème et al. 2018) if the following crop's N requirements and ability to develop an efficient root system sufficiently early (e.g., with cereals, vegetables and some annual forage crops such as silage maize) are lower than the N mineralized from SOM and ley pasture residues.

3.3 Soil water retention

Water retention in soil depends on runoff and on the soil's ability to retain infiltrated water. Whatever the type of agricultural system, multiannual and short-duration ley pastures physically impede water flow, which decreases runoff and increases water infiltration. For example, on the Chinese Loess plateau, alfalfa stands reduced the velocity of water flows and in turn increased the soil infiltration capacity by 1.77 times compared to bare soils (Wu et al. 2011). Infiltration capacity is influenced mainly by biotic processes, especially SOM content; root biomass; and earthworm presence, biomass, and activity.

Under continuous arable cropping on Australian clay soils, soil hydraulic conductivity decreased exponentially over time but it displayed a fourfold and rapid (within 2–4 years) increase when ley pastures were introduced in the rotation (Silburn et al. 2007). On Chinese mine soils, mixed-species pastures (grass-legume or legume-shrubs) produced more root biomass than pure (i.e., single-species) stands, thus increasing soil infiltration as compared to a bare soil (−0.59 vs. 1.48 with soil infiltration assessed through a composite index of soil water infiltration rate over time; Wu et al. 2016). Comparing pasture subplots with different plant species, functional group richness, and

composition (e.g., legumes, grasses, small forbs, tall forbs), Fischer et al. (2014) observed that earthworm presence significantly increased infiltration in summer, while in autumn, effects of grasses and legumes on infiltration were due to plant-mediated changes in earthworm biomass. These hydrological properties vary depending on the duration of ley pastures in crop sequences, since earthworm abundance may increase over time. Anecic earthworm populations were around 3 times larger after 3 years of ley pasture than after 1 year of ley pasture and winter rye on a sandy loam soil (Lamande et al. 2017), also related to the absence of soil tillage during this period. Conversely, pasture harvest (in the case of haying and “cut and carry”), destruction (in the case of green manure), or grazing can decrease water infiltration by compacting the soil (Fig. 3; Franzluebbers et al. 2012).

SOM stored during the pasture period and dead roots left in the soil, by favoring soil stability, increase available water capacity and water infiltration and retention, thus decreasing surface runoff. Those positive effects of ley pastures on soil hydraulic conductivity could be mainly due to changes in SOM (Obour et al. 2018) that improve soil structure. As demonstrated by Zhao et al. (2013) on long-duration pastures in a natural restoration experiment (6-, 16-, 36-, 56-, and 79-year treatments), an increase in SOM in a cropland converted into a 6-year-old pasture (13.4 g/kg vs. 17.5 g/kg) led to a strong increase in soil infiltration rates (from 39.3 to 52.2 mm/h, 30.2 to 55.4 mm/h, 27.0 to 62.4 mm/h at low-, medium-, and high-intensity rainfall, respectively). This effect explains why soil infiltration rates decrease after conversion of pastureland to cropland (Sun et al. 2018). This decrease also relates to tillage frequency: tillage every 4 years in crop sequences including ley pastures decreased only earthworm abundance, while tillage every year in arable-crop sequences decreased both their abundance and functional diversity (Lamande et al. 2003).

However, ley pastures may also have negative effects on soil water retention. Overgrazing and trampling by animals or tractors (at pasture harvest or destruction) on ley pastures in either arable, mixed, or livestock farms can decrease significantly water infiltration rate to only 10–15% of that in non-trampled pastures (Pietola et al. 2005). Also, Kunrath et al. (2015) observed that soil dried out more rapidly under pastures than crops. In southwestern France, Tribouillois et al. (2018) showed that, compared to bare soil, cover crops, including some in the form of ley pastures (e.g., Italian ryegrass/*Lolium multiflorum*, vetch/*Vicia sativa*), increased evapotranspiration by a mean of 20 mm/year and accordingly decreased water drainage by 21 mm/year. Conversely, cover crops induced a decrease in soil evaporation proportional to their biomass, due to greater soil coverage. Ultimately, when well managed (e.g., killed on time), cover crops did not decrease the water available to the following cash crops. This conclusion may apply especially to summer crops in temperate climates, in which the effective rainfall (rainfall minus evapotranspiration) generally exceeds soil available water capacity.

The seedlings of cereal crops sown in a living mulch of ley pasture may have difficulty competing for water with the pasture plants, while the opposite may occur when pasture plants are undersown in a cover of cereals (Fig. 3).

3.4 Biological control of pests and weeds

Crop diversification is a key component of agroecological pest management (Liebman and Dyck 1993; Liebman and Gallandt 1997; Colbach et al. submitted). Diversification in time allows farmers to alternate (i) host and non-host crop species, thus reducing pest survival (e.g., Colbach et al. 1994), and (ii) growing seasons, potentially exposing pests to unfavorable growth conditions (e.g., Chauvel et al. 2001). Diversification in space allows farmers to alternate host and non-host crop species within a field, thus reducing pests' ability to find suitable hosts or environments (Finckh et al. 2000; Hiddink et al. 2010; Petit et al. 2018). In addition to these general benefits, specifically introducing ley pastures into cropping systems based mainly on annual crops is a powerful mechanism for managing pests.

For weeds, the ley pasture period provides particularly unfavorable growth conditions regardless the type of agricultural system, for several reasons (Meiss et al. 2010c):

- Plants in pastures compete intensely and almost continuously for light, water, and nutrients (due to canopy closure, rapid regrowth of forage crops after haying, and deep and dense rooting) (Gosse et al. 1988; Meiss et al. 2008).
- Disturbances caused by regular cutting (either for haying in livestock and mixed farms or cut and carry in arable farms) or grazing throughout the year may compromise the ability of weed species to regrow (Norris and Ayres 1991; Hiltbrunner et al. 2008; Meiss et al. 2008).
- Absence of soil tillage and presence of permanent plant cover may form a weed-suppressing mulch, while favoring decomposition and predation of weed seeds (see section 3.5) (Westerman et al. 2005; Heggenstaller et al. 2006; Meiss et al. 2010a).
- Ley pastures with legume species often receive little or no low N fertilization, thus reducing pressure from weed species with high N requirements (Andersson and Milberg 1996).
- Some species such as alfalfa (*Medicago sativa*) and bird's-foot trefoil (*Lotus corniculatus*) release allelopathic compounds that can inhibit weed growth (Khanh et al. 2005).
- Ley pasture cover can intercept weed seeds, which may decrease replenishment of the soil seed bank (Doisy et al. 2014).

Over the short term (i.e., during the ley pasture period), these factors can influence composition of weed species and

reduce their growth. Based on a 12-year study, Schuster et al. (2019) assessed the differences in weed abundance among crop rotations including or not ley pastures established for 3 or 6 years. Crop type (i.e., pasture or cereal) had a strong effect: weed abundance during maize and wheat cropping was on average about three times higher than in ley pastures and barley crops. This study also showed that a cereal crop following 6 years of well-fertilized ley pasture (mix of 3 grass species) had a significantly lower weed abundance, 25–50% lower than in other rotations (Fig. 3). Beyond pasture management, those authors identified a critical ley pasture biomass of ca. 4.7 t/ha above which weeds become suppressed in the following year. But at present, this kind of experiment or observations is clearly lacking to quantify ley pasture impacts on weed dynamics.

