



A review of transformative strategies for climate mitigation by grasslands

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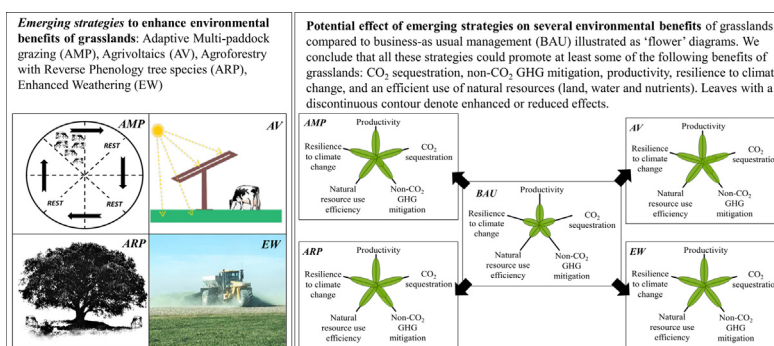
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HIGHLIGHTS

- Four strategies to mitigate warming and enhance efficiency of grasslands were evaluated.
- Adopting some of these strategies could offer almost exclusively environmental benefits.
- These strategies have the potential to enhance the resilience of grasslands to climate change.
- Their implementation in grasslands could be combined.
- Future research work is needed to secure food and energy from sustainable grasslands using these strategies.

GRAPHICAL ABSTRACT



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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 CO₂ 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: CO₂ sequestration, non-CO₂ 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.

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1. 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 km²) (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 ± 0.7 Gt CO₂e yr⁻¹ 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 (17,000 km² 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 CO₂e 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 CO₂e 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 CO₂e yr⁻¹ of mitigation potential, that could provide 8.7% of CO₂ 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 CO₂ from the atmosphere, and could provide an additional mitigation potential between 15 and 45 GtCO₂ 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 CO₂ and as they reach coastal systems, allowing the ocean to store more CO₂.

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

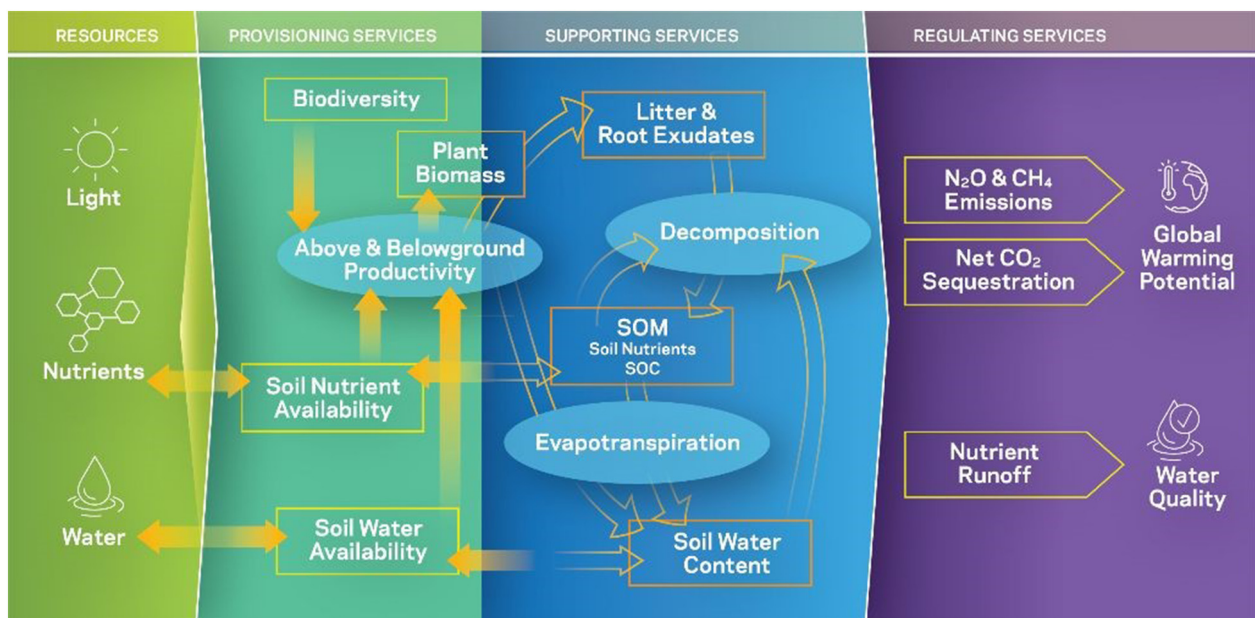


Fig. 1. Key ecosystem services provided by grasslands. The figure represents provisioning, supporting and regulating services as well as resources that limit plant and microbial growth including light, nutrients and water. We include supporting services as an ecosystem service as listed in the Millennium 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.

