

Title: A review of transformative strategies for climate mitigation by grasslands

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## Abstract

Grasslands can significantly contribute to climate mitigation. However, recent trends indicate that human activities have switched their net cooling effect to a warming effect due to management intensification and land conversion. This indicates an urgent need for strategies directed to mitigate climate warming while enhancing productivity and efficiency in the use of land and natural (nutrients, water) resources. Here, we examine the potential of four innovative strategies to slow climate change including: 1) Adaptive multi-paddock grazing that consists of mimicking how ancestral herds roamed the Earth; 2) Agrivoltaics that consists of simultaneously producing food and energy from solar panels on the same land area; 3) Agroforestry with a reverse phenology tree species, *Faidherbia (Acacia) albida*, that has the unique trait of being photosynthetically active when intercropped herbaceous plants are dormant; and, 4) Enhanced Weathering, a negative emission technology that removes atmospheric CO<sub>2</sub> from the atmosphere. Further, we speculate about potential unknown consequences of these different management strategies and identify gaps in knowledge. We find that all these strategies could promote at least some of the following benefits of grasslands: CO<sub>2</sub> sequestration, non-CO<sub>2</sub> GHG mitigation, productivity, resilience to climate change, and an efficient use of natural resources. However, there are obstacles to be overcome. Mechanistic assessment of the ecological, environmental, and socio-economic consequences of adopting these strategies at large scale are urgently needed to fully assess the potential of grasslands to provide food, energy and environmental security.

Key words: GHG, CO<sub>2</sub> fluxes, CH<sub>4</sub> fluxes, N<sub>2</sub>O fluxes, adaptive multipaddock grazing, patch burn grazing, agrivoltaics, agroforestry, reverse phenology, climate change.

## Introduction

Climate mitigation targets set by the United Nations (UN) Paris Climate Agreement has stimulated a new research agenda to redefine land management strategies to limit global warming below 2°C. With 70% of global agricultural area (~42,7 million km<sup>2</sup>) (FAO 2005; Ramankutty et al. 2008), grasslands can significantly contribute to climate mitigation while providing a myriad of additional ecosystem services (Fig. 1) (Bengtsson et al. 2019). Over the last decades, human activities have switched grasslands impacts on climate from a net cooling effect to a net warming effect (net source of GHGs of  $1.8 \pm 0.7$  Gt CO<sub>2</sub>e yr<sup>-1</sup> during the 2000s), indicating an urgent need for sustainable management strategies in grasslands directed to mitigate climate warming (Chang et al. 2021).

Grasslands co-evolved with herbivores over millions of years contributing to their C-rich soils (Follett and Reed 2010). The transition from a sink to a source of GHGs of grasslands is attributed to land conversion from natural ecosystems to grasslands, and of grasslands to cropland, and intensification for livestock production. Around 20% of global grasslands have been converted to crops (17000 km<sup>2</sup> every year) to meet growing energy and food demands (FAO 2005; O'Mara 2012), most of which were monocultures, with North America, Europe and South Asia dominating land use change emissions attributed to grasslands (1.01 Gt CO<sub>2</sub>e in the last 60 years) (Chang et al. 2021).

A common consequence of grassland intensification is overgrazing, which occurs when vegetation consumption exceeds the system ability to recover. Overgrazing reduces biodiversity and the productive capacity of grasslands, and accelerates soil erosion causing the progressive depletion of soil organic C (SOC) and disruption of soil aggregates (Follett and Reed 2010). Agricultural land has suffered global losses of 133 PgC from the original SOC stocks, and over

half of that C has been lost in grazing lands (Sanderman et al. 2017). Grassland intensification also increases nutrient and water requirements increasing the necessity for fertilization and irrigation to sustain high productivity (Foley et al. 2005). Fertilization is associated with enhanced soil GHG emissions, eutrophication of coastal systems, losses in biodiversity, and increases in N deposition that can limit productivity by other nutrients (e.g. phosphorus and micronutrients) (Tilman 1999; Mahowald et al. 2008; Gomez-Casanovas et al. 2016). In addition, the production of fertilizers contributes 575 Mt of CO<sub>2</sub>e to GHGs emissions from the agricultural sector annually (Vermeulen et al. 2012). Further, losses of soil organic matter and constraints in water holding capacity associated with intensification reduce grasslands resilience to extreme climate events. With droughts and flooding events becoming more intense and frequent, shrinking natural water resources and increased water requirements, this loss of resilience jeopardizes the future of grasslands in a changing climate (Godfray et al. 2010).

The most mature sustainable strategies to improve the mitigation potential of grasslands (e.g. avoided grassland conversion, optimizing grazing intensity, fire, legume sowing, animal management, and biochar amendments; Fig. S1) offer up to 1.2 Pg CO<sub>2</sub>e yr<sup>-1</sup> of mitigation potential, that could provide 8.7% of CO<sub>2</sub> mitigation needed through 2030 (Fig. S1) (Griscom et al. 2017). Although this mitigation potential is substantial, it is uncertain whether we will be able to hold global warming below 2°C without using negative emission technologies (NETs) (Fuss et al. 2016). NETs target the removal of atmospheric CO<sub>2</sub> from the atmosphere, and could provide an additional mitigation potential between 15 and 45 GtCO<sub>2</sub> annually (Fuss et al. 2016). An understudied NET is enhanced weathering (EW), which consists of the application of pulverized silicate-rich (Si) rocks on soils. These rocks applied on the land accelerate chemical weathering

and absorb atmospheric CO<sub>2</sub> and as they reach coastal systems, allowing the ocean to store more CO<sub>2</sub>.

In this Discussion paper, we summarize current knowledge and hypothesize likely effects of the adoption of four emerging strategies that albeit understudied have the potential to improve the GHG mitigation of grasslands while enhancing productivity. We focus on strategies that are designed to both mitigate climate change and minimize the environmental stressors grasslands are under including land degradation, water and land scarcity, nutrient requirements and climate change. We focus on: 1) Adaptive multi-paddock grazing that consists of managing grasslands mimicking how ancestral herds roamed the Earth; 2) agrivoltaics that consists of simultaneously producing food and energy from solar panels on the same land area; 3) agroforestry with a reverse phenology tree species, *Faidherbia (Acacia) albida*, that has the unique trait of being photosynthetically active when intercropped herbaceous plants are dormant; and, 4) EW on grasslands. We also identify gaps in knowledge critical for the full assessment of the potential of these strategies for increasing food and energy security, environmental sustainability, and the resilience of grasslands to changes in climate.

## **1. Adaptive Multi-Paddock Grazing: Mimicking how ancestral herds roamed the Earth**

Grasslands typically are grazed for relatively long periods in large paddocks, and grazers often choose to graze some areas more heavily than others (continuous grazing; CG) (Byrnes et al. 2018). It has been argued that by mimicking the intensive grazing patterns of ancestral herds, adaptive multi-paddock (AMP) grazing, a type of rotational grazing, could enhance the ecological and environmental benefits from grasslands over CG management. AMP involves using multiple small fenced paddocks to avoid selective grazing; these small paddocks are

123 grazed by large herds for short periods of time (hours to days) in which vegetation consumption  
124 does not exceed 50% of available forage to maintain enough plant and litter cover to decrease  
125 bare ground and retain soil wetness (Fig. S2) (Teague et al. 2013). Grazing periods are followed  
126 with sufficient resting time to maintain plants in a state of rapid growth (from 30-45 days in  
127 mesic ecosystems during the growing season to 90 days during the non-growing season and four  
128 or more months in xeric grasslands during the growing season). AMP differs from rotational  
129 grazing and other management approaches (e.g. cell grazing, short duration grazing) (di Virgilio  
130 et al. 2019) in that livestock intensity and grazing timing are adjusted as environmental  
131 conditions change to ensure adequate recovery of the grassland; it requires maintaining and  
132 reestablishing plant diversity, preferably native species, and avoids fertilizer and herbicide inputs  
133 (Teague et al. 2013).

134         Our literature search revealed that overall AMP grazing can increase Soil Organic Carbon  
135 (SOC) relative to business-as-usual managed grasslands (18% increase; Fig. 2; Table S1; n = 23).  
136 This SOC increase could be explained by a combination of mechanisms including the combined  
137 stimulation of photosynthesis and subsequent increase in plant productivity (21% increase; Fig.  
138 2; Table S2; n = 15), and the enhancement of C allocation to roots along with enhanced soil  
139 nutrient cycling and soil cation exchange capacity (Teague et al. 2011; Norton et al. 2013;  
140 Machmuller et al. 2015). AMP grazing can also stimulate CO<sub>2</sub> sequestration by increasing the  
141 fungal-bacterial ratio in the soil (Teague et al. 2011), likely preventing the decline of arbuscular  
142 mycorrhiza fungi (AMF) (Barto and Rillig 2010) and thereby enhancing soil structure and  
143 aggregation (Ondrasek et al. 2019), and by enhancing the C use efficiency of soil microbes that  
144 has been shown to stimulate C accrual in persistent mineral SOC pools in AMP pastures (Mosier  
145 et al. 2021). We found soil C accrual rates of 3.3 Mg C ha<sup>-1</sup> yr<sup>-1</sup> on average in temperate and

subtropical grasslands under AMP grazing ( $n = 5$ ; Table S1). To put these values into perspective, a recent synthesis study (Conant et al. 2017) showed that improved management of grasslands using well-established sustainable strategies (e.g. sowing legumes, fertilization, irrigation), known to enhance SOC pools in grasslands, could lead to an increase of soil C sequestration rates of  $1.5 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$  within a decade of implementation (Table S3).