Short-term effects have delayed impacts over the longer term at the cropping system level by changing the weed seed bank. Generally, following a ley pasture, density of problematic weed species decreases, while overall weed diversity may increase (reviewed by Meiss et al. 2010c), highlighting the role of ley pastures in sustaining plant diversity in agroecosystems (Marshall et al. 2003). Interestingly, weed diversity may increase mainly due to establishment of perennial weed species that are not problematic for annual crops that are tilled (Ominski et al. 1999; Albrecht 2005; Meiss et al. 2010b). For these reasons, cropping systems integrating ley pastures generally have lower herbicide inputs (Lechenet 2017). Effects of ley pastures on weed species can vary depending on the management techniques applied to the ley pastures (e.g., species sown, sowing period, ley pasture duration, haying and/or grazing frequency, and N fertilization; Fig. 3) (Norris and Ayres 1991; Schuster et al. 2019). Finally, sowing ley pastures as cover crops into a cash crop may help regulate weeds (Amossé et al. 2013a, b; Petit et al. 2018). The challenge is to minimize competition of pasture plants with the cash crop while maximizing their competition with weeds.

Ley pastures have no direct effects on pest populations or diseases. However, indirect effects of ley pastures on them, within the context of manipulating habitats for beneficial organisms and natural enemies, are well described (see Sect. 4.3). For example, based on a unique French national network of arable farms involved in a pesticide-reduction program, Lechenet et al. (2016) highlighted that mixed farms with livestock relied less on pesticides than those without livestock. Indeed, mixed farms combining crops and livestock have more opportunities to diversify crop sequences with ley pastures and forage crops (e.g., silage maize, intercrops, triticale, other secondary cereals), since the presence of livestock provides extra outlets for ley pastures and forage crops. In an additional study, Lechenet et al. (2017) observed that most (72%) farms with a significant negative effect of the total Treatment Frequency Index (TFI) on crop productivity

(indicating a potential productivity gain or no effect associated with a reduction of pesticide use) were mixed farms that had mainly soils with low available water capacity, medium-to-high yield potentials, and a large proportion of ley pastures and silage maize on their agricultural area. These crops generally had high productivity and low TFI.

4 Output services provided by ley pastures in cropping systems

4.1 Water purification

In all types of agricultural systems, ley pastures, by covering the soil during periods at risk for deep water contamination (winter in oceanic western Europe), reduce N leaching through plant uptake of N. Leaching is particularly reduced when hayed pastures with balanced fertilization are introduced into arable-crop sequences (from 37 to 8 kg N/ha/year on average in Kunrath et al. 2015), while leaching under grazed pastures depends largely on stocking rates and pedoclimatic conditions (Fig. 4; Ledgard et al. 2009; Vertès et al. 2008). Risk of N leaching also varies with the species sown: introducing pastures of perennial forage legumes into arable cropping systems decreases the risk over the crop sequence (Anglade et al. 2015). After a ley pasture is killed, however, if the following crop cannot take up the large amount of N mineralized in the soil (as is the case with cereals, vegetables and

some forage crops such as silage maize without undersown catch crop able to uptake soil mineral N in autumn and winter), N leaching is high, ranging from 60 to 250 kg N/ha/year (Vertès et al. 2007). N leaching tends to increase with pasture age, autumn plowing, previous high fertilization rates on the pasture, a large proportion of legumes, and/or high stocking rates during grazing. Denitrification resulting in N₂O emissions also tends to increase after pasture plowing (Davies et al. 2001).

The influence of ley pastures on decreasing P, chemical oxygen demand, and pesticides in water has not been studied to date. Still, since pastures are not usually treated for pests (Lechenet et al. 2017), integrating them into cropping systems results in lower pesticide inputs over an entire crop sequence, whatever the agricultural system and pasture use (Fig. 4). Moreover, water purification results from a variety of processes such as nutrient uptake by plants, adsorption of elements on SOM and mineral elements, biotic and abiotic transformations, and gaseous emissions that allow trends of the influence of ley pastures on this ecosystem service to be deduced. In a rare study of dissolved organic carbon (DOC), Kindler et al. (2011) showed little difference in mean DOC concentration in topsoil or DOC leaching between pastureland and cropland (5.3 ± 2.0 and 4.1 ± 1.3 g/m²/year, respectively). More research is required to better estimate the influence of faster drainage on DOC leaching, especially since Brye et al. (2001) reported a fivefold increase in DOC leaching for 4 years after conversion of native tall-grass pasture to maize

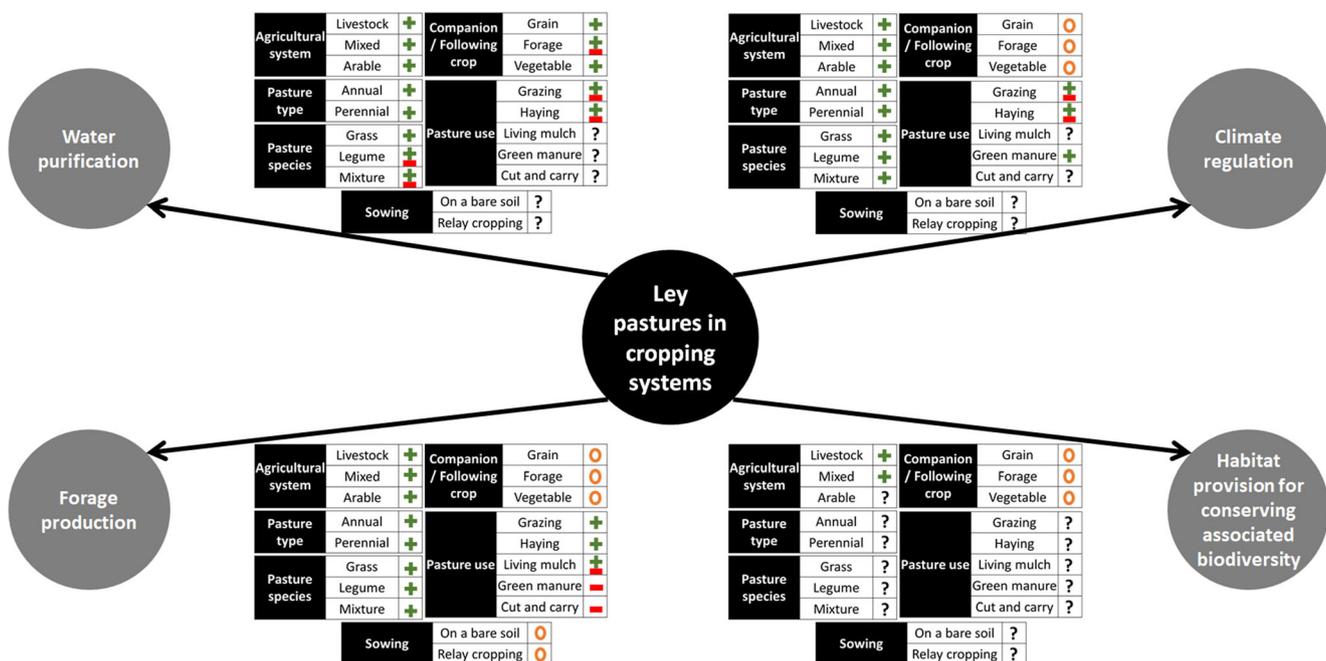


Fig. 4 Synthesis of the effects of introducing ley pastures in cropping systems on output ecosystems services according to the management options considered in this review. Symbols have the following meaning: known positive effects (plus sign), known negative effects

