Managing grasslands to optimize soil carbon sequestration

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Understanding and fostering soil carbon sequestration

Edited by Dr Cornelia Rumpel, CNRS, Sorbonne University, Institute of Ecology and Environmental Sciences Paris, France

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Managing grasslands to optimize soil carbon sequestration

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1 Introduction

Grasslands have large soil carbon (C) sequestration potential due to permanent vegetation cover and prolific belowground biomass inputs, making their implementation a negative emission technology (IPCC, 2018). However, the extent of carbon sequestration in grassland soils will be dependent on a variety of management approaches and environmental conditions that affect the balance between productivity (i.e. C fixation) and decomposition (i.e. soil respiration). Grasslands are typically used for grazing livestock or to grow hay to feed livestock elsewhere. Both practices may ultimately affect soil microbial activity and influence soil organic carbon (SOC) storage (Gilmullina

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et al., 2020), SOC release and emissions of CO_2 and other potent greenhouse gases. While both systems are intended for feeding ruminants, the choice of management will have an impact on a variety of ecosystem services, including SOC sequestration, water quality and above- and belowground biodiversity.

Grassland management may be intensive or extensive involving contrasting animal types, stocking rates, mineral fertilizer input and/or irrigation (Box 1). It is generally region-specific with typically extensive management with naturalized botanical composition in semi-arid and arid regions and more intensive management in sub-humid and humid regions. Intensive management in the latter regions occurs with inputs of fertilizer, reseeding with annual and/or preferred perennial species and variations in stocking method and season of grazing.

Box 1 Grassland management systems

Permanent grasslands

- Prairies — cut for hay and typically fed to livestock off-site
- Pastures — grazed directly by livestock

Temporary grasslands

- Leys — Short-term (typically <5 years), grazed or hayed, in rotation with cropping
- Integrated systems — seasonal forages (<1 year) composed of cover crops and/or crop residues grazed by livestock, in rotation with cropping

Grasslands, in rotation with cultivated croplands (temporary grasslands or leys) can be considered non-permanent as their renewal is carried out with a variety of frequency intervals suited to the nature of the agricultural systems. Short-term leys are sometimes used for soil fertility restoration of otherwise crop-dominated systems, whereas longer-term pastures rotated with crops may be a part of a diverse agricultural operation with a greater focus on livestock production.

At grassland installation, the choice of botanical composition often determines various other management decisions. Forage legumes for high-quality hay production have lower N fertilizer requirements and may be more resistant to climatic hazards such as drought (Sanaullah et al., 2012). Similarly, planting mixed-species annual forages may have greater nutritive value for

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pasture-based finishing operations but must be renewed seasonally to keep land productive. Robust perennial forages are often planted with the intent to maintain pasture production on the same parcel of land for a decade or more. The choice of warm-season or cool-season forage species will determine when the forage is best utilized and, depending on environmental conditions, whether opportunities exist to overseed these perennial forages with annual forages to further enhance productivity. These management choices have an impact on greenhouse gas emission and SOC sequestration (Franzluebbers et al., 2000), as they impact the biogeochemical cycling of elements and may lead to disruption of C, N and P cycles (Rumpel et al., 2015; Vertes et al., 2019), resulting in element losses from the system (Fig. 1).

When these losses occur in gaseous form, such as CO_2, CH_4 and N_2O, they may contribute to greenhouse gas accumulation in the atmosphere. In terms of global warming potential, N_2O is ~300 times and CH_4 ~40 times more potent than CO_2. N_2O emission rates from grassland systems are fortunately often orders of magnitude lower than that of CO_2. Agriculture is globally responsible for nearly a quarter of all greenhouse gas emissions (IPCC, 2014), with livestock production systems being major contributors.

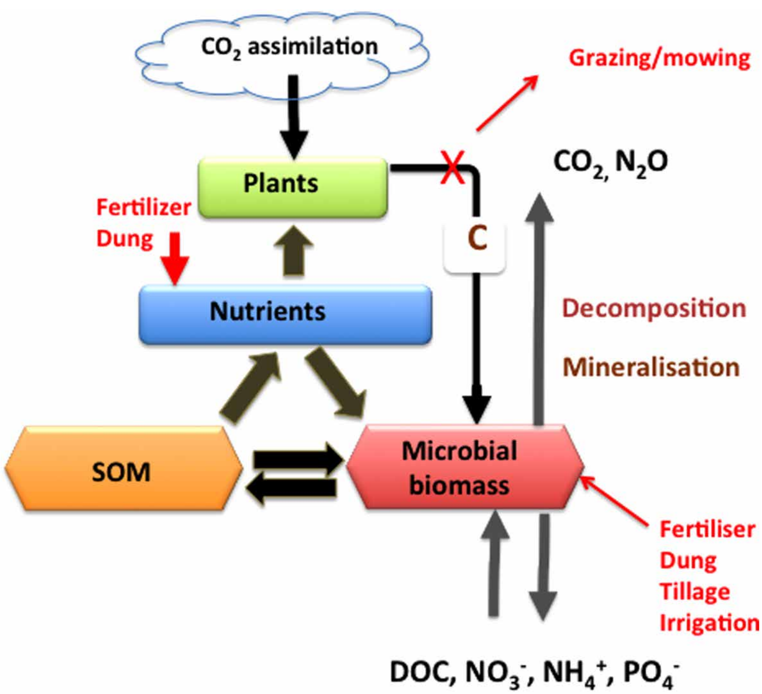

Figure 1 Disruption of biogeochemical cycles leading to greenhouse gas emissions of pastures and prairies.

Prominent greenhouse gases lost from grassland soils are CO_2 during ubiquitous soil respiration across systems and N_2O, particularly following pulses of N availability either from N fertilization or disruption of perennial sods with tillage.