Although we showed that AMP enhances SOC pools of grasslands, results varied by site (from 135% increase to 40% decrease; Table S1) and several management and climate factors could contribute to this variability. It is likely that the stimulating response of AMP vs CG on SOC pools varies nonlinearly with grazing intensity. According to our literature search, when grazing intensity is similar in both treatments, SOC accrual increases by 14%, and it increases to 27% when grazing intensity is  $\sim 2$ -fold higher in AMP than in CG pastures. As grazing intensity continues to increase, however, the benefit of AMP management declines increasing SOC accrual by only 3% (Fig. S3).

Using a larger number of paddocks to ensure short grazing periods and adequate but not excessive long recovery periods as well as high plant functional diversity can enhance the ecological benefits of AMP (Norton et al. 2013; Teague and Kreuter 2020). Grasslands subject to low precipitation, which are more vulnerable to degradation, will likely require low grazing intensity and high additional C inputs (e.g. hay, biochar, compost, etc.) to improve baseline conditions and forage quantity before AMP management is implemented (Table 1) (Dlamini et al. 2016; Rowntree et al. 2020). Future studies evaluating how AMP affects SOC across geographical gradients and grazing intensities are granted to help elucidate under which circumstances AMP is most beneficial in terms of SOC accrual (Fig. 2).



The impact of AMP in the long-lived GHG N<sub>2</sub>O and CH<sub>4</sub> is limited; some studies have shown that AMP decreases both N<sub>2</sub>O and CH<sub>4</sub> emissions (average reductions of 84% and 91% in N<sub>2</sub>O and CH<sub>4</sub>, respectively; Fig. 2; n = 7; Table S4). Reductions in N<sub>2</sub>O can occur via two potential mechanisms. First, AMP involves maintaining a highly diverse plant community including N-fixing species, species with root exudates containing biological nitrification inhibition compounds (BNIs), and alternative forage species (Teague et al. 2013; Balvert et al. 2017; Luo et al. 2018). The relatively abundant N fixing community could reduce the need for fertilizers, reducing N<sub>2</sub>O emissions and N runoff (Vicente & Dean, 2017), and species with root exudates containing BNIs (e.g. *Plantago lanceolata*) could also decrease N<sub>2</sub>O emissions (Simon et al. 2019). Second, in AMP grasslands grazing occurs when soil wetness is sufficient for plant growth (Teague et al. 2013), which may optimize the synchrony between forage N demand and soil N availability, thus increasing Nitrogen Use Efficiency (NUE) and reducing N<sub>2</sub>O emissions from soils (Venterea et al. 2012).

While evidence suggests that AMP decreases CH<sub>4</sub> emissions from soils (Fig 2; Table S4), ecosystem CH<sub>4</sub> emissions could be higher in AMP vs CG particularly at higher AMP grazing intensities due to enhanced enteric ruminant fermentation emissions (Table S2). Whether decreases in CH<sub>4</sub> emissions in AMP soils could be partly offset by higher emissions from ruminants is unknown, which suggests that sustainable strategies directed at lowering enteric CH<sub>4</sub> emissions in AMP grasslands may play an important role on the overall potential of AMP as a climate mitigation strategy (Figs. S1 and 2) (Herrero et al. 2016).

In the absence of climate change manipulations studies, we hypothesize that AMP could increase the resilience of grasslands to global environmental changes through a set of mechanisms. A principle of AMP management is to maintain enough plant and litter cover to

decrease bare ground and retain soil wetness. Bare ground declined from 30% under conventional grazing to 1% in an AMP grassland with corresponding increases in soil water holding capacity (SWHC) (Teague et al. 2010, 2011), thereby reducing water and nutrient runoff by about 30% in AMP relative to conventional grazing (Park et al. 2017). These benefits of AMP management along with increases in SOC (Fig. 1) can improve the resilience of AMP grasslands against drought and flooding (Teague et al. 2010, 2011; FAO 2005). Increasing plant functional diversity in AMP managed grasslands may stabilize or even increase productivity along with productivity-dependent ecosystem functions by increasing grassland resilience (Fig. 2; Table S2) (Craine et al. 2013; Isbell et al. 2015), and enhancing plant diversity promotes diversity of other grassland organisms including pest predators and parasites, which could reduce the impact of increased pest outbreaks predicted with climate change (Giulio et al. 2001).

## **2. Agrivoltaics and Agroforestry with a reverse phenology species**

The spatial and temporal efficiency of natural resources (land, light, nutrients, water) can be optimized to increase the Land Equivalent ratio (LER), defined as the combined output of yield, biomass production or electric power production per acre relative to a business-as-usual managed grassland. In this section, we include ‘agrivoltaics’ (AV), defined as the combination of solar photovoltaic panels and grasslands on the same land, and agroforestry with a reverse phenology species, *Faidherbia (Acacia) albida*, as emerging strategies that can enhance the productive efficiency of grasslands while enhancing their climate mitigation potential (Fig. S2).

AV combines standard agronomic systems with solar panels to meet both agricultural and energy demands from a single field (Fig. S2), and differs from regular Photovoltaic systems (PV) or solar farms that produce energy and compete with food production for land. There is an

increasing body of evidence that shows that AV can increase LER, especially when the orientation of PV panels, tilt, size, distance, and design are optimized (n = 18; Table S6; Fig. 3A). Grasslands are ideal for AV adoption because they generally occupy areas with high solar irradiance including temperate, subtropical, tropical, arid and semi-arid regions (Table 1), and have minimal management, therefore causing minimal disturbance of farm operations (Adeh et al. 2019).

AV can enhance LER as well as the productivity and photosynthesis of grasslands through two mechanisms. The first is that AV has the potential to increase WUE enhancing productivity of grasslands particularly in regions limited by water availability. It has been shown that AV reduces ET of food crops grown under the shade of AV panels (Barron-Gafford et al. 2019). This shift away from latent heat flux could increase soil moisture and water use efficiency (WUE; i.e. greater increased efficiency in C capture relative to water use) in AV grasslands compared to conventionally managed grasslands. A recent study found that WUE of a temperate AV grassland was 328% higher than of a conventional grassland with an associated 90% increase in biomass (Adeh et al. 2018). AV panels also offer the possibility of a tighter regulation of water if rainfall collected from the panels is routed to irrigated areas under or adjacent to the panels, which together with improved WUE of AV systems could enhance drought and heat wave resilience. The second mechanism by which AV can increase photosynthesis is by shading, particularly in high irradiance regions (Adeh et al. 2019). Excess radiation, typically above  $\frac{1}{3}$  to  $\frac{1}{2}$  of full sunlight, can potentially damage photosynthetic machinery, reducing quantum efficiency and decreasing photosynthesis (Murata et al. 2007). Growing grasses under the partial shade of solar panels can reduce this damage, particularly at midday when irradiance and temperature are high.

We only found one study that investigated how PV panels impact CO<sub>2</sub> fluxes in a solar park seeded with plant-rich grassland species. In that study, enhanced net CO<sub>2</sub> uptake of areas between the panels were offset by decreased photosynthesis due to shading under panels (Armstrong et al. 2016); however, photosynthesis of plants under the panels could be enhanced by using PV systems with optimal design (panel placement, density and height; Table S6), with high light transmission (>80%) (Husain et al. 2018) and built from materials with selective wave-length technology that absorb some wavelengths of the solar spectrum but transmit wavelengths used by photosynthesis (Loik et al. 2017).

Changes in the interactions between microclimate and vegetation due to AV deployment will likely impact non-CO<sub>2</sub> GHGs and temperature at regional scales although observations are limited. We speculate that increases in soil wetness under panels will stimulate N<sub>2</sub>O and CH<sub>4</sub> production. However, there is evidence that shading stimulates plant N uptake (Cruz 1997; Andrew et al. 2021), improving NUE and suppressing N<sub>2</sub>O emissions, which might not support this prediction. While shading from PV panels in grasslands reduces leaf temperature, AV grasslands could warm the atmosphere (0.4-1 Celsius) if albedo, the proportion of incident radiation reflected by an ecosystem, decreases (Barron-Gafford et al. 2016; Lu et al. 2021).