(minus sign), known as a non-key factor (0), unknown effect (question mark), and positive or negative effect depending on management (plus-minus sign)

cultivation. In addition, ley pastures promote pesticide retention and degradation through biotic and abiotic processes (Parkin 1993), depending on the soil's ability to adsorb pesticides from the soil solution, adsorb them to the soil matrix, and degrade them. SOM can adsorb pesticides and favor degraders of organic compounds, thus improving filtering capacity. Thus, an increase in SOC such as that during the ley pasture period improves the soil's general ability to filter organic pesticides. Soil bioturbation by earthworms, which are abundant below ley pastures, may also influence distribution and degradation of organic compounds such as pesticides (Monard et al. 2008).

4.2 Climate regulation

C storage by pastures is an important mechanism to mitigate climate change (Pellerin et al. 2017; Klumpp and Fornara 2018). While there is general agreement on trends in C storage or release, more precise estimates vary widely in the scarce literature focused on cropping systems integrating ley pastures. Converting cropland into pastureland results in C storage for several years (Don et al. 2009; Johnston et al. 2017). Meta-analyses have estimated a few annual storage rates (Mg C/ha/year) in the topsoil (0–30 cm): 0.54 (Conant et al. 2001), and 0.60 over 30 years (Loiseau and Chevallier 2002). In a study analyzing conversion to pastureland and “deconversion” to cropland, Poeplau et al. (2011) predicted mean C storage and release rates of 0.92 ± 0.25 and 2.08 ± 0.26 Mg C/ha/year, respectively, over 20 years.

The rate of C storage or release is known to vary with pasture age (Franzuebbers et al. 2000; Johnston et al. 2017; Conant et al. 2001). For the first 2–3 years, a pasture stores C in the topsoil due to C input (Whitehead et al. 1990) and then begins to store it in deeper soil layers (Rumpel and Chabbi 2018). Similarly, the rate of C release decreases quickly after the pasture is killed, with losses of 50–80% of the initial C stock (Guo and Gifford 2002; Lal 2008). Little literature is available that describes effects of ley pasture duration on soil C dynamics. A long-term experiment on a soil with high initial C stock (90 t C/ha from 0 to 25 cm) compared SOC dynamics under 48-month maize-pasture crop sequences including 6, 12, 18, and 42 months of grass-based ley pastures: in all cases, SOC decreased at a rate inversely proportional to pasture duration (Vertès and Mary 2014, 2007), as also shown by Rumpel and Chabbi (2018). Even in soil with high initial C content and a hayed pasture (which inputs less C to the soil than grazed pasture), only the crop sequence with 42 months of pasture and 6 months of maize strongly limited the decrease in C stock (–5% over 27 years), as modeled by Dollé and Klumpp (2015), who suggested that 7-year ley-arable crop sequences should have ley pastures for at least 3 years to keep SOM stock stable. This is however highly dependent on initial C stock and on other organic matter management

implemented in the arable phase (tillage practices, presence/absence of cover crops, management of crop residues, and fertilization practices). Clivot et al. (2019) and Constantin et al. (2010) found lower soil C and N release, respectively, when integrating ryegrass (*Lolium* sp.) cover crops in arable cropping systems than when leaving soil bare during winter (–30% and –22% of initial C stock, respectively). However, since the rate of C storage decreases with increasing C stock (Minasny et al. 2017), ley pastures and cover crops are expected to be able to store more C per year than permanent grasslands (Pellerin et al. 2019). Little literature is available that describes effects of the species sown on C storage (Fig. 4; Lange et al. 2015), although C storage may be higher under species-rich mixtures (Skinner and Dell 2016). After 4 years, Steinbeiss et al. (2008) reported increases in carbon stocks in the complete plow horizon by nearly 50% and by more than 100% when moving from 1 to 2 species sown and from 1 to 16 species sown, respectively.

Although little is known about impacts of emerging uses of ley pastures (e.g., living mulch, cut and carry), traditional uses (mainly grazing and haying) may counteract positive effects of pastures on climate-change mitigation (Fig. 4), especially in livestock and mixed farms as ruminants are high contributors to greenhouse gas emissions through methane emissions from enteric fermentation in their rumen. Those methane emissions are mainly related to the digestibility of ingested feed (Sauvant et al. 2011) which is usually high (75–80%) in grazed grass, lower in silage maize or grass silage (70–72%), and lower in late hay and poor feeding quality grasslands (INRA-CIRAD-AFZ 2018). Ingestion rates also vary with animal needs and feed quality. Thus, the contribution of ruminants to greenhouse gas emissions varies with animal management especially feeding management (Basset-Mens et al. 2009), and results depend on the functional units used (per unit mass of animal product, per ha, per produced value; Salou et al. 2017). Emissions related to other types of pasture use (e.g., living mulch) have not been extensively documented to date. In presence of living mulch, Bartel et al. (2017) found decreases in maize yield from 23 to 73% and subsequently decreases in ethanol yield from 12 to 119% leading to higher emissions per unit mass of product and per hectare. Kura clover (*Trifolium ambiguum* M. Bieb.) living mulch in corn-soybean systems increased N₂O emissions (from 131.3 to 226.5 mg N/m² on year 1 and from 72.8 to 161.3 mg N/m² on year 2) even with a 43% reduction of N fertilizer application rate (Turner et al. 2016). However, the use of living mulch might reduce nitrate leaching and result in lower indirect (offsite) N₂O emissions. When including other activities of pasture-based dairy cattle systems such as storage, processing, and application of manure, no clear trends in greenhouse gas emissions emerge from comparisons with those of maize-soybean dairy cattle systems. Life cycle assessments on the topic (Thomassen et al. 2008; Nguyen et al. 2013a, b) estimated high variability

in climate-change impacts depending on the main features of the production system (e.g., grazing management, presence/absence of crops and cover crops, cow productivity) and the functional unit used.

Finally, since bare soil generally has lower albedo than vegetation, using ley pastures as cover crops (for several months) in arable crop farms or long-term cover (for several years) in mixed or livestock farms could help mitigate climate change (Fig. 4). Carrer et al. (2018) recently estimated that introducing 3-month cover crops to 4.2% of the EU-28's area, corresponding to 22% of its agricultural area, would provide a mitigation potential of 3.16 Mt CO₂-eq/year. This albedo-related mitigation potential corresponds to 0.74% of the EU-28's annual agricultural greenhouse gas emissions (reference year: 2011), which would be added to the mitigation potential of soil C storage. This mitigation potential could increase by 27% if cover crops lasted longer than 3 months but decrease by 28% if no irrigation were used to support cover crop emergence. These initial results indicate that effects of ley pastures on soil water flows and albedo must be considered jointly in future research.

