1   Title: A review of transformative strategies for climate mitigation by grasslands
2
3
4   Authors: Nuria Gomez-Casanovas[1,2,3], Elena Blanc-Betes[1,2,3], Caitlin E Moore[1,2,3,4], Carl J
5   Bernacchi[5,1,2,3,6], Ilsa Kantola[1,2,3], Evan H DeLucia[1,2,3,7].
6
7   [1] Institute for Sustainability, Energy, and Environment, University of Illinois at Urbana-
8   Champaign, Urbana, IL, USA

9   [2] Center for Advanced Bioenergy and Bioproducts Innovation, University of Illinois at Urbana-
10   Champaign, Urbana, IL, USA

11   [3] Carl R. Woese Institute for Genomic Biology, University of Illinois at Urbana-Champaign,
12   Urbana, IL, USA

13   [4] School of Agriculture and Environment, University of Western Australia, Crawley, WA, 6010,
14   Australia

15   [5] Global Change and Photosynthesis Research Unit, USDA-ARS, Urbana, IL, USA

16   [6] Department of Crop Sciences, University of Illinois at Urbana-Champaign, Urbana, IL, USA

17   [7] Department of Plant Biology, University of Illinois at Urbana-Champaign, Urbana, IL, USA
18
19
20
21
22
23
24
25
26
27   Corresponding Author: Evan H. DeLucia

28   Tel. 1 217 333 6177

29   Email: delucia@illinois.edu

1   Title: A review of transformative strategies for climate mitigation by grasslands
2
3
4   Authors: Nuria Gomez-Casanovas[1,2,3], Elena Blanc-Betes[1,2,3], Caitlin E Moore[1,2,3,4], Carl J
5   Bernacchi[5,1,2,3,6], Ilsa Kantola[1,2,3], Evan H DeLucia[1,2,3,7].
6
7   [1] Institute for Sustainability, Energy, and Environment, University of Illinois at Urbana-
8   Champaign, Urbana, IL, USA

9   [2] Center for Advanced Bioenergy and Bioproducts Innovation, University of Illinois at Urbana-
10 Champaign, Urbana, IL, USA

11 [3] Carl R. Woese Institute for Genomic Biology, University of Illinois at Urbana-Champaign,
12 Urbana, IL, USA

13 [4] School of Agriculture and Environment, University of Western Australia, Crawley, WA, 6010,
14 Australia

15 [5] Global Change and Photosynthesis Research Unit, USDA-ARS, Urbana, IL, USA

16 [6] Department of Crop Sciences, University of Illinois at Urbana-Champaign, Urbana, IL, USA

17 [7] Department of Plant Biology, University of Illinois at Urbana-Champaign, Urbana, IL, USA

18

19

20

21

22

23

24

25

26

27 Corresponding Author: Evan H. DeLucia

28 Tel. 1 217 333 6177

29 Email: delucia@illinois.edu

30

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_2 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_2 sequestration, non-CO_2 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_2 fluxes, CH_4 fluxes, N_2O fluxes, adaptive multipaddock grazing, patch burn grazing, agrivoltaics, agroforestry, reverse phenology, climate change.

55 **Introduction**

56   Climate mitigation targets set by the United Nations (UN) Paris Climate Agreement has

57 stimulated a new research agenda to redefine land management strategies to limit global

58 warming below 2°C. With 70% of global agricultural area (~42,7 million km^2) (FAO 2005;

59 Ramankutty et al. 2008), grasslands can significantly contribute to climate mitigation while

60 providing a myriad of additional ecosystem services (Fig. 1) (Bengtsson et al. 2019). Over the

61 last decades, human activities have switched grasslands impacts on climate from a net cooling

62 effect to a net warming effect (net source of GHGs of 1.8 ± 0.7 Gt CO_2e yr^{-1} during the 2000s),

63 indicating an urgent need for sustainable management strategies in grasslands directed to

64 mitigate climate warming (Chang et al. 2021).