Economic factors are critical in the decision-making process of adopting new technologies including AV. Economic profits depend on multiple aspects including establishment costs, profitability based on LER (including market fluctuations and national policies on grid regulation), government incentives, and potentially on additional revenue associated to C credits from reduced and avoided GHG emissions. While the deployment of PV systems has increased dramatically worldwide, the economic benefits of combining PV systems

with grassland or crop production on the same land are yet to be fully analyzed (Miao and Khanna 2020). AV systems could enhance the economic value of agricultural land as noted by some authors (Dinesh and Pearce 2016; Proctor et al. 2021) but to fully realize their potential, studies exploring how to maximize the land efficiency in the context of energy, water and GHG emissions are urgently needed (Ravi et al. 2014). These studies must consider the life-cycle analysis of solar installation, including logistic constraints, energy and materials used in the manufacturing of PV modules, PV energy efficiency, and the recycling of panels (often projected at 25 to 30 years) (Fthenakis and Kim 2011; Hsu et al. 2012).

*Faidherbia (Acacia) albida* is a reverse leaf phenology, N-fixing tree that thrives in hot weather, and grows well in climates with precipitation ranging from 50 to 1800 mm (Table 1). The natural distribution of this tree is Africa and South East Asia (Barnes and Fagg 2003), where 33% of grasslands are degraded and together make up 35% of global degraded grasslands (Kwon et al. 2016). Managed grasslands in Africa and Asia contribute ~42% to the warming effect of global grasslands (85.9 W m<sup>-2</sup> of radiative forcing) (Chang et al. 2021). Agroforestry with reverse phenology differs from regular agroforestry in that *F. albida* is photosynthetically active when intercropped herbaceous or crops are dormant. Reverse phenology trait is unique to this tree species (Barnes and Fagg 2003). Thus, this reverse phenology strategy could enhance not only spatial productive efficiency of an ecosystem as a regular agroforestry system does but also its temporal efficiency due to the temporal asynchrony of its growth and use of natural resources (e.g. light, water and nutrients) compared with herbaceous plants (Fig. S2).

Current research seeks to identify conditions in which growing trees and crops together yield more biomass than growing crops and grasses alone. *F. albida* sheds its leaves, ceasing transpiration when grasses are active, which minimizes natural resource competition (i.e. light

and nutrients) (Roupsard et al. 1999). This as well as the additional N fixed that provides slow-release N via decaying leaves, pods, and roots (Ndoye et al. 1995) enhances the productivity of the integrated system compared to a crop or grassland alone (Barnes and Fagg 2003). Our literature search showed that SOC consistently increased under the tree canopy compared to open row crops or grasslands in a wide variety of soils and herbaceous species (41% increase;  $n = 21$ ; Fig 3A; Table S7) likely because of high tree biomass, stimulated C input from crops and grasslands due to enhanced atmospheric N fixation, and enhanced proliferation of AMF in intercropped plant species (Birhane et al. 2018).

An aspect that will likely influence C storage as well as the productivity of the integrated system is tree planting density. A low tree planting density will not optimize the synergies between *Faidherbia albida* and grasses, and a high planting density will likely enhance the competition between species for water, nutrients and light and increase tree mortality (Barnes and Fagg 2003; Sileshi et al. 2014). Based on observations, medium planting densities at the time of tree establishment (i.e. 100 trees per hectare) and consequent thinning optimizes the use of site resources and C storage, and enhances the productivity of this integrated system (Garrity et al. 2010; Sileshi et al. 2014).

In the absence of N<sub>2</sub>O and CH<sub>4</sub> studies in grasslands-*F. albida* integrated systems we use biogeochemical knowledge to hypothesize its potential. The N content in *Faidherbia albida* biomass entering soils is comparable to fertilization of between 39 and 234 kg N ha<sup>-1</sup> annually depending on environmental conditions and tree density (Umar et al. 2012). Tropical, subtropical, and semi-arid grasslands are typically fertilized at between 20 and 240 kg N ha<sup>-1</sup> yr<sup>-1</sup> (Gomez-Casanovas et al. 2016), which suggests that grassland agroforestry with *Faidherbia albida* would not require fossil-fuel based fertilizers. While fast-release soluble nitrogen

fertilizers (e.g. urea, ammonium sulfate) are particularly susceptible to loss (Snyder et al. 2009), N-rich *Faidherbia albida* biomass may act as a slow-release fertilizer decreasing N<sub>2</sub>O emissions and N leaching, and enhancing NUE of integrated grasslands compared to conventionally managed grasslands (Wang and Alva 1996; Fernández et al. 2015).

We hypothesize that integrating *Faidherbia albida* in grasslands might increase CH<sub>4</sub> emissions from subtropical and tropical pastures, especially during wetter periods, and increase CH<sub>4</sub> uptake rates during drier times. *Faidherbia albida* roots go deeper (down to 7 meters) (Roupsard et al. 1999) than roots of grasslands and CH<sub>4</sub> produced in deep soil layers could bypass the top soil methanotrophic layer via root transport (Blanc-Betes et al. 2016). However, this impact might be counterbalanced by an increase in net CH<sub>4</sub> uptake rates during the dry season as ET in *Faidherbia albida* areas are larger than in the conventional grassland.

It has been suggested that agroforestry enhances the resilience of ecosystems to climate change (Field et al. 2014). Based on this observation, we expect reverse phenology agroforestry grasslands to be more resilient to changes in climate than conventional grasslands as agroforestry protects grasses from wind stress (Böhm et al. 2014), stabilizes air and soil temperatures (Lin, 2007), increases soil water storage (Anderson et al., 2009; Siriri et al., 2013), and stratifies rooting systems to better utilize water stored at depth. Given the vulnerability of subtropical, arid and semi-arid grasslands to environmental changes, future research should examine the potential of the adoption of this strategy under suitable conditions to reverse land degradation, decrease GHG emissions and enhance the resilience of grasslands to changes in climate and extreme weather events.

### 3. Enhanced weathering

EW – the acceleration of inorganic C sequestration by the mineral dissolution of fine-dust silicate rocks – is a promising, albeit understudied, NET strategy in the climate mitigation portfolio (Fig. S1). When applied to soils, the acidity of the soil rhizosphere enhances the dissolution of these powdered silicate rocks, releasing base cations ( $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ ) and  $\text{HCO}_3^-$  that not only basify the soil but also generate alkaline leachates that allow the ocean to store more C. These pulverized rocks have varying levels of calcium, P, K and Fe. In a modeling study, Taylor et al. (2016) predicted that the application of basalt over weathering ‘hotspots’ in the tropics and subtropics could reduce atmospheric temperatures by 0.2°C to 1.6°C by the end of the century, and its potential deployment in temperate climates looks promising (Table 1) (Beerling et al. 2020).

Among the fast-reactive silicate rocks, the adoption of basalt is particularly attractive in agricultural systems as the alleviation of nutrient limitation by the delivery of weathered nutrients (i.e. P, K, Ca, Mg and Fe) can restore soil fertility while avoiding the accumulation of harmful metals associated with olivine-rich ultramafic rocks (Beerling et al. 2018). Model estimates suggest that the large-scale deployment of basalt on cropland could counter up to 40% of current fossil fuel emissions by 2100 (Smith et al. 2017). Grasslands comprise a large global land area with potential for basalt deployment, and their dense root system and high incidence of AMF suggests that grasslands could be particularly suited for EW as plant-produced organic acids and a complex hyphae system typical of grasslands can facilitate the physical and chemical weathering of basalt (Quirk et al. 2012; Burghellea et al. 2018; Porder 2019).



Few studies have investigated how basalt affects productivity in grasslands. However, many studies have documented the benefits of applying Si slag on productivity in crops including wheat, rice, corn and sugarcane as extensively reviewed with productivity improvements over 40% (Tubana et al. 2016; Das et al. 2019). Basalt dust amendments can improve the productivity of grasslands and stimulate biological C sequestration through three mechanisms. First, fertilization, urine deposition, and sowing legumes cause the progressive acidification of soil, slowing organic matter and root turnover and limiting plant nutrient uptake and productivity (Neina 2019). Basalt-induced increases in soil pH may alleviate the limitation of soil acidification on plant productivity. In fact, basalt dust is often prescribed as an agricultural amendment on nutrient-poor acidic soils to counter soil degradation (Beerling et al. 2018). Second, the productivity of grasslands worldwide is constrained by P, K, Fe and silicate (Si) as they become depleted through repeated harvest or grazing (Blecker et al. 2006; Elser et al. 2007). Basalt contains varying levels of calcium, P, K and Fe and may provide a continued supply to sustain plant and microbe growth (Hartmann et al. 2013; Basak et al. 2017). In addition, basalt amendments, with 40-60% of Si content, could help restore soil Si levels and sustain the productivity of grasslands, which are high Si accumulating systems (Carey and Fulweiler 2012). Finally, albeit controversial, many studies report a negative correlation between grazing intensity and the presence of AMF, plant P uptake, and productivity (Barto and Rillig 2010). Fast-reactive silicate rocks stimulate AMF proliferation (Porder 2019), which enhances plant growth through a combination of high photosynthesis rate and improved nutrient and water uptake by promoting an extended extraradical hyphae network (Bitterlich et al. 2018; Begum et al. 2019).