Greenhouse gas production in pasture-based livestock systems occurs during the digestive process via CH_4 production in the rumen, and following excretion with N_2O production in urine patches and during decomposition of fecal pats. The feedlot phase of cattle production can exacerbate N_2O losses (Aguilar et al., 2014) but typically reduces CH_4 emissions due to higher quality dietary intake (Beauchemin and McGinn, 2006; Cole et al., 2020). Monogastric livestock production on pastures, such as swine and poultry, will likely have reduced greenhouse gas emissions than when produced in confinement due to the spatial distribution of excreta that reduces the concentration of C and N resources. Robust forage production and its effects on SOC sequestration in grassland soils may counterbalance part of these emissions when well managed with few inputs, appropriate stocking rates and site-specific vegetation composition.

In this chapter, we will discuss the effect of different grassland management practices on greenhouse gas emissions and SOC sequestration. This includes a comparison of grasslands with arable croplands, the role of N fertilization and grazing strategies. Special emphasis will be given to grasslands in rotation with cropping systems and their integration with cropping or timber systems to improve sustainable land management and SOC sequestration.

2 Soil organic carbon storage and N_2O emissions from grassland soils versus cropland soils

Grasslands and arable croplands are both integral parts of agriculture. Industrial agriculture since the mid-twentieth century has largely led to the separation of these land use systems. This has exacerbated the decoupling of elemental cycles leading to widespread pollution from N and P leaching and runoff and greenhouse gas (GHG) emissions (Lam et al., 2021; IPCC Smith et al., 2014). Worldwide, ~60% of the grassland biome has been modified by human interventions, leading to important changes in soil processes and, in particular, biogeochemical cycling.

In general, grassland soils store more SOC than arable croplands, and they tend to have more closed biogeochemical cycles resulting in fewer opportunities to lose C, N and P to surface and ground waters, but they may emit more N_2O if intensively managed (Soussana and Lemaire, 2014; Franzluebbers et al., 2014; Crème et al., 2018). Due to their permanent cover, they also positively affect the energy balance as compared to continuous cropping systems, which include periods with bare soil (Martin et al., 2020).

Differences in surface SOC stock between grasslands and arable croplands vary considerably, depending upon geographical setting, soil type, landscape position and the various management approaches deployed in each system. Paired land use comparisons offer an excellent opportunity to separate the environmental and edaphic factors from important management factors. This approach also sets the stage for better characterizing the relative influence of environmental, edaphic, and management factors on the magnitude of difference in SOC between grassland and cropland systems. With sufficient observations, these data can be assembled into a robust dataset. Some examples of this approach are described in the following sections.

From a comparison of broad land use categories across 28 studies in the southeastern United States, which is defined as a warm-humid region with relatively weathered and coarse-textured soils, SOC stock (surface layer of 24 $\pm$ 6 cm) was estimated as 31.1 Mg C ha^{-1} under cropland <47.4 Mg C ha^{-1} under grassland = 49.9 Mg C ha^{-1} under forestland (Franzluebbers, 2005). In the same region, a total of 92 tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort.] pastures were sampled at 0–10 cm depth and characterized with regard to two environmental factors (elevation and soil texture) and two management factors (forage utilization and pasture age) (Franzluebbers and Poore, 2020b). Using a novel approach to estimate the mass of SOC enriched within the upper rooting zone (0–30 cm depth) in the southeastern United States, SOC enrichment was estimated as 16–26 Mg C ha^{-1} (interquartile range) under grassland management (n = 29), while it was estimated as 4–9 Mg C ha^{-1} under conventional-till cropland (n = 45) and 14–30 Mg C ha^{-1} under no-till cropland (n = 97) (Franzluebbers, 2021).

With this same novel approach used across an additional 52 studies from the literature in other regions of the world, SOC enrichment was estimated as 6–16 Mg C ha^{-1} (interquartile range) under conventional-till cropland (n = 210), 9–22 Mg C ha^{-1} under no-till cropland (n = 270), 13–26 Mg C ha^{-1} under grassland (n = 88), and 9–40 Mg C ha^{-1} under forestland (n = 23) (A. J. Franzluebbers, unpublished data).

Using a multiple regression analysis to separate potentially confounding factors, SOC concentration:

- was 26% greater with improved grazing management (i.e. rotational stocking) than with conventional management (i.e. haying and/or continuous stocking);
- increased in a non-linear manner with pasture age (effective SOC sequestration rate of 0.9 Mg C ha^{-1} yr^{-1} during the first 20 years);
- increased with increasing elevation gradient (effective increase of 1.3 g kg^{-1} for every 100 m of elevation);
- was greater in fine-textured than coarse-textured soils.

These data illustrate the high SOC storage potential of grasslands with regards to croplands and the importance of pedoclimatic conditions and grassland management practices. It is highly likely that, with more detailed environmental, edaphic and management conditions going beyond determination of SOC stocks and/or enrichment, a robust assessment could be made of how management factors influence SOC sequestration in specific pedoclimatic situations. Assembling historical information on previous management practices may be challenging in some situations, but essential to understanding the cumulative effects of practices on SOC sequestration. Environmental and edaphic information may be less difficult to obtain due to readily available online databases for historical weather and relatively static soil conditions, at least in many developed countries.

Similar to croplands, harvest of grasslands for hay removes nutrients from the site of production. And, unless manure from livestock fed elsewhere is returned to these fields, this practice results in a potential need for nutrient replacement to maintain fertility so that productive forage swards can continue to provide their ecosystem services (fix atmospheric CO_2 via photosynthesis, produce high-quality forage and enhance SOC storage, e.g. Poeplau et al., 2018). However, nitrogen fertilization can lead to soil acidification and increase in nitrifier and denitrifier activity, both of which can lead to N_2O losses (Hijbeek et al., 2019). Fertilization as a strategy to enhance SOC storage may thus generate trade-offs, in the form of reduced soil quality and other greenhouse gas (GHG) emissions (see Chapter 6 of this book).

Despite the large global warming potential of N_2O and its importance as a GHG from grassland soils, adequate characterization of the controls of these emissions is lacking in many cases, and the processes are still poorly understood (Chapter 6 of this book). While it is recommended to apply mineral N fertilization carefully and synchronized with plant needs, microbial acquisition of N is necessary to store SOC when its levels are low, and there is large potential for additional SOC sequestration. Mineral N fertilization may be necessary in some instances simply due to the close coupling of C and N in soil so that microbial transformation of plant and animal residues into soil organic matter can be effective.