4.3 Habitat provision for conserving associated biodiversity

The vast expansion and extreme intensification of agriculture is one of the major drivers of natural habitat fragmentation and loss of farmland biodiversity (Wade et al. 2007; Lu et al. 2014), especially of natural enemies and pollinators (Meyer et al. 1992; Benton et al. 2003; Tscharntke et al. 2005). These negative consequences have been in the spotlight recently, with studies claiming that 40% of world insect species are threatened with extinction due to current agricultural practices (Hallmann et al. 2017; Habel et al. 2019; Sánchez-Bayo and Wyckhuys 2019). Ley pastures have a key role to play in the redesign of agricultural systems in order to maintain and improve biodiversity and populations of species, especially endangered species and organisms used for biocontrol such as natural enemies of pests (Stuhldreher et al. 2012).

It is widely accepted that both ley and semi-natural pastures play a vital role in maintaining biodiversity in many agricultural areas since they provide overwintering sites, food resources, refuges, and source populations for recolonization of disturbed habitats (Tscharntke et al. 2005; Chaplin-Kramer et al. 2011). There is increasing evidence that ley pastures may support many arthropod species, birds, small mammals, and vascular plants (Benton et al. 2003; Burel et al. 2004; Hendrickx et al. 2007; Billeter et al. 2008; Duflot et al. 2014). Likewise, populations of many species, including the blue spot hairstreak butterfly (*Satyrrium spini*) in the Spanish Pyrenees, the marsh fritillary butterfly (*Euphydryas aurinia*), and butterfly orchid (*Platanthera chlorantha*) in Culm pastures in the UK (Gardiner et al.

2005) and common starlings in Europe (Smith and Bruun 2002), have declined as the area of permanent pastures has decreased due to land-use change.

When focusing exclusively on impacts of ley pastures on habitat provision and biodiversity conservation, much less scientific literature is available (Fig. 4). Nonetheless, Duflot et al. (2015) observed that landscapes with ley pastures had the same species richness of carabid beetles and vascular plants as those with semi-natural pastures, probably due to similar agricultural practices (e.g., grazing, haying, fertilization, oversowing with desirable plants). Similar results were found for Chironomidae populations in other landscapes (Burel et al. 1998). In contrast, common vole populations had much higher abundance on ley pastures (Delattre et al. 2009). Arthropod abundance and diversity may also depend on the species sown; for example, grasshoppers had lower densities in alfalfa pastures than in other ley pastures (Bretagnolle et al. 2011).

However, it is unclear to date whether reintroduction of ley pastures to intensive arable-crop areas or emerging uses of ley pastures may have similar impacts on conserving associated biodiversity. Moreover, there is also evidence that ley pastures serve as a reservoir for secondary pest infestation, such as wireworms, which can severely damage potato fields (Parker and Howard 2001; Hermann et al. 2013), requiring additional pest control (East and King 1977; Willoughby et al. 1997; Delattre et al. 2009; Vernon and van Herk 2013).

4.4 Forage production

Producing forage is of primary interest for feeding ruminants in mixed and livestock farms. The value of forage depends on the quantity and quality of shoot biomass harvested and consumed by animals (Ball et al. 2001). Several factors strongly influence ley pasture productivity, including climate (particularly solar radiation, rainfall, and temperature; Gosse et al. 1986; Jones and Lazenby 1988; Gastal and Durand 2000; Huyghe et al. 2014), botanical composition, soil characteristics, and pasture management, particularly fertilizer application and haying and/or grazing (Lemaire et al. 2000). Official statistics on ley pasture productivity in European countries are lacking (Lee 1988; Smit et al. 2008). The data available come from survey summaries or predictions of pasture-growth simulation models (e.g., Duru et al. 2009; Durand et al. 2010). Pure grass stands have the highest yields in temperate regions of northwestern Europe (latitudes 52–57° N) with on average 8–11 (up to 15) t dry matter (DM)/ha/year (Graux et al. 2020) when sufficient nutrients are available. However, pastures rarely receive enough fertilizers to achieve the non-limiting conditions that would maximize biomass production. In southern Europe (Mediterranean countries and southern Portugal), water stress usually limits productivity and can decrease yields to 1–5 t DM/ha/year or less (Durand

et al. 2010; Poirier et al. 2012). In all regions of Europe, pure legume stands generally have lower yields than pure grass stands under high N fertilization, but higher yields than pure grass stands under low N (Nyfeler et al. 2011; Finn et al. 2013). In pure legume stands, alfalfa (*Medicago sativa*) and red clover (*Trifolium pratense*) have the highest annual yields: 11–15 t DM/ha/year in favorable temperate areas (e.g., 13 t DM/ha for alfalfa in the Champagne-Ardenne region, France from 1980 to 2012; Huyghe et al. 2014). Unirrigated alfalfa has lower yield (Durand et al. 1989), 2.0–5.5 t DM/ha/year in Mediterranean climates (Julier et al. 2017), and protein content (Lemaire et al. 1989). For both grasses and legumes, potential productivity varies over time: it is lowest during the establishment year, peaks for the 2–3 years that follow, and then often decreases depending on the species (Beuselinck et al. 1994). Consequently, species mixtures often increase the longevity of ley pastures (Capitaine et al. 2008) under low-input management. Mixed-species stands, especially those with grasses and legumes, can achieve higher yields (Capitaine et al. 2008; Nyfeler et al. 2009). Mixed-species stands commonly “overyield” (i.e., produce more yield than those of pure stands of each species in the mixture) in all climates by up to 0.5–4.0 t DM/ha/year (Finn et al. 2013). Forage production by pastures can also produce bioenergy (66–119 GJ/ha/year, depending on pasture type and soil depth) (Rösch et al. 2009).

Forage quality aggregates effects of ingested forage on animal performance (Ball et al. 2001). It encompasses forage nutritive value (i.e., digestibility and nutrient contents) as well as indigestibility and anti-quality factors (i.e., compounds that can lower animal performance, such as tannins, alkaloids, cyanoglycosides, phytoestrogens, and mycotoxins). The feed value of forages is closely related to their botanical composition (grass, legume, and forb proportions), yield, maturity stage and organ composition at harvest, and pasture management, especially fertilization. For all types of ley pasture, forage digestibility and biochemical composition vary throughout the year (generally lower in summer; see Lemaire et al. (1989) for alfalfa digestibility) and as a function of plant growth (Lemaire et al. 1989; Ducrocq and Duru 1996; Duru et al. 2008). Forage digestibility decreases as plant tissues age, related to phenology. The proportion of structural organs increases with plant age (e.g., decreasing leaf-to-stem ratio, increasing proportion of reproductive organs; Lemaire et al. 1989; Duru et al. 2008), decreasing contents of digestible compounds (e.g., crude protein, soluble sugars) and increasing fiber content. Accordingly, forage digestibility usually decreases linearly with plant age and allometrically with yield (Duru et al. 2008; Gastal et al. 2015). From early to late growth stages, forage digestibility decreases from 750 to 400 g/kg, respectively, in alfalfa (Lemaire et al. 1989) and from 800 to 550 g/kg, respectively, in cocksfoot under high N fertilization (Duru et al. 2008). For a given productivity level, legumes usually have higher crude protein content than grasses but lower energy

content. Grass species and varieties of different productivity levels can also differ in digestibility for a given yield (Baumont et al. 2007). Finally, species mixtures generally have a more adequate protein:energy ratio than pure species do (Baumont et al. 2008) due to complementarities in their compositions that make the mixture slightly more digestible than the weighted average of each species (Brown et al. 1991).