With its positive impact on productivity and AMF proliferation, EW could increase SOC sequestration in grasslands (Beerling et al. 2018). In addition, enhanced soil pH and cation release from EW enhances the cation exchange capacity of soils and nutrient availability, which could also increase SOC accumulation (Gillman et al. 2001). However, at the moment, the impacts of EW on SOC of terrestrial ecosystems is unknown and requires further research.

While EW schemes are intended as a CO<sub>2</sub> removal strategy, these materials could impact non-CO<sub>2</sub> GHG emissions from amended soils. We only found one study that documented the impact of EW on N<sub>2</sub>O fluxes (Blanc-Betes et al. 2020) (Table S8). In this study, the authors found that the application of basalt decreased N<sub>2</sub>O emissions by 16 and 8%, respectively, in a temperate corn field and *Miscanthus* grassland used for bioenergy production; and they attributed such decreases to pH-driven stimulations of the N<sub>2</sub>O reductase, and to a lesser extent, to enhanced NUE associated with basalt-induced increases in soil P content and availability.

Although few studies have investigated how basalt affects N<sub>2</sub>O and CH<sub>4</sub>, numerous studies have documented the impact of applying Si and Fe slag on these gases (Tables S8 and S9). We found that these slag materials decreased N<sub>2</sub>O and CH<sub>4</sub> emissions by 32% and 21%, respectively, and their response depended on slag type and application rate (Fig. 3B; Tables S8 and S9). The mechanisms explaining how EW, and Si and Fe slag decrease CH<sub>4</sub> fluxes are likely similar. Under anaerobic conditions, Fe accepts electrons and Si enhances oxygen transport to roots, which reduce methanogenic activity (Das et al. 2019). In aerobic soils, increasing pH and P stimulate CH<sub>4</sub> uptake (Mosier et al. 1998).

Farming with crushed silicate rocks can improve the resilience of grasslands to changes in climate through silicon and calcium-mediated mechanisms (e.g. increase in AMF effectiveness) (Moradtalab et al. 2019) that can maximize WUE (Green et al. 2013), protect

plants against other biotic and abiotic stresses like heat, drought, and pathogens (Liang et al. 2007; Frew et al. 2017), and enhance water storage in agricultural watersheds (Green et al. 2013).

Overall, the beneficial impact of EW on productivity, GHG emissions, and on enhanced resilience to climate change will likely depend on EW material, rate of application, and soil properties including initial pH and soil buffering capacity, and Si and Fe levels of amended soils. This suggests that more studies in response to EW material are needed across geographically diverse grasslands at multiple rates and type of EW material. In addition, trade-offs related with the large-scale deployment of basalt amendments need to be further assessed to characterizing its potential for climate mitigation (Beerling et al. 2018).

#### **4. Outlook and future directions**

Achieving food and energy security will only be possible with a shift to ecologically and environmentally sustainable management of agricultural systems that build resilience to climate change. We conclude that environmental benefits vary between emerging management strategies (Table 1), and that all of them have potential to enhance the resilience of grasslands to climate change. The adoption of AMP, *F. albida* agroforestry, and EW could offer almost exclusively positive impacts (Table 1). AV grasslands could enhance productivity per land area as evidenced in other ecosystems while decreasing the land competition for food and energy but our knowledge of its impact on climate regulating services of grasslands is limited (Table 1).

Some of these strategies are not mutually exclusive and their implementation in grasslands to help slow climate change could be combined. For instance, EW could be combined with AV to suppress the stimulation of N<sub>2</sub>O emissions hypothesized in AV grasslands. However,

417 these novel strategies have yet to be fully evaluated in large scale field trials, and findings  
418 incorporated in models for evaluating their potential under future climate change scenarios.  
419 Evaluating their economic and social viability requires a systematic understanding of the  
420 environmental and the economic benefits of adopting these emerging strategies as well as the  
421 social barriers for adoption, because solutions for sustainable grasslands must be adapted to local  
422 climates, edaphic characteristics, and socio-economic drivers (Paustian et al. 2016; Smith et al.  
423 2019). If extensive adoption is proven effective, these strategies have the potential to support the  
424 United Nations Sustainable Development Goals of Achieving Food and Energy Security and  
425 Climate Action while enhancing the resilience of grasslands to climate change (United Nations  
426 2018). We urge the scientific community to work across disciplines to rigorously address  
427 unanswered ecological and environmental, and socio-economic questions for realizing increased  
428 efficiency to provide food and energy from sustainable grasslands using these emerging  
429 management strategies.

430    **Acknowledgements**

431    This research was funded in part by Arizona State University (AZ, USA; award No.  
432    ASU092762), the Center for Advanced Bioenergy & Bioproducts Innovation (CABBI; Univ. of  
433    Illinois at Urbana-Champaign, Urbana, IL, USA), the US Department of Energy SunGrant  
434    Program (DE-FG36-08GO88073), the US Department of Agriculture NIFA (Project No. 2016-  
435    67019-24988), and the Leverhulme Trust (Leverhulme Centre for Climate Change Mitigation;  
436    Award No. RC-2015-029).

Table 1. Potential effect of emerging strategies on productivity, biodiversity, C sequestration, non-CO<sub>2</sub> GHG mitigation, and Water Use Efficiency (WUE) of grasslands, and hypothesized grassland type (temperate, T; tropical, Tr; sub-tropical, S, semi-arid, Sa; and, arid, A) in which the adoption of these strategies could be more successful according to ecological theory and available literature (Tables S1, S2, S3, S4, S6-S9; Figs. 2, 3 and 4). ‘+’ denotes enhanced effect; ‘-’ denotes reduced effect; ‘±’ denotes either enhanced or reduced effect. Ecosystem C sequestration refers to the complementary approach of inferring C stored using eddy covariance methods that measure continuous CO<sub>2</sub> fluxes at high frequency (i.e. 0.1s). This method enables to gain mechanistic understanding of how management influences fluxes from ecosystems at multiple temporal scales and also to estimate gross photosynthesis fluxes (Gross Primary Productivity; GPP) and CO<sub>2</sub> losses (ecosystem respiration), which is crucial for accurate predictions of the resilience of agricultural ecosystems in environmental change scenarios (De Klein et al. 2006; Field et al. 2014). Biodiversity refers to plant, soil fauna, insect and bird diversity. We expect enhanced weathering to enhance soil fauna (e.g. AMF) (Porder 2019) due to higher pH, Si additions and enhanced soil health compared to control (Frąc et al. 2018). Asterisks by the symbol reflect that knowledge of the potential effect of the strategy on each variable derives from observations in grasslands and other ecosystems (Tables S1, S2, S3, S4, S6-S9; Figs. 2, 3 and 4) as well as investigations reported in this study; the absence of an asterisk by the symbol reflects that the potential impact is hypothesized. † We expect that grasslands subject to semi-arid and arid climates to require low grazing intensity and high additional C inputs (e.g. hay, biochar, compost, etc.) to improve baseline conditions and forage quantity before AMP management is implemented (Dlamini et al. 2016; Rowntree et al. 2020).

Emerging strategy	Productivity	Biodiversity	Ecosystem/soil C sequestration	N <sub>2</sub> O emission	CH <sub>4</sub> emission	WUE	Grassland type
Adaptive Multi- paddock grazing	+	+	+	-	+*/-*	+	T, Tr, S, Sa <sup>†</sup> and A <sup>†</sup>
Agrivoltaics	+	+/-	+/-	+/-	+/-	+	T, Tr, S, Sa and A
Integration of Faidherbia albida	+	+	+	-	+/-	+	T, S, Tr, Sa, and A
Enhanced Weathering	+	+	+	-	-	+	T, S, Tr

Figure 1. Key ecosystem services provided by grasslands. The figure represents provisioning, supporting and regulating services as well as resources that limit plant and microbial growth including light, nutrients and water. We include supporting services as an ecosystem service as listed in the Millennium Ecosystem Assessment (Watson et al., 2005). Pools are depicted inside squares and include plant, nutrient, water and carbon pools. Processes are depicted in circles and greenhouse gas (GHG) as well as water and nutrient fluxes are depicted in arrow boxes. The figure also represents the interaction between pools through depicted processes. Only plant diversity, and C, nutrient, and water cycles are considered and hence, the figure does not represent a comprehensive overview of ecosystem services.

Figure 2. Impact of Adaptive Multi-paddock Grazing (AMP) management on Soil Organic Carbon (SOC), productivity and the emission of N<sub>2</sub>O and CH<sub>4</sub> of grasslands. The literature search was conducted using Science Citation Index Expanded database from ISI Web of Knowledge, Web of Science (n = 21 for SOC; n = 15 for productivity; n = 7 for N<sub>2</sub>O fluxes; n = 7 for CH<sub>4</sub> fluxes; Tables S1, S2, S3 and S4). The % change refers to the relative increase or decrease of SOC, productivity, N<sub>2</sub>O and CH<sub>4</sub> emissions of AMP versus Continuous Grazing (CG). For N<sub>2</sub>O and CH<sub>4</sub> fluxes, negative indicates uptake and positive, emission. Error bars represent uncertainty in reported observations.