Grassland management strategies that minimize GHG emissions and enhance SOC sequestration must be developed to maximize coupling between the cycling of C and N avoiding leakage of both elements. To do this, GHG fluxes of CO_2, CH_4 and N_2O should be evaluated simultaneously. When N is deficient in soil, fertilization leads to greater biomass production and C input, which in turn stimulates microbial activity (Lu et al., 2011) (Fig. 2). Enhanced production of microbial sugars leads to greater aggregate formation, and deposition of microbial necromass, which is beneficial for enhancing aggregation and SOC storage. In some pedoclimatic environments, these processes may be stimulated under grassland by P input in addition to N (Poblete et al., 2020).

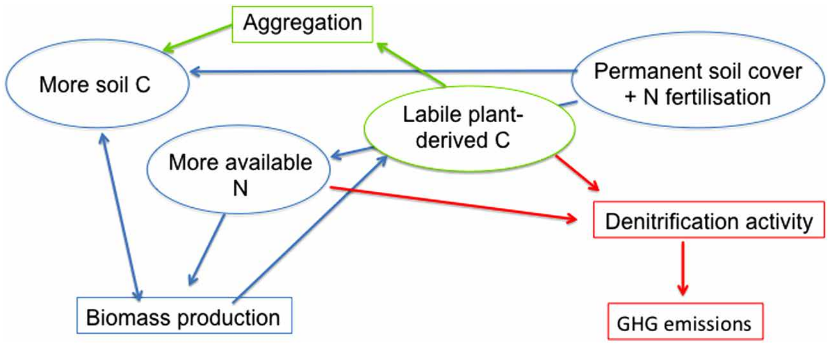

Figure 2 Processes leading to SOC storage and greenhouse gas emissions in productive grasslands.

On the other hand, mineral N fertilization and labile plant litter input stimulate denitrifier activity and N_2O emissions (Fig. 2) (Szukics et al., 2019). The evaluation of SOC sequestration capacity of grassland soils has to take into account these competing processes (Lugato et al., 2018; Guenet et al., 2020; Frank et al., 2015). A recent study suggested that grassland and cropping systems could have similar emissions, when SOC stock changes along with all emission types including those from livestock are considered (Meier et al., 2020).

As with croplands, the accurate determination of N fertilizer requirements to optimize productivity of grasslands and minimize trade-offs in form of associated N_2O emissions has been complicated by the variable nature of N mineralization processes, which are strongly affected by antecedent temperature and moisture conditions, as well as the type of management deployed and depth distribution and quality of soil organic matter. These complications have befuddled researchers in making specific N fertilizer recommendations for the numerous soil, landscape and management conditions within a particular region.

Recently, a short-term measure of soil biological activity that is strongly associated with potential N mineralization was shown to adequately predict the N fertilizer requirements in a variety of soil types, landscape settings and management conditions in the southeastern United States. On fall-stockpiled tall fescue, the level of soil-test biological activity was inversely related to the economically optimum N fertilizer rate (Franzluebbers and Poore, 2020). Young pastures and those that typically had biomass removal with hay cutting were the most responsive to N fertilizer while older pastures that were grazed were typically unresponsive to N fertilizer. This same predictive capability was shown for a gradient of conservation cropping systems with maize (Zea mays) production in the region (Franzluebbers, 2020). More refined N fertilizer recommendations will allow grassland management systems to achieve high productivity when soil cannot supply enough N and still likely limit the extent of

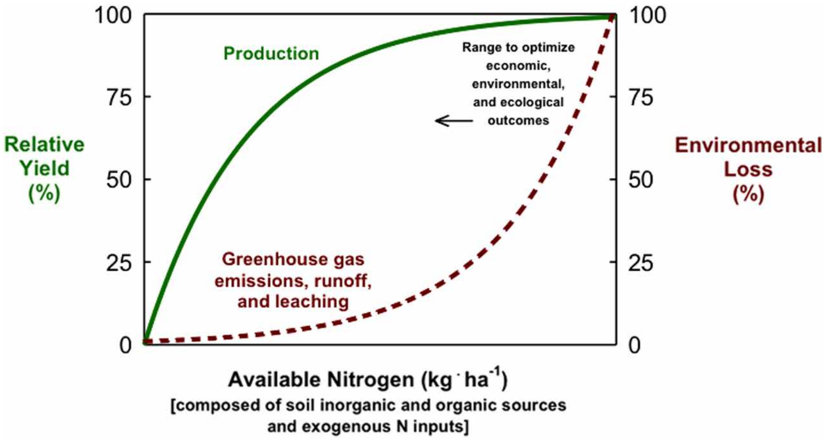

Figure 3 Conceptual diagram of how soil N availability can lead to trade-offs between grassland productivity and environmental degradation.

N_2O emission (Fig. 3). Moreover, high grassland productivity while minimizing loss of N from runoff, leaching and N_2O emissions can be equally achieved if N fertilizer inputs can be reduced or eliminated when soil is capable of supplying sufficient N. Soil analytical tools like the simple, rapid and reliable approach of determining pre-season soil-test biological activity can help to determine these gradations in soil N supplying capacity.

Grassland management needs to recognize the positive and negative effects of fertilization on SOC sequestration and GHG emissions. This is particularly important considering the functions of temporary grasslands in arable crop rotations, since this ley-cropping rotation scheme has been suggested as a solution to increase SOC stocks and to reduce GHG emissions and other environmental externalities from agriculture (Lemaire et al., 2015; Launay et al., 2021).

3 Temporary (ley) grasslands

Grass-crop rotations can experience high fluctuations of SOC stock – large increases in SOC stock during early years of temporary grassland development followed by large declines in SOC stock with tillage termination of these grasslands (Studdert et al., 1997). However, when temporary grasslands are terminated without tillage and by chemical desiccation only, then there may be preservation of surface SOC concentration (Follett et al., 2009; Franzluebbers and Stuedemann, 2009).