65   Grasslands co-evolved with herbivores over millions of years contributing to their C-rich

66 soils (Follett and Reed 2010). The transition from a sink to a source of GHGs of grasslands is

67 attributed to land conversion from natural ecosystems to grasslands, and of grasslands to

68 cropland, and intensification for livestock production. Around 20% of global grasslands have

69 been converted to crops (17000 km^2 every year) to meet growing energy and food demands

70 (FAO 2005; O'Mara 2012), most of which were monocultures, with North America, Europe and

71 South Asia dominating land use change emissions attributed to grasslands (1.01 Gt CO_2e in the

72 last 60 years) (Chang et al. 2021).

73   A common consequence of grassland intensification is overgrazing, which occurs when

74 vegetation consumption exceeds the system ability to recover. Overgrazing reduces biodiversity

75 and the productive capacity of grasslands, and accelerates soil erosion causing the progressive

76 depletion of soil organic C (SOC) and disruption of soil aggregates (Follett and Reed 2010).

77 Agricultural land has suffered global losses of 133 PgC from the original SOC stocks, and over

78 half of that C has been lost in grazing lands (Sanderman et al. 2017). Grassland intensification

79 also increases nutrient and water requirements increasing the necessity for fertilization and

80 irrigation to sustain high productivity (Foley et al. 2005). Fertilization is associated with

81 enhanced soil GHG emissions, eutrophication of coastal systems, losses in biodiversity, and

82 increases in N deposition that can limit productivity by other nutrients (e.g. phosphorus and

83 micronutrients) (Tilman 1999; Mahowald et al. 2008; Gomez-Casanovas et al. 2016). In

84 addition, the production of fertilizers contributes 575 Mt of CO_2e to GHGs emissions from the

85 agricultural sector annually (Vermeulen et al. 2012). Further, losses of soil organic matter and

86 constraints in water holding capacity associated with intensification reduce grasslands resilience

87 to extreme climate events. With droughts and flooding events becoming more intense and

88 frequent, shrinking natural water resources and increased water requirements, this loss of

89 resilience jeopardizes the future of grasslands in a changing climate (Godfray et al. 2010).

90   The most mature sustainable strategies to improve the mitigation potential of grasslands

91 (e.g. avoided grassland conversion, optimizing grazing intensity, fire, legume sowing, animal

92 management, and biochar amendments; Fig. S1) offer up to 1.2 Pg CO_2e yr^{-1} of mitigation

93 potential, that could provide 8.7% of CO_2 mitigation needed through 2030 (Fig. S1) (Griscom et

94 al. 2017). Although this mitigation potential is substantial, it is uncertain whether we will be able

95 to hold global warming below 2°C without using negative emission technologies (NETs) (Fuss et

96 al. 2016). NETs target the removal of atmospheric CO_2 from the atmosphere, and could provide

97 an additional mitigation potential between 15 and 45 $GtCO_2$ annually (Fuss et al. 2016). An

98 understudied NET is enhanced weathering (EW), which consists of the application of pulverized

99 silicate-rich (Si) rocks on soils. These rocks applied on the land accelerate chemical weathering

100   and absorb atmospheric CO_2 and as they reach coastal systems, allowing the ocean to store more

101   CO_2.

102   In this Discussion paper, we summarize current knowledge and hypothesize likely effects

103   of the adoption of four emerging strategies that albeit understudied have the potential to improve

104   the GHG mitigation of grasslands while enhancing productivity. We focus on strategies that are

105   designed to both mitigate climate change and minimize the environmental stressors grasslands

106   are under including land degradation, water and land scarcity, nutrient requirements and climate

107   change. We focus on: 1) Adaptive multi-paddock grazing that consists of managing grasslands

108   mimicking how ancestral herds roamed the Earth; 2) agrivoltaics that consists of simultaneously

109   producing food and energy from solar panels on the same land area; 3) agroforestry with a

110   reverse phenology tree species, *Faidherbia (Acacia) albida,* that has the unique trait of being

111   photosynthetically active when intercropped herbaceous plants are dormant; and, 4) EW on

112   grasslands. We also identify gaps in knowledge critical for the full assessment of the potential of

113   these strategies for increasing food and energy security, environmental sustainability, and the

114   resilience of grasslands to changes in climate.