Figure 3. Impact of agrivoltaics (AV) on Land Equivalent Ratio (LER) in agricultural land, and of *Faidherbia albida* cultivation on SOC of crops, grasses and savannah (A), and impact of silicate and iron rich materials on the emission of N<sub>2</sub>O and CH<sub>4</sub> from terrestrial ecosystems (B). The LER ratio measures the combined output (yield or biomass production of the crop and

electric power production of the PV – photovoltaic – panels) per acre relative to a PV system or monoculture or grassland alone. The AV literature search was conducted using Science Citation Index Expanded database from ISI Web of Knowledge, Web of Science (n = 18; Table S6). The *Faidherbia albida* literature search was conducted using Science Citation Index Expanded database from ISI Web of Knowledge, Web of Science (n = 21; Table S7). The % change refers to the relative increase or decrease of SOC of areas under the tree versus areas in open beyond the tree canopy. The silicate and iron rich materials literature search was conducted using Science Citation Index Expanded database from ISI Web of Knowledge, Web of Science (n = 30 for N<sub>2</sub>O fluxes; n = 36 for CH<sub>4</sub> fluxes; Tables S8 and S9). The % change refers to the relative increase or decrease of N<sub>2</sub>O and CH<sub>4</sub> fluxes of slag application treatment vs control. For N<sub>2</sub>O and CH<sub>4</sub> fluxes, negative indicates uptake and positive, emission. Error bars represent uncertainty in reported observations.



## References

- Adeh E, Selker JS, Higgins CW (2018) Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency. *PloS One* 13:e0203256. <https://doi.org/10.1371/journal.pone.0203256>
- Adeh EH, Good SP, Calaf M, Higgins CW (2019) Solar PV Power Potential is Greatest Over Croplands. *Sci Rep* 9:1–6. <https://doi.org/10.1038/s41598-019-47803-3>
- Andrew AC, Higgins CW, Smallman MA, et al (2021) Herbage Yield, Lamb Growth and Foraging Behavior in Agrivoltaic Production System. *Front Sustain Food Syst* 5:. <https://doi.org/10.3389/fsufs.2021.659175>
- Armstrong A, Ostle NJ, Whitaker J (2016) Solar park microclimate and vegetation management effects on grassland carbon cycling. *Environ Res Lett* 11:074016. <https://doi.org/10.1088/1748-9326/11/7/074016>
- Balvert SF, Luo J, Schipper LA (2017) Do glucosinolate hydrolysis products reduce nitrous oxide emissions from urine affected soil? *Sci Total Environ* 603–604:370–380. <https://doi.org/10.1016/j.scitotenv.2017.06.089>
- Barnes RD, Fagg CW (2003) *Faidherbia albida*: monograph and annotated bibliography. Oxford Forestry Institute, University of Oxford
- Barron-Gafford GA, Minor RL, Allen NA, et al (2016) The Photovoltaic Heat Island Effect: Larger solar power plants increase local temperatures. *Sci Rep* 6:1–7. <https://doi.org/10.1038/srep35070>
- Barron-Gafford GA, Pavao-Zuckerman MA, Minor RL, et al (2019) Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *Nat Sustain* 2:848–855. <https://doi.org/10.1038/s41893-019-0364-5>
- Barto EK, Rillig MC (2010) Does herbivory really suppress mycorrhiza? A meta-analysis. *J Ecol* 98:745–753
- Basak BB, Sarkar B, Biswas DR, et al (2017) Chapter Three - Bio-Intervention of Naturally Occurring Silicate Minerals for Alternative Source of Potassium: Challenges and Opportunities. In: Sparks DL (ed) *Advances in Agronomy*. Academic Press, pp 115–145
- Beerling DJ, Kantzas EP, Lomas MR, et al (2020) Potential for large-scale CO<sub>2</sub> removal via enhanced rock weathering with croplands. *Nature* 583:242–248. <https://doi.org/10.1038/s41586-020-2448-9>
- Beerling DJ, Leake JR, Long SP, et al (2018) Farming with crops and rocks to address global climate, food and soil security. *Nat Plants* 4:138–147. <https://doi.org/10.1038/s41477-018-0108-y>

- Begum N, Qin C, Ahanger MA, et al (2019) Role of Arbuscular Mycorrhizal Fungi in Plant Growth Regulation: Implications in Abiotic Stress Tolerance. *Front Plant Sci* 10:. <https://doi.org/10.3389/fpls.2019.01068>
- Bengtsson J, Bullock JM, Egoh B, et al (2019) Grasslands—more important for ecosystem services than you might think. *Ecosphere* 10:e02582. <https://doi.org/10.1002/ecs2.2582>
- Birhane E, Gebremeskel K, Taddesse T, et al (2018) Integrating *Faidherbia albida* trees into a sorghum field reduces striga infestation and improves mycorrhiza spore density and colonization. *Agrofor Syst* 92:643–653. <https://doi.org/10.1007/s10457-016-0027-8>
- Bitterlich M, Franken P, Graefe J (2018) Arbuscular Mycorrhiza Improves Substrate Hydraulic Conductivity in the Plant Available Moisture Range Under Root Growth Exclusion. *Front Plant Sci* 9:. <https://doi.org/10.3389/fpls.2018.00301>
- Blanc-Betes E, Kantola IB, Gomez-Casanovas N, et al (2020) In silico assessment of the potential of basalt amendments to ameliorate yields and reduce the N<sub>2</sub>O emission factor of agriculture. *Glob Change Biol Bioenergy*. <https://doi.org/10.1111/gcbb.12757>
- Blanc-Betes E, Welker JM, Sturchio NC, et al (2016) Winter precipitation and snow accumulation drive the methane sink or source strength of Arctic tussock tundra. *Glob Change Biol* 22:2818–2833. <https://doi.org/10.1111/gcb.13242>
- Blecker SW, McCulley RL, Chadwick OA, Kelly EF (2006) Biologic cycling of silica across a grassland bioclimate sequence. *Glob Biogeochem Cycles* 20:. <https://doi.org/10.1029/2006GB002690>
- Böhm C, Kanzler M, Freese D (2014) Wind speed reductions as influenced by woody hedgerows grown for biomass in short rotation alley cropping systems in Germany. *Agrofor Syst* 88:579–591. <https://doi.org/10.1007/s10457-014-9700-y>
- Burghilea CI, Dontsova K, Zaharescu DG, et al (2018) Trace element mobilization during incipient bioweathering of four rock types. *Geochim Cosmochim Acta* 234:98–114. <https://doi.org/10.1016/j.gca.2018.05.011>
- Byrnes RC, Eastburn DJ, Tate KW, Roche LM (2018) A Global Meta-Analysis of Grazing Impacts on Soil Health Indicators. *J Environ Qual* 47:758–765. <https://doi.org/10.2134/jeq2017.08.0313>
- Carey JC, Fulweiler RW (2012) The Terrestrial Silica Pump. *PLoS ONE* 7:. <https://doi.org/10.1371/journal.pone.0052932>
- Chang J, Ciais P, Gasser T, et al (2021) Climate warming from managed grasslands cancels the cooling effect of carbon sinks in sparsely grazed and natural grasslands. *Nat Commun* 12:118. <https://doi.org/10.1038/s41467-020-20406-7>
- Conant RT, Cerri CEP, Osborne BB, Paustian K (2017) Grassland management impacts on soil carbon stocks: a new synthesis. *Ecol Appl* 27:662–668. <https://doi.org/10.1002/eap.1473>

- Craine JM, Ocheltree TW, Nippert JB, et al (2013) Global diversity of drought tolerance and grassland climate-change resilience. *Nat Clim Change* 3:63–67. <https://doi.org/10.1038/nclimate1634>
- Cruz P (1997) Effect of shade on the growth and mineral nutrition of a C4 perennial grass under field conditions. *Plant Soil* 188:227–237. <https://doi.org/10.1023/A:1004296622463>
- Das S, Kim GW, Hwang HY, et al (2019) Cropping With Slag to Address Soil, Environment, and Food Security. *Front Microbiol* 10:. <https://doi.org/10.3389/fmicb.2019.01320>
- De Klein C, Novoa RSA, Ogle S, et al (2006) IPCC Guidelines for National Greenhouse Gas Inventories. Cambridge University Press, Cambridge, UK and NY, USA
- di Virgilio A, Lambertucci SA, Morales JM (2019) Sustainable grazing management in rangelands: Over a century searching for a silver bullet. *Agric Ecosyst Environ* 283:106561. <https://doi.org/10.1016/j.agee.2019.05.020>
- Dinesh H, Pearce JM (2016) The potential of agrivoltaic systems. *Renew Sustain Energy Rev* 54:299–308. <https://doi.org/10.1016/j.rser.2015.10.024>
- Dlamini P, Chivenge P, Chaplot V (2016) Overgrazing decreases soil organic carbon stocks the most under dry climates and low soil pH: A meta-analysis shows. *Agric Ecosyst Environ* 221:258–269. <https://doi.org/10.1016/j.agee.2016.01.026>
- Elser JJ, Bracken MES, Cleland EE, et al (2007) Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. *Ecol Lett* 10:1135–1142. <https://doi.org/10.1111/j.1461-0248.2007.01113.x>
- FAO (2005) Grassland of the world
- Fernández FG, Terry RE, Coronel EG (2015) Nitrous oxide emissions from anhydrous ammonia, urea, and polymer-coated urea in illinois cornfields. *J Environ Qual* 44:415–422. <https://doi.org/10.2134/jeq2013.12.0496>
- Field CB, Barros V, Dokken, et al (2014) IPCC: Impacts, Adaptation and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, UK and NY, USA
- Foley JA, Defries R, Asner GP, et al (2005) Global consequences of land use. *Science* 309:570–574. <https://doi.org/10.1126/science.1111772>
- Follett RF, Reed DA (2010) Soil Carbon Sequestration in Grazing Lands: Societal Benefits and Policy Implications. *Rangel Ecol Manag* 63:4–15. <https://doi.org/10.2111/08-225.1>