The location in the soil profile, where SOC changes as a result of grass-crop rotations occur, is of particular interest in understanding how to manage these transitions to avoid loss of SOC and reduce the risk of enhanced N_2O emissions (Franzluebbers et al., 2014). Some data suggest that changes in SOC may be relegated to the superficial zone of soil within the plow layer (Franzluebbers and Stuedemann, 2010), while other data suggest there may be changes below this zone (Carter and Gregorich, 2010). Other studies indicate little detectable change in SOC over short periods of time following pasture termination (Pierce et al., 1994; Grandy and Robertson, 2006). A decade of differently managed temporary grasslands seemed to maintain SOC stocks under temperate climate conditions in contrast to cropped soils, which lost SOC and continuous grasslands, which gained SOC (Crème et al., 2020).

Recently, deep soil flipping (1–3 m full inversion of the soil profile) of podzolized soils in New Zealand has been suggested as a valuable grassland conversion practice to increase SOC storage due to burial of SOC-rich A horizons and exposure of SOC-poor B horizons at the soil surface (Schiedung et al., 2019). Randomized and replicated plot studies or paired land use studies with this treatment of ultra-deep plowing are needed in different types of soils to know the full magnitude of such a large effect on profile SOC stocks and other soil properties.

Although positive effects of the introduction of temporary grasslands on SOC storage in arable croplands occur, various soil properties and, in particular, SOC stocks decline more rapidly when grasslands are terminated than when they are being established (Sanderman and Baldock, 2010; Poeplau et al., 2011). Recent meta-analyses have shown that SOC stocks with an average of 14 years of grassland management were 18% greater than under arable cropland (Kaempf et al., 2016). Even after 40 years since perennial grassland establishment, SOC stock may still accumulate at a substantial rate, e.g. 0.62 Mg C ha^{-1} yr^{-1} (McLauchlan et al., 2006). However, the rate of SOC storage may vary with pasture age (Franzluebbers et al., 2000; Johnston et al., 2017; Franzluebbers and Poore, 2021). SOC stock increases as well as decreases upon grassland establishment or conversion may not be linear as indicated by some studies. However, at the moment, there are not enough data to confirm that the trends observed are generalizable and applicable to contrasting management systems and/or pedoclimatic regions. In particular, most data were recorded in temperate regions with ruminant grazing, whereas relatively little is known about tropical systems, non-ruminant grazing animals and cut and carry systems, which may have contrasting effects on soil microbial functioning and biogeochemical cycling (Moinet et al., 2019; Gilmullina et al., 2020, 2021).

Temporary (ley) grasslands have numerous (positive) effects on ecosystem services and may be one solution for the diversification of tomorrows cropping systems (Martin et al., 2020). However, the effects of contrasting grassland management practices and their legacy effect on organic matter dynamics, and SOC sequestration (including their quantitative effects on trade-offs and other ecosystem services) are only just being elucidated. For example, legacy effects of temporary grasslands include soil structure maintenance and biodiversity conservation (Hoeffner et al., 2021). However, these effects may depend on grassland age and may be quantitatively less important than those of permanent grasslands, as even 91 years after the abandonment of arable cropland, certain prairies recovered only half of their productivity and 75% of their biodiversity (Isbell et al., 2019).

It is clear that temporary grasslands have the potential for SOC accrual when rotated with arable cropland, (Johnston et al., 2017), thereby supporting soil fertility restoration and SOC sequestration (Minasny et al., 2017). Temporary grasslands can also carry legacy effects into the cropping phase in terms of GHG emissions, SOC storage and organic matter composition (Crème et al., 2018; Rumpel and Chabbi, 2010). Although there are positive effects of short-term grasslands for SOC accumulation (Johnston et al., 2017), conservation of permanent grasslands should not be neglected as these lands often hold greater quantities of SOC in larger land areas that are not suitable for arable cropping (Minasny et al., 2017).

4 Grassland management options: species choice, fertilization and irrigation

Since grassland botanical diversity and SOC storage are intimately linked (Cong et al., 2014; Lange et al., 2015), focusing on grassland biodiversity may be the best way to improve ecological functioning of restored grasslands. Greater plant diversity increases the type and location of rhizosphere C inputs, as well as soil microbial utilization and processing, resulting in greater microbial activity and greater SOC storage of recently fixed C (see Chapter 3 of this book). Although enormous biodiversity can be achieved in permanent grasslands, temporary prairies in intensive agricultural systems usually have relatively low biodiversity because they are composed of only a few intentional forage species. It takes time for seed recruitment and development of more functional biodiversity in newly planted swards. Nonetheless, a balance should be sought among forage species diversity, grassland productivity, SOC storage and grassland age (Soussana and Lemaire, 2014; Kohler et al., 2020).

There are two reasons for applying N fertilization to productive grasslands (Crème et al., 2018):

(1) High nutritive value of harvested hay may only be possible, depending on the type of soil and its concentration and depth of soil organic matter, with intermittent application of N fertilizer during the two to three harvests expected to be taken each year.
(2) N-addition may be necessary to store SOC

Indeed, recent meta-analyses confirmed that a significant increase of SOC stocks (0.6 Mg C ha^{-1} yr^{-1}) can occur with N fertilization (Conant et al., 2017; Eze et al., 2018). However, there is a non-linear relationship between the amount of N fertilizer added and SOC accrual, depending intrinsically on grassland management. Poeplau et al. (2018) showed that 1.15 kg N ha^{-1} was needed to sequester 1 kg SOC ha^{-1}. However, since the C cost embedded within N fertilizer is of the same magnitude (West and Marland, 2002), there is a need to make good evaluations of the need for enhancing forage nutritive value and quantity of additional forage biomass harvested. There may be situations in which the quantity of N fertilizer applied to productive prairie soils exceeds that applied to cropland soil due to greater biomass export, thereby increasing the potential for greater N_2O emissions (Guenet et al., 2020; Hauggaard-Nielsen et al., 2016). In grass-crop rotations, duration of the grassland phase can have an impact on plant available mineral N in the soil solution and can reduce leaching loss (Kunrath et al., 2015).