5 Which diversity of ley pastures for tomorrow's cropping systems?

5.1 Pasture species composition

A pasture may contain one (pure stand), two (association or binary mixtures), or multiple species (complex mixtures or multispecies pastures). Pure species pastures have been sown widely since the 1960s to secure the nature, amount, and composition of harvested forage, as long as fertilizers and/or herbicides could be applied.

Mixtures of perennial grass and legume species are considered essential to provide ecosystem services (Fig. 1) under low-input management (Porqueddu et al. 2016; Lemaire et al. 2015). Grasses and legumes form two complementary functional groups (Roscher et al. 2004): legumes can fix atmospheric N through symbiosis, while grasses absorb NO₃ efficiently and have higher productivity. Achieving balance between species, and especially persistence of legumes over several years, is key (Kirwan et al. 2007). A legume proportion of 0.3–0.7 is considered the most effective for producing N to maximize yield (Nyfeler et al. 2011). Species within each functional group have contrasting traits related to factors such as above- and belowground growth, earliness, and chemical composition (Roscher et al. 2004). Since taller species may outcompete shorter species for light, mixtures usually combine species of similar potential height, either tall (e.g., alfalfa/*Medicago sativa*, red clover/*Trifolium pratense*, cocksfoot/*Dactylis glomerata*, tall fescue/*Festuca arundinacea*) or short (e.g., white clover/*Trifolium repens*, perennial ryegrass/*Lolium perenne*, timothy/*Phleum pratense*, smooth meadow grass/*Poa pratensis*). Water and mineral acquisition also depends on root depth and architecture (Gastal et al. 2010). Although plant architecture shows plasticity, the rooting system of forage species is described as deep (e.g., alfalfa, tall fescue), intermediate (e.g., red clover/*Trifolium pratense*, perennial ryegrass/*Lolium perenne*), or shallow (e.g., white clover/*Trifolium repens*, cocksfoot/*Dactylis glomerata*) (Gastal et al. 2010). Mixing species with different rooting depths increases exploration and exploitation of soil resources (Gastal et al. 2010). Because growth dynamics of grasses and legumes differ after sowing, after haying and among seasons, grass-legume mixtures cover the soil throughout the year and thus provide weeds with less opportunity to develop than pure stands (Helgadottir et al. 2018; Hayes et al. 2018) and limit soil erosion

(Porqueddu et al. 2016). The species selected for multiservice pastures must be adapted to specific soil, management, and climatic constraints (Frick et al. 2008; Lüscher et al. 2017).

The optimal number of species in ley pastures is controversial. Species richness has long been recognized as a key driver of pasture productivity (Hector and Hooper 2002, citing Darwin 1858). Increasing species richness in a pasture stabilizes biomass production over time (Gross et al. 2014) and in space (Weigelt et al. 2008). These advantages emerge from species traits and species interactions. Species' functional traits, especially N acquisition and use, explain biomass production better than species richness (Buchmann et al. 2018). Maximizing rooting depth and root distribution by selecting species adapted for the pasture is a priority to increase water uptake throughout the soil profile (Barkaoui et al. 2016). Pasture species diversity has been shown to influence the habitat provision service, with more diverse pastures having greater diversity in above- or below-ground organisms (Schaffers et al. 2008, 2010) and lower susceptibility to biological invasion or pathogen infestation. As for biomass, damages caused by insect or mollusk herbivory are related more to species traits than to species richness (Scherber et al. 2006).

The EU authorized the sale of seeds of species mixtures for forage production in 2004 (Commission Decision 2004/371/EC); since then, all seed companies have developed mixtures for specific uses. The species chosen for sowing in a new pasture is key. General rules have been established to benefit from complementarity and decrease competition between species. The need to choose at least one grass and one legume species emerges from their complementarity in N-use efficiency. Since competition and complementarity between the species chosen interact with forage use by animals and local conditions of soil, climate, and management, expert systems have been developed to help farmers choose the most adapted mixtures (AFPF 2017a, b; Frick et al. 2008; Goutiers et al. 2016; Lüscher et al. 2017). Recently, detailed ecophysiological models have helped decipher the influence of complex interactions of environmental variables on mixed-species yield and quality (Gaudio et al. 2019; Faverjon et al. 2019). More precisely, models can be used to identify important traits to consider when mixing legume and non-legume species to achieve both productivity and stability (Louarn et al. 2018). Such tools could be used for testing yield, quality, and persistence of different species mixtures.

5.2 Choice of varieties for mixtures

In the most important forage species, available varieties have been improved for forage yield, forage quality, abiotic stress (mainly frost), and biotic stress (diseases). Farmers choose varieties because of their adaptation to different climates or uses, based on their autumn dormancy (for alfalfa/*Medicago sativa*) or flowering earliness (for grasses) (Annicchiarico et al. 2015;

Humphreys et al. 2006). Recently, traits related to adaptation to climate change and reduced inputs such as tolerance to drought (Ergon et al. 2018), low NO₃ fertilization for grasses (Pembleton et al. 2016), low P fertilization (Lopez-Arredondo et al. 2014), and competition with weeds (Annicchiarico and Pecetti 2010; Dear and Ewing 2008) have been identified, but their consideration in breeding programs requires costly phenotyping. Stand persistence, a trait that contributes not only to forage production but also indirectly to soil conservation is considered, but it is difficult to assess when the release of genetic progress (i.e., new traits exhibiting in the field) requires a minimum duration of experiments (usually 3 years).

For many traits (e.g., resistance, quality), the genetic progress achieved for pure stands is probably also useful when two or more species are mixed, with one or more varieties of each species. However, several results show that pure stands have different hierarchies of traits than mixtures (Maamouri et al. 2017). For example, lodging resistance is a major trait of interest in alfalfa (*Medicago sativa*) grown in pure stands, but alfalfa almost never lodges when it is grown in mixtures with grasses; thus, the focus on lodging resistance can be relaxed. Properties that emerge from grass-legume mixtures (e.g., N fixation and recycling (Louarn et al. 2018), weed and pest control, forage quantity and quality with low inputs) are determined by plant traits that should be selected for, in a view to breed new varieties specifically adapted to forage-species mixtures. Classes of aggressiveness or compatibility, such as those based on leaflet size in white clover, could be defined and used to reduce the number of variety mixtures. In addition, like for species choice, ecophysiological models could be used to design new ideotypes characterized by average trait values (Louarn et al. 2018). In a view to breed new varieties, populations with appropriate traits for breeding new varieties could thus be virtually pre-selected to reduce the otherwise large number of mixtures to assess in the field.