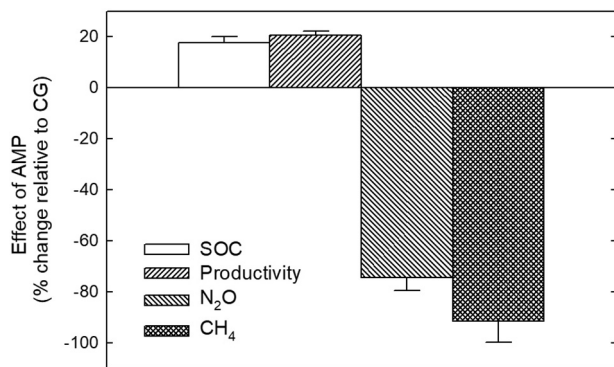


Fig. 2. Impact of Adaptive Multi-paddock Grazing (AMP) management on Soil Organic Carbon (SOC), productivity and the emission of N₂O and CH₄ of grasslands. The literature search was conducted using Science Citation Index Expanded database from ISI Web of Knowledge, Web of Science (n = 21 for SOC; n = 15 for productivity; n = 7 for N₂O fluxes; n = 7 for CH₄ fluxes; Tables S1, S2, S3 and S4). The % change refers to the relative increase or decrease of SOC, productivity, N₂O and CH₄ emissions of AMP versus Continuous Grazing (CG). For N₂O and CH₄ fluxes, negative indicates uptake and positive, emission. Error bars represent uncertainty in reported observations.

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.

2. 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 grazed by large herds for short periods of time (hours to days) in which vegetation consumption does not exceed 50% of available forage to maintain enough plant and litter cover to decrease bare ground and retain soil wetness (Fig. S2) (Teague et al., 2013). Grazing periods are followed with sufficient resting time to maintain plants in a state of rapid growth (from 30 to 45 days in mesic ecosystems during the growing season to 90 days during the non-growing season and four or more months in xeric grasslands during the growing season). AMP differs from rotational grazing and other management approaches (e.g. cell

grazing, short duration grazing) (di Virgilio et al., 2019) in that livestock intensity and grazing timing are adjusted as environmental conditions change to ensure adequate recovery of the grassland; it requires maintaining and reestablishing plant diversity, preferably native species, and avoids fertilizer and herbicide inputs (Teague et al., 2013).

Our literature search revealed that overall AMP grazing can increase Soil Organic Carbon (SOC) relative to business-as-usual managed grasslands (18% increase; Fig. 2; Table S1; n = 23). This SOC increase could be explained by a combination of mechanisms including the combined stimulation of photosynthesis and subsequent increase in plant productivity (21% increase; Fig. 2; Table S2; n = 15), and the enhancement of C allocation to roots along with enhanced soil nutrient cycling and soil cation exchange capacity (Teague et al., 2011; Norton et al., 2013; Machmuller et al., 2015). AMP grazing can also stimulate CO₂ sequestration by increasing the fungal-bacterial ratio in the soil (Teague et al., 2011), likely preventing the decline of arbuscular mycorrhiza fungi (AMF) (Barto and Killig, 2010) and thereby enhancing soil structure and aggregation (Ondrasek et al., 2019), and by enhancing the C use efficiency of soil microbes that has been shown to stimulate C accrual in persistent mineral SOC pools in AMP pastures (Mosier et al., 2021). We found soil C accrual rates of 3.3 Mg C ha⁻¹ yr⁻¹ 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 Mg C ha⁻¹ 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 ~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

Table 1
Potential effect of emerging strategies on productivity, biodiversity, C sequestration, non-CO₂ 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). ‘+’ 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 CO₂ fluxes at high frequency (i.e. 0.1 s). 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 CO₂ 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 ₂ O emission	CH ₄ emission	WUE	Grassland type
Adaptive Multi-paddock grazing	+*	+*	+*	-*	+*/-*	+*	T, Tr, S, Sa [†] and A [†]
Agrivoltaics	+*	+/-	+/-	+/-	+/-	+*	T, Tr, S, Sa and A
Integration of <i>Faidherbia albida</i>	+*	+*	+*	-	+/-	+	T, S, Tr, Sa, and A
Enhanced Weathering	+*	+*	+*	-*	-*	+*	T, S, Tr

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_2O and CH_4 is limited; some studies have shown that AMP decreases both N_2O and CH_4 emissions (average reductions of 84% and 91% in N_2O and CH_4 , respectively; Fig. 2; $n = 7$; Table S4). Reductions in N_2O 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_2O emissions and N runoff (Vicente and Dean, 2017), and species with root exudates containing BNIs (e.g. *Plantago lanceolata*) could also decrease N_2O 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_2O emissions from soils (Venterea et al., 2012).