Dominant forage species within a sward can determine forage productivity, SOC storage and the extent of GHG emissions (Conant et al., 2017; Sebastia et al., 2018). For instance, long-term biodiversity restoration increased SOC and total soil N storage, especially when forage treatments were combined with the legume, *Trifolium pratense* (De Deyn et al., 2022). Moreover, the use of legumes in hayed grasslands can be a viable option to reduce mineral N fertilization requirements (IPCC, 2013), to increase protein concentration of forage and to increase resilience to short-term drought (Sanaullah et al., 2012).

Relying on biological N fixation (BNF) with incorporation of legume species in temporary grasslands may require additional mineral P fertilizer inputs, as P availability is known to limit the development and growth of many legume species (Graham and Vance, 2003). The high demand of legume species for soil P may be attenuated when grown in a mixture with gramineous plants, depending on the species (Crème et al., 2016), partly because various grass-legume combinations can influence the biogeochemical composition of soil organic matter (Crème et al., 2017). Therefore in grass-legume mixtures, optimization of P fertilization to maximize N inputs may not be so straightforward but requires site-specific strategies (Mendoza et al., 2016; Stiles et al., 2017).

While grass-legume mixtures often enhance forage N content and digestibility of herbage (de Wit et al., 1966), the impacts of such mixtures on N_2O emission from soil have only been recently studied (Fuchs et al., 2018). Although some BNF from legumes in a mixed sward may increase grass N nutrition through direct N transfer, the majority of benefit is more likely through slow release of mineral N following decomposition of legume plant litter (Fustec et al., 2010). Direct N transfer was found to be species-specific (Marty et al., 2009), while indirect transfer is a general phenomenon and depends on soil microbial activity.

Several recent studies have shown that replacement of mineral N fertilization with BNF from legumes in the sward can reduce N_2O emissions while maintaining or even improving grassland productivity (Fuchs et al., 2018; Barneze et al., 2020). Use of legumes in temporary grasslands may therefore be highly beneficial, especially on N-poor soil with low organic matter following many years of arable cropping with inversion tillage.

In some regions, irrigation is used to overcome water limitations and to increase herbage production and subsequent SOC sequestration (Hunt et al., 2016). Despite greater forage biomass production with irrigation, change in SOC stock may be limited due to greater soil microbial activity that consumes additional C resources (Mudge et al., 2017). The net effect of irrigation on C input via production and C output via soil respiration needs to be considered (Condron et al., 2014), along with its effect on N_2O emissions after fertilization due to changing pH and redox conditions (Yu and Patrick, 2004, Chapter 6 of this book).

5 Harvesting strategies: grazing versus mowing and grazing regimes

Grazing of grasslands by ruminant livestock is a fundamental change in how forage is harvested and utilized as compared with cutting for hay. Instead of two or three abrupt and complete biomass removals per year with export of harvested nutrients, grazing tends to gradually consume biomass with a continuous stocking method (i.e. long duration, high frequency of return).

The implications of grazing style on SOC storage and GHG emissions have received more attention recently and more assessments are needed under different environments to understand the impact of grazing style on production and environmental outcomes (e.g. SOC sequestration, GHG emissions, water quality and soil health), as well as on livestock herd health, farm economics, farmers' quality of life and rural community development.

A comprehensive review of the literature on the impacts of prescribed grazing on key ecological outcomes was conducted in the United States (Sollenberger et al., 2012). This literature review illustrated some key findings of stocking rate on SOC sequestration and other soil conditions that will be covered in the following but also spurred subsequent research on the effects of stocking method.

Livestock grazing on pasture leads to consumption of forage while moving around the pasture with nutrients and C return in the form of dung and urine. Placement of these nutrients depends on how pastures are managed, i.e. continuous or rotational stocking. With 50–70% of C embedded in forage considered digestible, a large portion of the C fixed in forage is returned directly back to the land with dung and urine deposition. Dung is the primary source of returned C, and urine is the primary source of returned N. Biomass

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carbon is utilized for maintenance and growth of livestock, and at least half of the C can be considered either stored in animal tissue or respired as CO_2, CH_4 and other volatile organic compounds. Biomass nitrogen is utilized for the production of animal proteins, and the vast majority of N (70%) is returned to the land via urine and dung.

The fate of this N is dependent on soil and environmental conditions, but a portion of it can be (1) nitrified and denitrified leading to N_2O emissions, (2) volatilized as NH_3, (3) utilized by soil microorganisms and (4) transformed into stable organic structures. Organic N may also be mineralized into inorganic N, and this inorganic N can be leached or lost via runoff if not taken up by plants or microorganisms. In which of these compartments C and N are found and at what rate and intensity they are transformed are complex questions and require detailed analyses of pasture ecosystems and thus have received attention but require greater scrutiny of the factors explaining these fluxes under various soil, environmental and management conditions.

Well-managed pastures with appropriate stocking rates to maintain and improve botanical sward structure can lead to significant SOC sequestration with increasing pasture age (Franzluebbers et al., 2000, 2010, 2012a;). At specific pasture ages with grazing management, more SOC may be sequestered relative to hayed management (Franzluebbers et al., 2001, 2012b). Net GHG emissions can also be reduced when extensively managed pastures are grazed by livestock as compared with cutting forage for hay and feeding livestock elsewhere (Koncz et al., 2017). Greater SOC stock has been observed in grazed native grassland as compared to an ungrazed treatment (Orgill et al., 2018), and in planted pastures relative to a conservation reserve without harvest (Franzluebers and Studdemann, 2009). Positive grazing impacts on SOC storage are often attributed to enhanced plant productivity (Franzluebbers et al., 2004) and greater allocation of C to a more robust root system. It has been suggested that plants increase root exudation and thus C input to soil as a response to grazing (Hamilton et al., 2008), thus leading to greater soil microbial activity and OC use (Klumpp et al., 2009). Greater SOC accumulation with grazing of pastures might also be explained by decreased soil organic matter mineralization due to shifts in the microbial community composition (Gilmullina et al., 2020) and reduced abundance of fungi (Shahzad et al., 2012).