The degree of within-species genetic diversity in a mixture may also be key. Recent studies strongly suggest that using several varieties per species rather than only one secures yield, stability, and legume proportion in the stand (Meilhac et al. 2019) and increases drought tolerance and persistence of the stand (Prieto et al. 2015). Mixing varieties in multispecies pastures is an additional complexity but a promising way to improve pasture value.

6 Research agenda

6.1 Defining a safe operating space for ley pastures in cropping systems

To address the challenges of climate change, food security, and human health, agrifood systems require deep change, especially a decrease in livestock production and consumption

in developed countries (Tilman and Clark 2014). Monogastric animals such as pigs and poultry produce protein more efficiently than ruminants. However, ruminants can be fed from permanent pastureland and wetlands unsuitable for crop production, thus avoiding competition with human food production. On this basis, as mentioned, most future-oriented food system scenarios assume production of fewer ruminant livestock and feeding them only from permanent pastureland and wetlands (Westhoek et al. 2014; Schader et al. 2015; Rööß et al. 2017). These scenarios ignore ley pastures or sharply reduce them despite the large set of ecosystem services they provide, including better composition of animal products for human health (Duru et al. 2018) when their spatial and temporal insertion within cropping systems is well-managed. Only Poux and Aubert (2018) considered ley pastures when designing a sustainable European food system scenario called “Ten Years For Agroecology” (TYFA) to feed the European population in 2050. This scenario relies on a profound revision of the human diet, with less protein and a lower proportion of it coming from animal products, no mineral fertilizers or agrochemicals for crop production, and no importation of soybeans. The authors used certified organic farming as a model to design the scenario because a large amount of consolidated data about its performances, especially yield, is already available. In the TYFA scenario, biological N fixation is the only source of N input to crops, and much of it is provided by legume-based ley pastures and, to a lesser extent, by grain legumes whose fixed N is recycled via previous-crop effects or via livestock manure deposited on other crops such as cereals. In the scenario, ley pastures are also assumed to play a central role in biological regulation of pests, thus replacing pesticides. The authors concluded that supplying Europe with healthy food in 2050 would require more equal distribution of pastures in Europe, even in areas specialized in arable cropping. In line with the TYFA scenario, we claim that the role and importance of ley pastures in tomorrow’s cropping systems should be reconsidered through an ecologically intensive lens that brings together new technologies and organizations at multiple levels.

To benefit from ecosystem services provided by ley pastures in cropping systems while limiting their disservices to thresholds compatible with international commitments (e.g., greenhouse gas emissions) and/or political choices (e.g., feed/food competition for land use), it appears necessary to define a “safe operating space” (Rockström et al. 2009; Buckwell and Nadeu 2016) for ley pastures in cropping systems. The practical questions are how to identify this safe operating space and how to transition cropping systems into this space. To expand upon this concept, we describe what this space could be, considering only a few services and disservices. As disservices, we considered degrees of feed/food competition for land use (as a % of total land dedicated to livestock feed production; Fig. 5, Y-axis) and greenhouse gas emissions of cropping systems including ley pastures

(e.g., crop–livestock farms, cover crops) (as kg CO₂ eq./ha/year; Fig. 5, Y-axis). Greenhouse gas emissions increase as ley pastures are increasingly used to feed livestock. In a scenario in which all arable land is used to produce food, land-use competition begins as soon as arable land is used for ley pastures instead of food crops (Fig. 5, X-axis). A threshold is defined for each disservice to represent the sustainability boundary and the levels of disservices are plotted relatively to these thresholds. However, ley pastures provide bundles of ecosystem services such as N supply (kg N/ha/year), C storage (kg C/ha/year), and biological regulations allowing to reduce pesticide use (load avoided/ha/year or treatment frequency index reduction in %) more or less proportionally not only to their relative area but also to their spatial and temporal insertion within cropping systems, up to a known level of maximum benefits. Increases in the provision of services are plotted relatively to each of those levels of maximum benefits. Beyond those points, the relationships may keep increasing, remain stable or even decrease, and eventually become negative (Fig. 5, green triangles). For example, beyond a given area of legume-based ley pastures in cropping systems, N supply may become excessive and create disservices. The safe operating space for ley pastures in cropping systems is the space located between the maximum level of services observed and the lowest boundary of disservices, here defined by N supply by legumes and greenhouse gas emissions, respectively (Fig. 5).

The range of the levels of ecosystem services and disservices provided by ley pastures depends mainly on the relative durations of ley pastures within crop sequences in cropping systems (Fig. 5, horizontal arrows) and on pasture management, especially the relevance of their spatial and temporal insertion within cropping systems (Fig. 5, vertical arrows). For example, stocking rates of ley pastures must be adapted to pasture characteristics (e.g., annual or perennial, species sown) and level of intensification (e.g., fertilization, frequency of use). Currently, certain issues need to be addressed to reach the safe operating space for ley pastures in cropping systems. Several environmental factors influence the levels of services and disservices that can be reached. For example, annual pasture productivity is often limited by nutrient availability in temperate European regions. In addition, the probability that sowing will fail has increased in southern Europe due to climate change. Thus, strategies to reach the safe operating space for ley pastures in cropping systems should be defined at the regional level based on regional characteristics (e.g., pedoclimatic conditions, landscape structures).

Currently, defining and moving towards the safe operating space for ley pastures in cropping systems requires (i) adjusting breeding programs to consider multiservice ley pastures (Annicchiarico et al. 2019), (ii) addressing ley pasture management issues that may decrease disservices through better management or use of new technologies (e.g., new varieties and species mixtures), (iii) better quantifying the

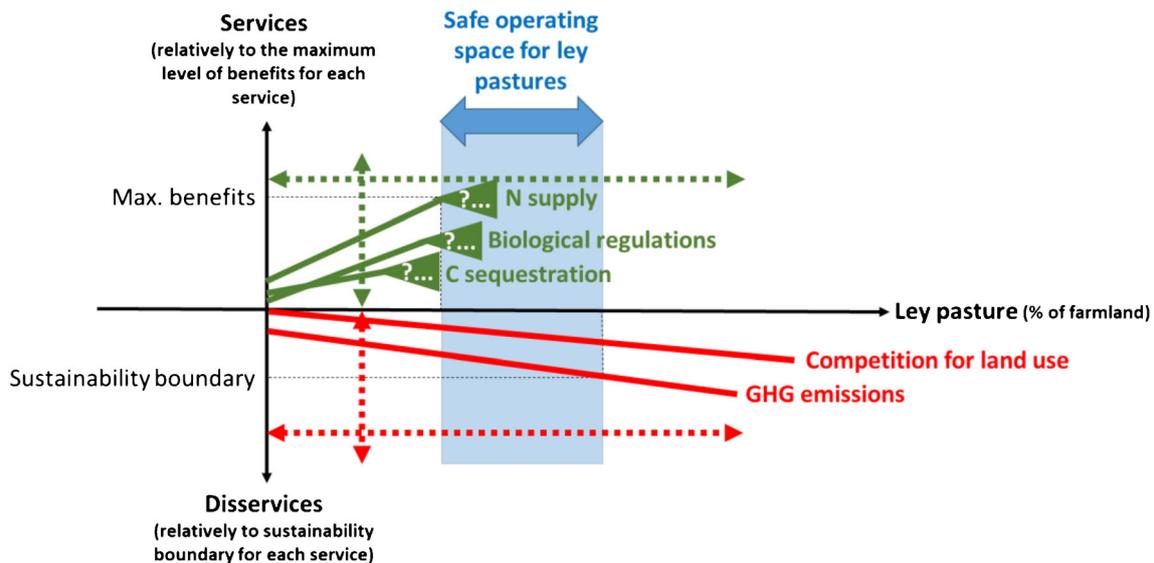


Fig. 5 A framework for defining a safe operating space for ley pastures in cropping systems according to their services and disservices (adapted from Buckwell and Nadeu (2016)). Illustration is provided for 3 services and 2 disservices. The safe operating space for ley pastures in cropping systems is the space located between the maximum level of services observed and the lowest boundary of disservices. Evolution of services and disservices are plotted relatively to their known maximum levels of benefits and sustainability boundaries, respectively. Triangles indicate the uncertainty on the levels of services provided beyond a