- Fraç M, Hannula SE, Bełka M, Jędrzycka M (2018) Fungal Biodiversity and Their Role in Soil Health. *Front Microbiol* 9:. <https://doi.org/10.3389/fmicb.2018.00707>
- Frew A, Powell JR, Allsopp PG, et al (2017) Arbuscular mycorrhizal fungi promote silicon accumulation in plant roots, reducing the impacts of root herbivory. *Plant Soil* 419:423–433. <https://doi.org/10.1007/s11104-017-3357-z>
- Fthenakis VM, Kim HC (2011) Photovoltaics: Life-cycle analyses. *Sol Energy* 85:1609–1628. <https://doi.org/10.1016/j.solener.2009.10.002>
- Fuss S, Jones CD, Kraxner F, et al (2016) Research priorities for negative emissions. *Environ Res Lett* 11:115007. <https://doi.org/10.1088/1748-9326/11/11/115007>
- Garrity DP, Akinnifesi FK, Ajayi OC, et al (2010) Evergreen Agriculture: a robust approach to sustainable food security in Africa. *Food Secur* 2:197–214. <https://doi.org/10.1007/s12571-010-0070-7>
- Gillman GP, Burkett DC, Coventry RJ (2001) A laboratory study of application of basalt dust to highly weathered soils: effect on soil cation chemistry. *Soil Res* 39:799–811. <https://doi.org/10.1071/sr00073>
- Giulio MD, Edwards PJ, Meister E (2001) Enhancing insect diversity in agricultural grasslands: the roles of management and landscape structure. *J Appl Ecol* 38:310–319. <https://doi.org/10.1046/j.1365-2664.2001.00605.x>
- Godfray HCJ, Beddington JR, Crute IR, et al (2010) Food Security: The Challenge of Feeding 9 Billion People. *Science* 327:812–818. <https://doi.org/10.1126/science.1185383>
- Gomez-Casanovas N, Hudiburg TW, Bernacchi CJ, et al (2016) Nitrogen deposition and greenhouse gas emissions from grasslands: uncertainties and future directions. *Glob Change Biol* 22:1348–1360. <https://doi.org/10.1111/gcb.13187>
- Green MB, Bailey AS, Bailey SW, et al (2013) Decreased water flowing from a forest amended with calcium silicate. *Proc Natl Acad Sci* 110:5999–6003. <https://doi.org/10.1073/pnas.1302445110>
- Griscom BW, Adams J, Ellis PW, et al (2017) Natural climate solutions. *Proc Natl Acad Sci U S A* 114:11645–11650. <https://doi.org/10.1073/pnas.1710465114>
- Hartmann J, West AJ, Renforth P, et al (2013) Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Rev Geophys* 51:113–149. <https://doi.org/10.1002/rog.20004>
- Herrero M, Henderson B, Havlík P, et al (2016) Greenhouse gas mitigation potentials in the livestock sector. *Nat Clim Change* 6:452–461. <https://doi.org/10.1038/nclimate2925>

- Hsu DD, O'Donoghue P, Fthenakis V, et al (2012) Life Cycle Greenhouse Gas Emissions of Crystalline Silicon Photovoltaic Electricity Generation. *J Ind Ecol* 16:S122–S135. <https://doi.org/10.1111/j.1530-9290.2011.00439.x>
- Husain AAF, Hasan WZW, Shafie S, et al (2018) A review of transparent solar photovoltaic technologies. *Renew Sustain Energy Rev* 94:779–791. <https://doi.org/10.1016/j.rser.2018.06.031>
- Isbell F, Craven D, Connolly J, et al (2015) Biodiversity increases the resistance of ecosystem productivity to climate extremes. *Nature* 526:574–577. <https://doi.org/10.1038/nature15374>
- Kwon H-Y, Nkonya E, Johnson T, et al (2016) Global Estimates of the Impacts of Grassland Degradation on Livestock Productivity from 2001 to 2011. In: Nkonya E, Mirzabaev A, von Braun J (eds) *Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development*. Springer International Publishing, Cham, pp 197–214
- Liang Y, Sun W, Zhu Y-G, Christie P (2007) Mechanisms of silicon-mediated alleviation of abiotic stresses in higher plants: A review. *Environ Pollut* 147:422–428. <https://doi.org/10.1016/j.envpol.2006.06.008>
- Loik ME, Carter SA, Alers G, et al (2017) Wavelength-Selective Solar Photovoltaic Systems: Powering Greenhouses for Plant Growth at the Food-Energy-Water Nexus. *Earths Future* 5:1044–1053. <https://doi.org/10.1002/2016EF000531>
- Lu Z, Zhang Q, Miller PA, et al (2021) Impacts of Large-Scale Sahara Solar Farms on Global Climate and Vegetation Cover. *Geophys Res Lett* 48:e2020GL090789. <https://doi.org/10.1029/2020GL090789>
- Luo J, Balvert SF, Wise B, et al (2018) Using alternative forage species to reduce emissions of the greenhouse gas nitrous oxide from cattle urine deposited onto soil. *Sci Total Environ* 610–611:1271–1280. <https://doi.org/10.1016/j.scitotenv.2017.08.186>
- Machmuller MB, Kramer MG, Cyle TK, et al (2015) Emerging land use practices rapidly increase soil organic matter. *Nat Commun* 6:6995. <https://doi.org/10.1038/ncomms7995>
- Mahowald N, Jickells TD, Baker AR, et al (2008) Global distribution of atmospheric phosphorus sources, concentrations and deposition rates, and anthropogenic impacts. *Glob Biogeochem Cycles* 22:. <https://doi.org/10.1029/2008GB003240>
- Miao R, Khanna M (2020) Harnessing Advances in Agricultural Technologies to Optimize Resource Utilization in the Food-Energy-Water Nexus. *Annu Rev Resour Econ* 12:65–85. <https://doi.org/10.1146/annurev-resource-110319-115428>
- Moradtalab N, Hajiboland R, Aliasgharzad N, et al (2019) Silicon and the Association with an Arbuscular-Mycorrhizal Fungus (*Rhizophagus clarus*) Mitigate the Adverse Effects of

- Drought Stress on Strawberry. *Agronomy* 9:41.  
<https://doi.org/10.3390/agronomy9010041>
- Mosier AR, Delgado JA, Keller M (1998) Methane and nitrous oxide fluxes in an acid Oxisol in western Puerto Rico: effects of tillage, liming and fertilization. *Soil Biol Biochem* 30:2087–2098. [https://doi.org/10.1016/S0038-0717\(98\)00085-6](https://doi.org/10.1016/S0038-0717(98)00085-6)
- Mosier S, Apfelbaum S, Byck P, et al (2021) Adaptive multi-paddock grazing enhances soil carbon and nitrogen stocks and stabilization through mineral association in southeastern U.S. grazing lands. *J Environ Manage* 288:112409.  
<https://doi.org/10.1016/j.jenvman.2021.112409>
- Murata N, Takahashi S, Nishiyama Y, Allakhverdiev SI (2007) Photoinhibition of photosystem II under environmental stress. *Biochim Biophys Acta* 1767:414–421.  
<https://doi.org/10.1016/j.bbabi.2006.11.019>
- Ndoye I, Gueye M, Danso SKA, Dreyfus B (1995) Nitrogen fixation in *Faidherbia albida*, *Acacia raddiana*, *Acacia senegal* and *Acacia seyal* estimated using the <sup>15</sup>N isotope dilution technique. *Plant Soil* 172:175–180. <https://doi.org/10.1007/BF00011319>
- Neina D (2019) The Role of Soil pH in Plant Nutrition and Soil Remediation. In: *Appl. Environ. Soil Sci.* <https://www.hindawi.com/journals/aess/2019/5794869/>. Accessed 14 May 2020
- Norton BE, Barnes M, Teague R (2013) Grazing Management Can Improve Livestock Distribution: Increasing accessible forage and effective grazing capacity. *Rangelands* 35:45–51. <https://doi.org/10.2111/RANGELANDS-D-13-00016.1>
- O'Mara FP (2012) The role of grasslands in food security and climate change. *Ann Bot* 110:1263–1270. <https://doi.org/10.1093/aob/mcs209>
- Ondrasek G, Bakić Begić H, Zovko M, et al (2019) Biogeochemistry of soil organic matter in agroecosystems & environmental implications. *Sci Total Environ* 658:1559–1573.  
<https://doi.org/10.1016/j.scitotenv.2018.12.243>
- Park JY, Ale S, Teague R, Dowhower SL (2017) Simulating hydrologic responses to alternate grazing management practices at the ranch and watershed scales. *J Soil Water Conserv* 72:102–121. <https://doi.org/10.2489/jswc.72.2.102>
- Paustian K, Lehmann J, Ogle S, et al (2016) Climate-smart soils. *Nature* 532:49–57.  
<https://doi.org/10.1038/nature17174>
- Porder S (2019) How Plants Enhance Weathering and How Weathering is Important to Plants. *Elements* 15:241–246. <https://doi.org/10.2138/gselements.15.4.241>
- Proctor KW, Murthy GS, Higgins CW (2021) Agrivoltaics Align with Green New Deal Goals While Supporting Investment in the US' Rural Economy. *Sustainability* 13:137.  
<https://doi.org/10.3390/su13010137>