To achieve greater SOC storage and productivity, grazing systems with moderate stocking density have been suggested (Briske et al., 2008; Derner and Schuman, 2007). In fact, the effect of stocking rate on optimization of SOC storage was demonstrated in a warm-season pasture in the southeastern United States (Fig. 4). However, the impacts of stocking rate and grazing style will be dependent on soil and environmental conditions, such that region-specific grazing strategies need to be developed (McSherry and Ritchie, 2013; Abdalla et al., 2018).

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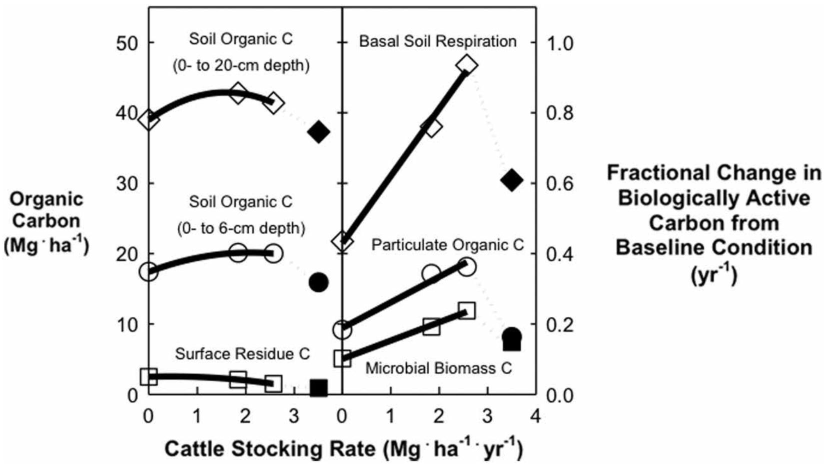

Figure 4 Effect of stocking rate on soil organic C accumulation during the first five years of bermudagrass (Cynodon dactylon) management in the southeastern United States (data from Franzluebbers et al., 2001).

When livestock graze pastures, they are not typically homogenously distributed unless restricted to small paddocks for short durations. Selective grazing may impact pasture production and therefore organic C input to soils. In particular, in continuous grazing systems, when livestock graze large pastures, they tend to repeatedly graze preferred plants and in areas close to water and shade (Bloor and Pottier, 2014; Bloor et al., 2020). Such animal behavior leads to greater than average stocking rate in preferred areas and lower than average stocking rate or total avoidance of other spaces (Wallisdevries et al., 1999; Teague et al., 2011). Pastures affected by selective grazing can lead to a change in species composition toward less palatable grasses, weedy forbs and woody plants. The resulting grasslands with undesirable species are more vulnerable to drought (Teague et al., 2011, 2013), may have greater proportions of bare ground, reduced aboveground and belowground biomass productivity and essentially enter into a state of degraded condition with numerous undesirable traits.

These processes also affect SOC storage due to reduced C inputs (Knopf, 1994; Frank et al., 1998; Teague et al., 2013; Park et al., 2017). On degraded grasslands, regulating the frequency and intensity of grazing may be the only low-cost solution to prevent further spiraling into eventual soil degradation (i.e. loss of SOC) by maintaining aboveground and root biomass, which act as primary C input sources to soil (Liu et al., 2016; Sun et al., 2014; McSherry and Ritchie, 2013). If existing botanical composition is sufficient, then using the livestock themselves to renovate a pasture is possible by subdividing the pasture so that high-density stocking disrupts the sward with heavy trampling followed by a resting period of one to several months so that forage species can fully recover. This short-duration, high-density impact moves to all other parcels of the pasture in sequence so that natural regeneration of desirable grasses and forbs can emerge following these disturbances that may occur one to several times a year depending on the environmental conditions of a region (Teague et al., 2011, 2013; Sanderman et al., 2015).

Another practice, known as rotational stocking, shifts grazing to another extreme of forage utilization (i.e. short duration, low frequency of return). This system is typically based on the axiom ‘graze half, leave half’. Of course, there can be gradations in how much actual forage is consumed and how much is returned to the soil to feed soil fauna and microorganisms. It can be as simple as a two-paddock system with one paddock grazed for a period of time while allowing the other paddock to rest and accumulate biomass. Livestock are moved to the other paddock when the farm manager decides, thereby allowing the previously grazed paddock to accumulate biomass until the next round of grazing. The duration of grazing and length of time for pasture rest and recovery can be set with different values depending on paddock size and number on a farm, or it can vary based on weather conditions, forage availability, livestock needs and farm management timelines. Rotational stocking has been found to be beneficial for SOC storage in different environments (Wang et al., 2015; Teague, 2018;), but not all (Ingram et al., 2008; Derner et al., 2019). An increasing number of farmers are adopting rotational stocking to increase profitability and improve ecosystem health (Ferguson et al., 2013).

An extreme case of rotational stocking is sometimes called ‘mob grazing’ or Adaptive Multi-Paddock (AMP) grazing with 10–1000 Mg body weight ha^{-1}, but only for a limited time (Photo 1). Livestock are typically restricted with temporary, electrified polywire fencing and forced to consume all forage species and trample some fraction of forage into the ground without removing apical meristems of desirable forage species for more rapid regrowth compared with hay cutting. The animals are moved frequently to new areas of a pasture. New paddocks may be offered a few times a day to once every few days. There can be gradients in between several movements of livestock to fresh forage per day to a move once every few weeks, depending on the type of forage and soil, landscape, and climatic conditions. This practice is becoming popular among some producers due to its perceived benefits on SOC sequestration and maintaining forage diversity (Wang et al., 2021). While few studies reported extremely high rates of SOC sequestration with a shift to mob or AMP grazing (Russell et al., 2013) and an increase of persistent SOC and N retention (Mosier and Cotrufo, 2022), the practice has also been found beneficial for controlling woody plant encroachment in rangelands (Mesléard et al., 2017).

However, scientific evidence for the benefits and trade-offs of this practice and its effect on SOC sequestration is weak as studies have been conducted

Photo 1 Mob grazing (photo: Tom Chapman).

on a limited number of grazing systems with a chronosequence approach to estimate change in SOC stock, which makes some assumptions of uniform conditions that may not always be verifiable. In addition, unreplicated field experiments are often used, due to the large space required for completely randomized block design with pasture management.