given area and frequency of ley pastures in cropping systems. Dotted vertical arrows indicate the range of the levels of services and disservices provided by ley pastures (along the Y-axis), which depend on ley pasture management, particularly the relevance of the spatial and temporal insertion of ley pastures within cropping systems. Dotted horizontal arrows indicate range of the levels of services provided according to the relative area and frequency of ley pastures used to produce livestock products (vs. other uses such as living mulch and green manure). *GHG* greenhouse gas

ecosystem services bundles they provide, and (iv) identifying acceptable societal compromises at multiple scales and translating them into policy decisions (e.g., regulations, incentives)

6.2 Breeding varieties for multiservice pastures

With some exceptions, variety selection and assessment are performed in pure stands. Breeding for mixtures is far more difficult, since it requires either choosing a typical mixture (e.g., alfalfa-cocksfoot/*Medicago sativa*-*Dactylis glomerata*, perennial ryegrass-white clover/*Lolium perenne*-*Trifolium repens*) or considering a huge number of mixture types (i.e., species, and the number of them). In addition, the one or more companion species chosen could affect how a given new variety performs in a mixture. These practical issues, combined with the major influence of the species themselves (and their varieties) on mixture traits, as mentioned, have strengthened the relevance of breeding in pure stands. Consequently, forage varieties recommended for mixtures are often chosen from those that have been bred and tested in pure stands, for example, in Switzerland (Suter et al. 2008; Frick et al. 2008). However, several experiments have shown that variety or genotype ranking in pure stands differs from that in mixtures (Maamouri et al. 2017; Waldron et al. 2017). This suggests that breeding to improve mixtures is of major importance, as previous studies have concluded (Litrice and Violle 2015).

In a literature review, selection for yield in pure stands was found to produce predicted yield gains that were 40% lower, on average, than selection for yield in mixed stands (Annicchiarico et al. 2019). Breeding for mixtures has been conceptualized using the concepts of “general combining ability” (GCA), which refers to the average value of a variety in any mixture, and “specific combining ability” (SCA), which equals the difference between the observed value of a mixture and the average GCA of the components of the mixture (Gallais 1970). Since GCA is usually much higher than SCA (Maamouri et al. 2015), varieties can be selected based on their GCA. In a theoretical study, the genetic progress in a GCA selection program, in which the GCA of the two species are improved in parallel, was higher than that in a “reciprocal combining ability” selection program (Sampoux et al. 2020). Both programs are more efficient than selection in pure stands.

In parallel, a functional approach based on relationships between traits and services could be used. In this approach, the main traits responsible for resource acquisition, complementarity, and competition are identified (Litrice and Violle 2015). This information can be used to define breeding traits in the first step of a selection cycle. For example, for an alfalfa-grass mixture in which the grass has low persistence because the alfalfa (*Medicago sativa*) shades it, an objective would be to select alfalfa plants with shorter stems and a less erect growth habit than the usual tall and erect ideotype

(Maamouri et al. 2015). Similarly, white clover (*Trifolium sp.*) genotypes with long petioles, large leaves, and strong ability to produce stolons can compete better with perennial ryegrass (*Lolium perenne*) (Davies 2001; Annicchiarico 2003). This kind of selection can be performed easily in a nursery of isolated plants or after progeny testing, in which the most adapted genotypes would enter the GCA selection program mentioned. This approach applies to all traits involved in interactions between plants in mixtures, including light interception, nutrient and water capture, and temporal resource use, and refers to aboveground plant architecture (e.g., height, branching, leaf area, growth habit), rooting depth, root distribution, and phenology.

Evolutionary plant breeding, based on the spontaneous dynamics that drive selection of genotypes in a multispecies pasture over time under a variety of constraints (Litrice and Violle 2015), could be an alternative. Its efficiency relies on the hypothesis that fitness and agronomic value are correlated. The hypothesis may be true if the surviving plants carry traits that confer both competitive ability and yield potential (e.g., plant height) but false if the surviving plants escape stress (e.g., grazing) only because of a prostrate growth habit and low aboveground biomass. Regardless of the breeding method, including the systems-based plant breeding (Lammerts van Bueren et al. 2018) that targets all components of sustainability, breeding programs that aim to improve the varieties used in mixtures should define specific ideotypes and test promising progeny in mixtures before releasing new varieties.

6.3 Developing a knowledge base on ways to introduce ley pastures into cropping systems

While traditional ways of sowing and using ley pastures (e.g., haying, grazing) are well-documented in the literature, this is much less the case for emerging ways (e.g., living mulch, cut and carry). Yet, these new forms of introduction of ley pastures into cropping systems could enhance the ecosystem service bundles and decrease the disservices previously mentioned. Improving knowledge about technical and organizational innovations that help introduce ley pastures into cropping systems is needed.

Intercropping is one emerging way to introduce ley pastures into cropping systems. It is a known technical innovation used to limit disservices and enhance ecosystem services in agriculture by taking advantage of functional complementarities among species (Cong et al. 2015). Intercropping takes the form of mixed intercropping (simultaneously growing two or more crops with no, or a limited, distinct arrangement), relay intercropping, and strip intercropping (growing two or more crops simultaneously in strips, allowing for crop interactions and independent cultivation; Brooker et al. 2015). Farmers are broadening this practice to the introduction of ley pastures into low-input cropping systems in at least three ways: sowing ley

pasture at the same time as a cash crop (simultaneous intercropping), oversowing ley pasture in an established annual crop as a relay crop, and undersowing an annual crop into the living mulch of ley pasture (Hartwig and Ammon 2002). In the last case, the pasture can remain on the field even after the cash crop is harvested.