- Quirk J, Beerling DJ, Banwart SA, et al (2012) Evolution of trees and mycorrhizal fungi intensifies silicate mineral weathering. *Biol Lett* 8:1006–1011
- Ramankutty N, Evan AT, Monfreda C, Foley JA (2008) Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. <https://doi.org/10.1029/2007GB002952>
- Ravi S, Lobell DB, Field CB (2014) Tradeoffs and Synergies between biofuel production and large solar infrastructure in deserts. *Environ Sci Technol* 48:3021–3030. <https://doi.org/10.1021/es404950n>
- Roupsard O, Ferhi A, Granier A, et al (1999) Reverse phenology and dry-season water uptake by *Faidherbia albida* (Del.) A. Chev. in an agroforestry parkland of Sudanese west Africa. *Funct Ecol* 13:460–472. <https://doi.org/10.1046/j.1365-2435.1999.00345.x>
- Rowntree JE, Stanley PL, Maciel ICF, et al (2020) Ecosystem Impacts and Productive Capacity of a Multi-Species Pastured Livestock System. *Front Sustain Food Syst* 4:. <https://doi.org/10.3389/fsufs.2020.544984>
- Sanderman J, Hengl T, Fiske GJ (2017) Soil carbon debt of 12,000 years of human land use. *Proc Natl Acad Sci* 114:9575–9580. <https://doi.org/10.1073/pnas.1706103114>
- Sileshi GW, Nyoka BI, Beedy TL, Chanyenga T (2014) Modelling the scaling of stem growth with crown size and optimum stocking densities for systematic grid plantation of *Faidherbia albida*. *New For* 45:699–714. <https://doi.org/10.1007/s11056-014-9432-x>
- Simon PL, de Klein CAM, Worth W, et al (2019) The efficacy of *Plantago lanceolata* for mitigating nitrous oxide emissions from cattle urine patches. *Sci Total Environ* 691:430–441. <https://doi.org/10.1016/j.scitotenv.2019.07.141>
- Smith P, Adams J, Beerling DJ, et al (2019) Land-Management Options for Greenhouse Gas Removal and Their Impacts on Ecosystem Services and the Sustainable Development Goals. *Annu Rev Environ Resour* 44:255–286. <https://doi.org/10.1146/annurev-environ-101718-033129>
- Smith RJ, Horgan BHN, Mann P, et al (2017) Acid weathering of basalt and basaltic glass: 2. Effects of microscopic alteration textures on spectral properties. *J Geophys Res Planets* 122:203–227. <https://doi.org/10.1002/2016JE005112>
- Snyder CS, Bruulsema TW, Jensen TL, Fixen PE (2009) Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agric Ecosyst Environ* 133:247–266. <https://doi.org/10.1016/j.agee.2009.04.021>
- Taylor LL, Quirk J, Thorley RMS, et al (2016) Enhanced weathering strategies for stabilizing climate and averting ocean acidification. *Nat Clim Change* 6:402–406. <https://doi.org/10.1038/nclimate2882>

- Teague R, Dowhower SL, Baker SA, et al (2011) Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. *Agric Ecosyst Environ* 141:310–322. <https://doi.org/10.1016/j.agee.2011.03.009>
- Teague R, Dowhower SL, Baker SA, et al (2010) Soil and herbaceous plant responses to summer patch burns under continuous and rotational grazing. *Agric Ecosyst Environ* 137:113–123. <https://doi.org/10.1016/j.agee.2010.01.010>
- Teague R, Kreuter U (2020) Managing Grazing to Restore Soil Health, Ecosystem Function, and Ecosystem Services. *Front Sustain Food Syst* 4:. <https://doi.org/10.3389/fsufs.2020.534187>
- Teague R, Provenza F, Kreuter U, et al (2013) Multi-paddock grazing on rangelands: why the perceptual dichotomy between research results and rancher experience? *J Environ Manage* 128:699–717. <https://doi.org/10.1016/j.jenvman.2013.05.064>
- Tilman D (1999) Global environmental impacts of agricultural expansion: The need for sustainable and efficient practices. *Proc Natl Acad Sci* 96:5995–6000. <https://doi.org/10.1073/pnas.96.11.5995>
- Tubana B, Babu T, Datnoff L (2016) A Review of Silicon in Soils and Plants and Its Role in US Agriculture: History and Future Perspectives. *Soil Sci* 181:393–411. <https://doi.org/10.1097/SS.0000000000000179>
- Umar BB, Aune J, Lungu O (2012) Effects of *Faidherbia albida* on the fertility of soil in smallholder conservation agriculture systems in eastern and southern Zambia
- United Nations (2018) Sustainable Development Goals. Sustainable Development Knowledge Platform. <https://sustainabledevelopment.un.org/?menu=1300>. Accessed 7 Feb 2020
- Venterea RT, Halvorson AD, Kitchen N, et al (2012) Challenges and opportunities for mitigating nitrous oxide emissions from fertilized cropping systems. *Front Ecol Environ* 10:562–570. <https://doi.org/10.1890/120062>
- Vermeulen SJ, Campbell BM, Ingram JSI (2012) Climate Change and Food Systems. *Annu Rev Environ Resour* 37:195–222. <https://doi.org/10.1146/annurev-environ-020411-130608>
- Wang FL, Alva AK (1996) Leaching of Nitrogen from Slow-Release Urea Sources in Sandy Soils. *Soil Sci Soc Am J* 60:1454–1458. <https://doi.org/10.2136/sssaj1996.03615995006000050024x>