Moreover, different grazing techniques are compounded by the inherent variability within and between paddocks, making detection of a small real change difficult within a short time period (Crème et al., 2020). Similarly, comparison of two fixed categories (i.e. rotational vs. continuous stocking) may not always be the most appropriate approach for comparing diverse management styles, given (a) the large spatial variability within a large farm with multiple paddocks and (b) a diversity of specific management approaches among farmers using what could be considered the same approach.

In the last decades, studies have become more common describing the effects of forages (grass, legumes or mixture) on animal N excretion and resulting N_2O emissions and C fluxes. Pasture-finished livestock approaches have also gained interest, thus bringing together pasture ecosystem services and livestock production strategies. Critically, forage digestibility and intake has become recognized as a major factor affecting rumen CH_4 emissions (Hristov et al., 2013). There has been increased research on forage nutritive value to develop appropriate mitigation practices. High nutritive value grass silage can reduce CH_4 emissions when fed to ruminant livestock, depending on stage of forage maturity that controls fiber and protein concentrations. These variables are dependent on harvest date, climate conditions, and botanical composition of the sward (Elgersma and Søegaard, 2018).

6 Integrated crop-livestock systems and silvopastures

Since the mid-twentieth century, greater specialization of agriculture has led to greater separation of crop and livestock production (Russelle et al., 2007). Agricultural expansion and its specialization has led to reduced diversity, greater agrochemical use and more damaging externalities from declines in water quality/availability, greenhouse gas emissions, rural community stresses, reliance on global markets, disruption of local supply chains and so on.

To counteract these negative effects of specialized agriculture, integrated crop-livestock systems and silvopasture systems offer great opportunities to enhance diversity from field to landscape scale, enhance agricultural resilience and reduce environmental pollution (Lemaire et al., 2014). These systems have been suggested as sustainable alternatives for diversified agriculture while, at the same time, leading to sustainable intensification without bringing additional land into cultivation (Kumar et al., 2019; Peterson et al., 2020). Such systems could diversify farm income sources, but they may also require new skills and investment.

Regarding nutrient cycling, integrated crop-livestock systems have an advantage over specialized cropping systems due to animal excreta deposited directly onto the land in a distributed manner as organic fertilizer. Organic fertilization may be more beneficial to SOC sequestration than mineral fertilization (Calabi-Floody et al., 2018). Moreover, re-use of animal waste materials may contribute to a circular economy. In contrast, on-farm storage and transformation of manure into organic amendments can generate N_2O and CH_4 emissions. Such emissions may be reduced by improving management at the farm level (Ditzler et al., 2018) and with improved waste management practices, e.g. composting and/or co-composting in the presence of minerals (Barthod et al., 2018) or biochar (Agegnehu et al., 2017).

Silvopastures and integrated crop-livestock-forestry systems (Photo 2) offer potential system-level production improvements, better animal welfare with thermal regulation of the microclimate in the dispersed shade of trees, greater water infiltration and nutrient cycling, and enhanced scenic beauty of rural landscapes (Carpinelli et al., 2020; Da Pontes et al., 2016). Randomized landscape distribution of trees in pastures has been a historical feature of many regions around the world. In fact, vast areas of semi-arid rangelands supporting the grazing of cattle, sheep and goats are common yet today, including the dehesa on the Iberian Peninsula and dispersed oak woodlands in California.

Since the mid-twentieth century, new silvopasture systems have also been introduced using more geometric arrangement of trees with an understory of planted and desirable forages, such as in Florida (Nair et al., 2008). In the southern part of the United States, tree-based pastures were shown to increase the soils' capacity to accumulate stabilized SOC and therefore increase SOC

Photo 2 Silvopastural system in Argentina (photo: F. Montagnini).

sequestration (Haile et al., 2008). Such regular arrangements of trees lining alleys of managed pastures are gaining popularity in countries with a large livestock industry, such as in Brazil (Alves et al., 2017).

From on-farm sampling in Alberta, Canada, SOC stock within the surface (i.e. 30 cm) was greater under silvopasture systems than under trees of hedgerow and shelterbelts (Lim et al., 2018). From on-farm sampling in Chiapas, Mexico, SOC stock at 0–15 cm depth was 23% greater under 5–50-year-old silvopastures than under open pastures dominated by forage species of *Cynodon dactylon*, *Cynodon plectostachium*, *Hiparrhenia rufa* and *Brachiaria dictyoneura* (Aryal et al., 2019). In Michoacán, Mexico, SOC stock at 0–30 cm depth was 54% greater under a silvopasture of *Leucaena leucocephala* undersown with *Panicum maximum* than under open pasture of *C. plectostachyus* (Lopez-Santiago et al., 2019). N_2O emissions were found to be reduced, while SOC stocks were increased, underneath the trees of silvopastoral systems (Amadi et al., 2016; Franzluebbers et al., 2017). Indeed, in a 4-year-old Eucalyptus silvopasture in Minas Gerais Brazil, SOC stock at 0–30 cm depth was up to 19% greater under nearest Eucalyptus trees than in the open pasture between tree lines (de Abreu et al., 2020). Consequently, it was calculated that 17–44 trees ha^{-1} are needed to offset the greenhouse gas emissions from livestock grazing pastures with trees in Brazilian silvopastoral systems. This tree density is easily exceeded in most tropical regions (Torres et al., 2017). Carbon storage in tree biomass is highly significant in silvopastoral systems, but significant SOC stock change has also been frequently reported in these and other regions of the world (Lorenz and Lal, 2014).

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Silvopastures have been shown to effectively limit net greenhouse gas emissions by increasing C storage in woody biomass and soil, as well as potentially mitigating CH_4 emissions from enteric methane (Resende et al., 2020). They are promoted as one of the top land use activities to mitigate against greenhouse gas emissions due to the large plant biomass accumulation on existing agricultural land (Jameel et al., 2022). However, due to the scarcity of investigations, their impact on the processes leading to SOC sequestration remains largely unknown.