While evidence suggests that AMP decreases CH_4 emissions from soils (Fig. 2; Table S4), ecosystem CH_4 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_4 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_4 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).

3. 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

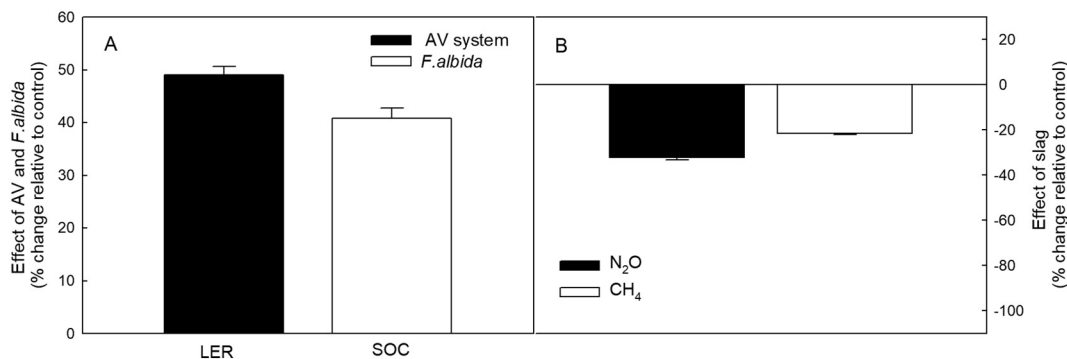


Fig. 3. Impact of agrivoltaics (AV) on Land Equivalent Ratio (LER) in agricultural land, and of *Faidherbia albida* cultivation on SOC of crops, grasses and savannah (A), and impact of silicate and iron rich materials on the emission of N_2O and CH_4 from terrestrial ecosystems (B). The LER ratio measures 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_2O fluxes; $n = 36$ for CH_4 fluxes; Tables S8 and S9). The % change refers to the relative increase or decrease of N_2O and CH_4 fluxes of slag application treatment vs control. For N_2O and CH_4 fluxes, negative indicates uptake and positive, emission. Error bars represent uncertainty in reported observations.

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 CO₂ fluxes in a solar park seeded with plant-rich grassland species. In that study, enhanced net CO₂ 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-CO₂ GHGs and temperature at regional scales although observations are limited. We speculate that increases in soil wetness under panels will stimulate N₂O and CH₄ production. However, there is evidence that shading stimulates plant N uptake (Cruz, 1997; Andrew et al., 2021), improving NUE and suppressing N₂O 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⁻² 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 N₂O and CH₄ 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⁻¹ 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⁻¹ yr⁻¹ (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 N₂O 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 CH₄ emissions from subtropical and tropical pastures, especially during wetter periods, and increase CH₄ uptake rates during drier times. *Faidherbia albida* roots go deeper (down to 7 m) (Roupsard et al., 1999) than roots of grasslands and CH₄ 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 CH₄ 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, 2010), 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.

4. 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 (Ca²⁺ and Mg²⁺) and HCO₃⁻ 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; Burghelca 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 CO₂ removal strategy, these materials could impact non-CO₂ GHG emissions from amended soils. We only found one study that documented the impact of EW on N₂O fluxes (Blanc-Betes et al., 2020) (Table S8). In this study, the authors found that the application of basalt decreased N₂O 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 N₂O 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 N₂O and CH₄, 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 N₂O and CH₄ 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 CH₄ 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 CH₄ 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).

5. 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 N₂O emissions hypothesized in AV grasslands. However, these novel strategies have yet to be fully evaluated in large scale field trials, and findings incorporated in models for evaluating their potential under future climate change scenarios. Evaluating their economic and social viability requires a systematic understanding of the environmental and the economic benefits of adopting these emerging strategies as well as the social barriers for adoption, because solutions for sustainable grasslands must be adapted to local climates, edaphic characteristics, and socio-economic drivers (Paustian et al., 2016; Smith et al., 2019). If extensive adoption is proven effective, these strategies have the potential to support the United Nations Sustainable Development Goals of Achieving Food and Energy Security and Climate Action while enhancing the resilience of grasslands to climate change (United Nations, 2018). We urge the scientific community to work across disciplines to rigorously address unanswered ecological and environmental, and socio-economic questions for realizing increased efficiency to provide food and energy from sustainable grasslands using these emerging management strategies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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