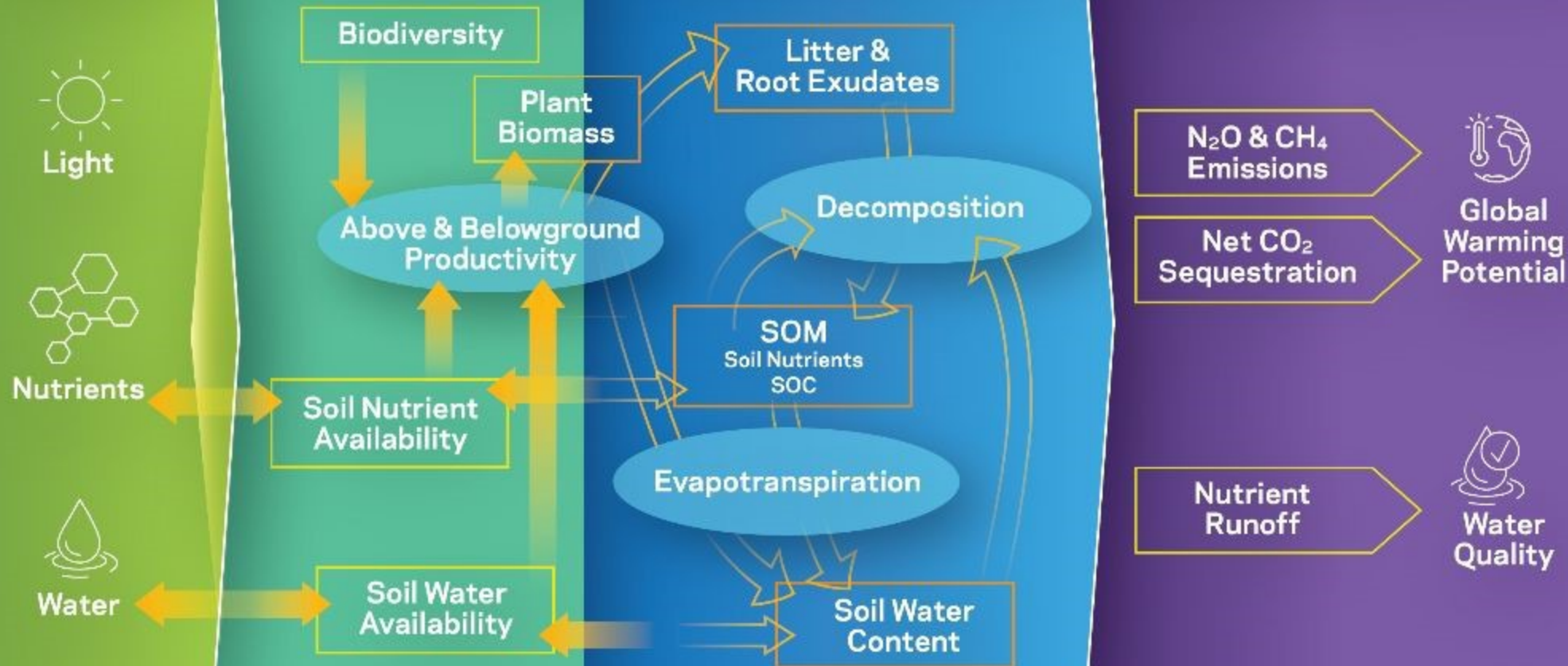


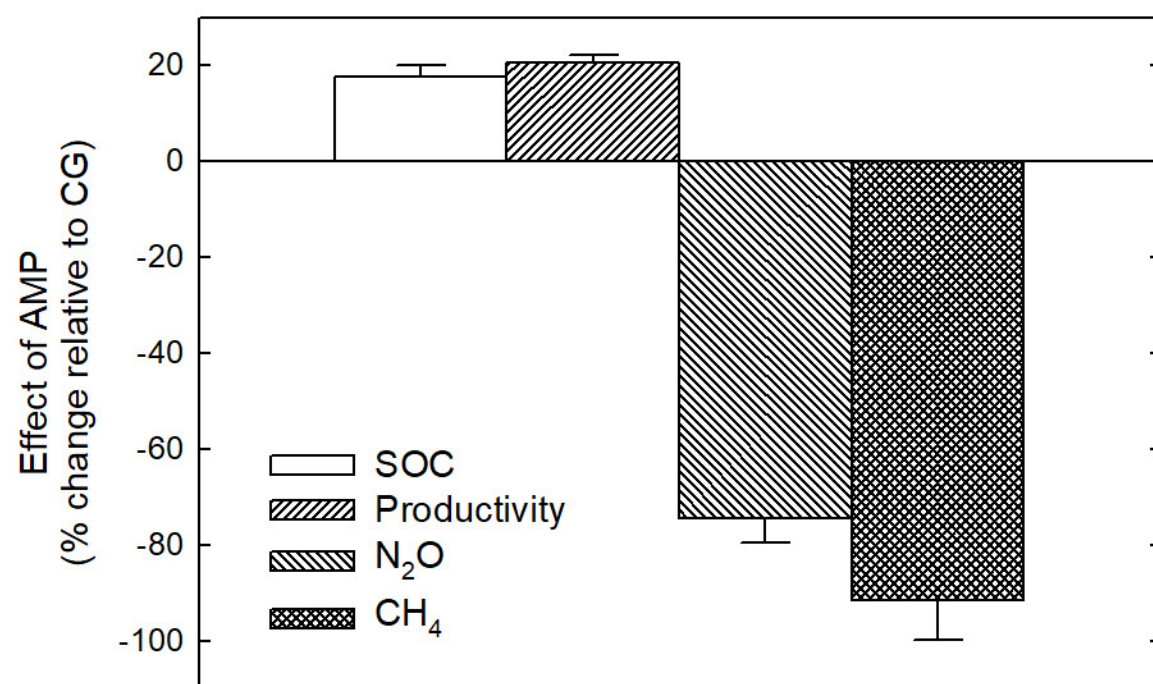
## RESOURCES

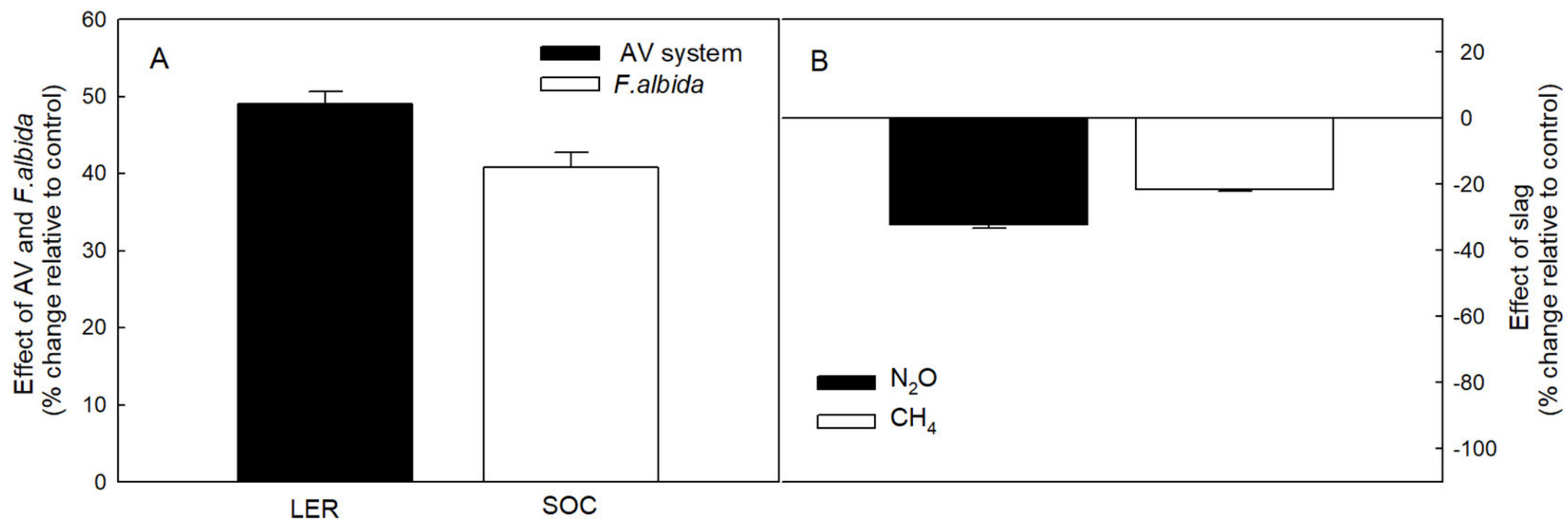
## PROVISIONING SERVICES

## SUPPORTING SERVICES

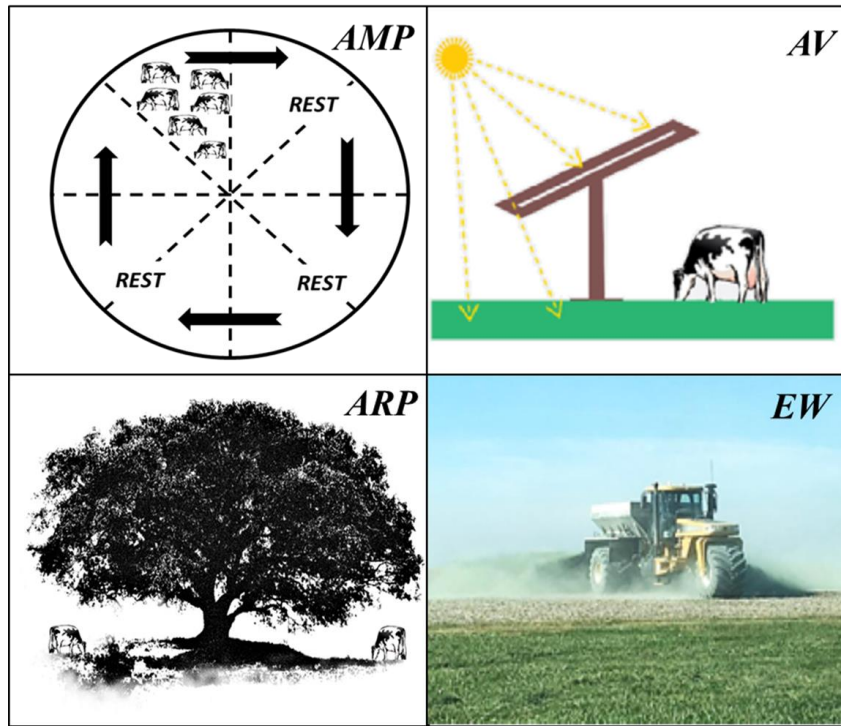
## REGULATING SERVICES







**Emerging strategies to enhance environmental benefits of grasslands:** Adaptive Multi-paddock grazing (AMP), Agrivoltaics (AV), Agroforestry with Reverse Phenology tree species (ARP), Enhanced Weathering (EW)



**Potential effect of emerging strategies on several environmental benefits of grasslands** compared to business-as usual management (BAU) illustrated as ‘flower’ diagrams. We conclude that all these strategies could promote at least some of the following benefits of grasslands: CO<sub>2</sub> sequestration, non-CO<sub>2</sub> GHG mitigation, productivity, resilience to climate change, and an efficient use of natural resources (land, water and nutrients). Leaves with a discontinuous contour denote enhanced or reduced effects.