7 Life-cycle assessment of agricultural production systems with grasslands

Table 1 summarizes the effect of the various grassland management practices on SOC storage and GHG emissions. In order to account for the benefits and trade-offs of prairies and pastures in terms of the GHG emission balance, a whole system modeling approach is necessary (Stewart et al., 2009; Chang et al., 2015) to account for lateral C and N fluxes. Managed grasslands are in general used to produce forage for animal feed in livestock or dairy production systems. This means that mineral fertilizers and/or manure are often needed to improve forage nutritive value and overall production. Therefore, in terms of GHG emissions, CO_2 respiration by soils and animals, CH_4 production by ruminants, and N_2O and CH_4 emissions from dung, urine and stored manure must be taken into account, as well as SOC sequestration that can mitigate some or all of these emissions (Fig. 5).

Generally, dairy and beef production systems have large enteric CH_4 emissions (about 40% of all methane emitted, FAO, 2013). This is a significant ecological footprint (Vermeulen et al., 2012). However, many life-cycle analyses

Table 1 Potential effects of management practices on SOC storage and GHG emissions

Grassland type	Management practice	Impact on SOC storage	Impact on GHG emissions
Hayed	Mineral fertilization	+++	+++
	Legume use	+++	–
	Grassland renewal	–	+
Grazed	Continuous stocking	+	++
	Rotational stocking	+++	++
	Short-duration, high-density stocking	++	+
	Irrigation	?	+

SOC, soil organic carbon; GHG, greenhouse gas.
+++ = high impact; ++ = medium impact; + = low impact; - = negative impact; ? = unknown impact.

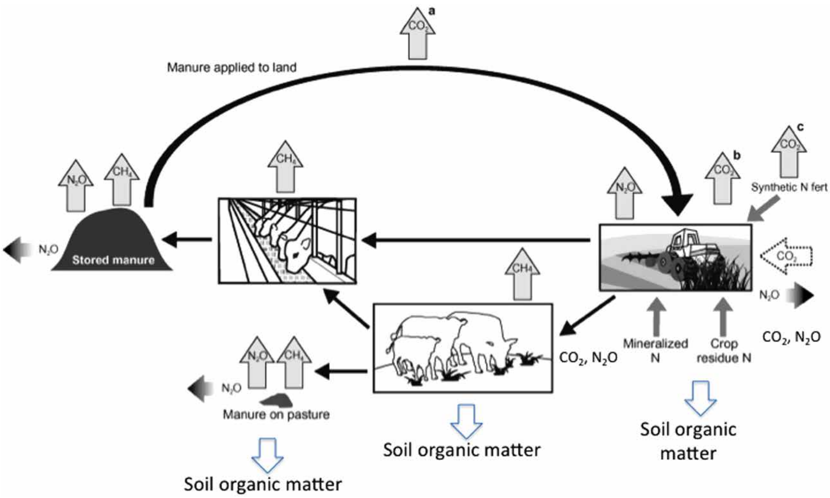

Figure 5 Greenhouse gas emissions and storage in animal production systems to be included in lifecyle analyses (Beauchemin et al., 2010, modified).

of pasture-based livestock systems (de Vries et al., 2015) do not include C and N changes in the form of soil organic matter. When SOC sequestration potential was included into life-cycle analyses of beef production systems on pastures in the Midwest United States, grazing strategies with low and high stocking densities were found to be an overall CO_2-equivalent sink (Rowntree et al., 2020). Recently, other life-cycle analyses have also suggested that SOC sequestration in well-managed grasslands can partially or fully offset GHG emissions (Stanley et al., 2018; Frank et al., 2015; Guenet et al., 2020). For this reason, it is necessary to include SOC sequestration as an integral part of any life-cycle analysis to evaluate the GHG emission contribution of agricultural systems including grasslands.

8 Conclusion

Managed grasslands, such as prairies and pastures, are favorable systems for increasing SOC storage. With ruminant livestock as the primary consumer of these forages, enteric CH_4 emission is the primary driver of greenhouse gas emissions from either hay-harvested prairies or grazed pastures. Nitrous oxide is a potent greenhouse gas and its emission is linked to the periodic concentration of available N in soil. Therefore, mineral fertilization of prairies and pastures can contribute substantially to global warming potential from N_2O emissions. Manure management of confined animal feeding operations can be a source of CH_4 and N_2O emissions. Accumulation of SOC with grassland development can be a strong sink for atmospheric CO_2, thus potentially negating other greenhouse gas emissions.

Grassland systems can be managed to reduce net greenhouse gas emissions by understanding the benefits and trade-offs of different management approaches that ultimately affect plant and animal productivity, environmental quality, biodiversity and socioeconomic outcomes. The net greenhouse gas emission potential of managed grasslands should be based on life-cycle analyses to include all components of the agricultural system.

In hayed systems particularly, N fertilization becomes a required input to increase forage production and nutritive value but can also lead to N_2O emissions. Such emissions may be limited when using organic fertilizers and leguminous species that reduce the high concentration of mineral N in soil at one time. Grassland management for ruminant livestock production varies by animal species and class, stocking rate, stocking method, season of grazing and livestock distribution on the landscape. Due to the selective grazing behavior of livestock, rotational stocking can be an effective strategy to maintain high biomass production and contribute to SOC accumulation over the entire pasture and not just isolated portions of the pasture due to uneven distribution of grazing, loafing and treading.

Achieving a positive balance between SOC sequestration and CH_4 and N_2O emissions from livestock, management strategies may need to acknowledge trade-offs in ecosystem service outcomes, which will be dependent on soil and climatic conditions of a particular region. Innovative systems to maximize the benefits of SOC sequestration and minimize trade-offs in form of greenhouse gas emissions may be derived with integrated crop-livestock systems or silvopastures that are more ecologically diverse. Co-benefits of these more complex agroecosystems include income stability for producers and increased resilience of agricultural systems against climate change.

9 Where to look for further information

- EIP AGRI Focus Group (2018) Grazing for carbon. Final Report. (https://ec.europa.eu/eip/agriculture/en/publications/eip-agri-focus-group-grazing-carbon-final-report).
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