Australian farmers have sown pastures at the same time as crops since the 1920s, primarily to offset costs of establishing ley pastures in cropping systems by selling grain (McCormick et al. 2014). The many experiments performed since then have reported that it decreases annual pasture seedset and perennial density. Yet, most farmers in southeastern Australia continue this practice (McCormick et al. 2014), indicating that research may underestimate its benefits. A few studies in Canada and France have addressed simultaneous or relay intercropping of ley pastures in established autumn-seeded winter rye (*Secale cereale*) and winter wheat (*Triticum aestivum*) (Edwards 1998), mostly in organic systems (Amossé et al. 2013a, b; Vrignon-Brenas et al. 2016, 2018). There, the short-term ley pasture was considered a cover crop between two cash crops, the services provided being enhanced by relay sowing. Although the practice of cover cropping is developing, relay intercropping of short-duration ley pastures as cover crops remains uncommon. Ley pastures as living mulch for winter cereals (Thorsted et al. 2002; Carof et al. 2007a; Kosinski et al. 2011; Barilli et al. 2017) and sugar beet (Kunz et al. 2016) have also seldom been studied. Most of these studies reported a significant decrease in weed pressure, an occasional increase in N content in the cash crop but frequently a sharp decrease in crop yield. However, some organic farmers value this practice greatly.

Crop–livestock integration is another way to promote introduction of ley pastures into cropping systems and can occur either at the farm level (Ryschawy et al. 2012) or among farms (Martin et al. 2016). While the former has long been studied and offers well-known opportunities for ley pastures in cropping systems, the latter is a more recent practice that has potential to improve interactions between crops and ley pastures. For example, in specialized crop-production areas experiencing weed and soil-fertility issues, reintroducing transhumant herds managed by independent shepherds to crop farms from mid-autumn to mid-spring before moving to summer mountain pastures is a promising option under development. It may allow crop farmers to reintroduce both short-duration ley pastures as cover crops that the herds can graze as well as perennial ley pastures (e.g., of alfalfa/*Medicago sativa*) that can reduce weed pressure and increase N supply for the following crop.

Knowledge of these technical and organizational options remains limited. As highlighted by McCormick et al. (2014) and Brooker et al. (2015), the major research challenges remain understanding complex interactions in these systems

(e.g., competition between the crop and pasture for light, soil water, and nutrients) and the dependence of these interactions on the context. To this end, experiments need to be performed. Testing cropping systems in realistic on-farm contexts may also provide an effective communication platform to facilitate spread of technical knowledge to commercial farms (Lechenet et al. 2017). Modeling approaches, combined with field experiments, can help gain insight into the complexity and long timeframe of this topic. Tracking on-farm innovations (Casagrande et al. 2017) can help identify promising technical innovations and provide knowledge to other farmers, inspiring them to design their own practices. Tracking farmer practices can provide insight into factors limiting or favoring new techniques.

6.4 Assessing bundles of ecosystem services provided by ley pastures in cropping systems

As mentioned, there is much evidence that ley pastures deliver many ecosystem services, but the question of how to bundle these services is difficult to answer since trade-offs may occur. Trade-offs between ecosystem services occur when delivery of one service decreases because that of another service increases. To address this question, we stress the need to consider the processes at the source of ecosystem services, a multiscale approach in space and time, and the influence of ley pasture management.

Rodríguez-Ortega et al. (2014) reviewed studies assessing trade-offs among multiple services at multiple scales (i.e., field, farm, and landscape) in grassland-dominated landscapes. Taking the example of the trade-off between forage production and bird conservation (e.g., Sabatier et al. 2013), they showed that at the field level, it was necessary to adjust grazing intensity over time to ensure conservation of several bird species by minimizing nest trampling and creating optimal grass heights for bird survival without decreasing forage production greatly. At the farm level, hayed and grazed pastures offered contrasting habitats for birds and contrasting feeding resources for livestock. The proportions of hayed/grazed fields in the farm area thus formed the key mechanism for adjusting the supply of both ecosystem services. At the landscape scale, increasing landscape heterogeneity by changing the spatial arrangement of hayed and grazed pastures increased bird populations without decreasing pasture production. The benefits of heterogeneous land use emerged from a set of interacting suboptimal habitats, in which each type of land use provided some of the resources needed, and species' mobility among land-use types enabled their populations to obtain the resources they needed.

Addressing trade-offs among these two ecosystem services in grassland-dominated landscapes required much effort and a combination of observations and simulation modeling. Thus, few studies consider more than two ecosystem services when

analyzing how their interactions support crop production. Garibaldi et al. (2018) analyzed two-way interactions among biotic pest regulation, pollination, and nutrient cycling on crop yield. They found that these three regulating services tended to have complementary or synergistic effects on crop yield and concluded that biodiversity-friendly practices, such as conserving (semi-) natural areas, promoting crop-sequence diversity, and increasing landscape heterogeneity, could alleviate multiple constraints on crop yield. However, their analysis was based on 20 analyses of two-way interactions from 16 studies and did not address the outlets for diversified crops and pastures that may represent lock-ins that impede their reintroduction. This result again shows the complexity of addressing ecosystem service bundles and their location-specific occurrence beyond trade-offs between two given ecosystem services.

Given the classic trade-off between food production and many regulating and cultural services, it is difficult to enhance all ecosystem services simultaneously (Dumont et al. 2018). However, by comparing conventional and organic farming in 12 dimensions of sustainability formulated as services (e.g., increase soil quality, minimize water pollution), Reganold and Wachter (2016) showed that organic farming tends to provide improved bundles. One reason for this may relate to the current place of ley pastures in cropping systems. A recent meta-analysis systematically compared organic and conventional crop sequences at the global scale (Barbieri et al. 2017). It showed that organic farming uses land differently than conventional farming: overall, crop sequences of the former are 15% longer and result in higher diversity and more even distribution of crop species. These changes are driven by higher area and frequency of ley pastures (e.g., alfalfa/*Medicago sativa*, clover/*Trifolium sp.*, clover-grass, Italian ryegrass/*Lolium multiflorum*), catch crops, and cover crops, mostly to the detriment of cereals. Again, the main limits of these studies are that they rely on partial assessment of one or a few ecosystem services and do not address trade-offs among these services when measured at the same location. A key challenge thus lies in performing more integrated assessment of ecosystem service bundles for several cropping systems including ley pastures in order to compare them to those of cropping systems based only on crops, in a variety of contexts (e.g., soil and climate conditions, farming practices, species sown).

7 Conclusions

We have demonstrated that ley pastures in cropping systems can provide a wide range of input services: soil conservation, nutrient provision and recycling, soil water retention, and biological control of pests and weeds. They also provide output services: water purification, climate regulation, habitat provision for conserving associated biodiversity, and forage

production. Provision of those services holds as long as locally adapted management practices are applied, especially concerning the spatial and temporal insertions of these pastures in cropping systems, the species sown, and pasture use. However, knowledge gaps were clearly identified for some services mainly habitat provision for conserving associated biodiversity and about the impacts of some management options on the level of services supplied especially in the case of emerging ways of introducing ley pastures into cropping systems (e.g., living mulch, “cut and carry”). Those facts indicate that the role and importance of ley pastures in tomorrow’s cropping systems and agricultural systems should be reconsidered through an ecologically intensive lens. To this end, interdisciplinary research involving soil scientists, agronomists, geneticists, and ecologists is needed to improve our understanding of the role of ley pastures in cropping systems. These efforts should allow new visions of sustainable cropping systems to be designed that intelligently bring together the new technologies, management practices, and organizations required to integrate ley pastures in tomorrow’s cropping systems from the local scale to large scale.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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