115

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

117   Grasslands typically are grazed for relatively long periods in large paddocks, and grazers

118   often choose to graze some areas more heavily than others (continuous grazing; CG) (Byrnes et

119   al. 2018). It has been argued that by mimicking the intensive grazing patterns of ancestral herds,

120   adaptive multi-paddock (AMP) grazing, a type of rotational grazing, could enhance the

121   ecological and environmental benefits from grasslands over CG management. AMP involves

122   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_2 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^{-1} yr^{-1} on average in temperate and

146 subtropical grasslands under AMP grazing (n = 5; Table S1). To put these values into

147 perspective, a recent synthesis study (Conant et al. 2017) showed that improved management of

148 grasslands using well-established sustainable strategies (e.g. sowing legumes, fertilization,

149 irrigation), known to enhance SOC pools in grasslands, could lead to an increase of soil C

150 sequestration rates of 1.5 Mg C ha^{-1} yr^{-1} within a decade of implementation (Table S3).

151   Although we showed that AMP enhances SOC pools of grasslands, results varied by site

152 (from 135% increase to 40% decrease; Table S1) and several management and climate factors

153 could contribute to this variability. It is likely that the stimulating response of AMP vs CG on

154 SOC pools varies nonlinearly with grazing intensity. According to our literature search, when

155 grazing intensity is similar in both treatments, SOC accrual increases by 14%, and it increases to

156 27% when grazing intensity is ~ 2-fold higher in AMP than in CG pastures. As grazing intensity

157 continues to increase, however, the benefit of AMP management declines increasing SOC

158 accrual by only 3% (Fig. S3).

159   Using a larger number of paddocks to ensure short grazing periods and adequate but not

160 excessive long recovery periods as well as high plant functional diversity can enhance the

161 ecological benefits of AMP (Norton et al. 2013; Teague and Kreuter 2020). Grasslands subject to

162 low precipitation, which are more vulnerable to degradation, will likely require low grazing

163 intensity and high additional C inputs (e.g. hay, biochar, compost, etc.) to improve baseline

164 conditions and forage quantity before AMP management is implemented (Table 1) (Dlamini et

165 al. 2016; Rowntree et al. 2020). Future studies evaluating how AMP affects SOC across

166 geographical gradients and grazing intensities are granted to help elucidate under which

167 circumstances AMP is most beneficial in terms of SOC accrual (Fig. 2).

168   The impact of AMP in the long-lived GHG N_2O and CH_4 is limited; some studies have

169   shown that AMP decreases both N_2O and CH_4 emissions (average reductions of 84% and 91% in

170   N_2O and CH_4, respectively; Fig. 2; n = 7; Table S4). Reductions in N_2O can occur via two

171   potential mechanisms. First, AMP involves maintaining a highly diverse plant community

172   including N-fixing species, species with root exudates containing biological nitrification

173   inhibition compounds (BNIs), and alternative forage species (Teague et al. 2013; Balvert et al.

174   2017; Luo et al. 2018). The relatively abundant N fixing community could reduce the need for

175   fertilizers, reducing N_2O emissions and N runoff (Vicente & Dean, 2017), and species with root

176   exudates containing BNIs (e.g. *Plantago lanceolata*) could also decrease N_2O emissions (Simon

177   et al. 2019). Second, in AMP grasslands grazing occurs when soil wetness is sufficient for plant

178   growth (Teague et al. 2013), which may optimize the synchrony between forage N demand and

179   soil N availability, thus increasing Nitrogen Use Efficiency (NUE) and reducing N_2O emissions

180   from soils (Venterea et al. 2012).

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

182   ecosystem CH_4 emissions could be higher in AMP vs CG particularly at higher AMP grazing

183   intensities due to enhanced enteric ruminant fermentation emissions (Table S2). Whether

184   decreases in CH_4 emissions in AMP soils could be partly offset by higher emissions from

185   ruminants is unknown, which suggests that sustainable strategies directed at lowering enteric

186   CH_4 emissions in AMP grasslands may play an important role on the overall potential of AMP as

187   a climate mitigation strategy (Figs. S1 and 2) (Herrero et al. 2016).

188   In the absence of climate change manipulations studies, we hypothesize that AMP could

189   increase the resilience of grasslands to global environmental changes through a set of

190   mechanisms. A principle of AMP management is to maintain enough plant and litter cover to

191 decrease bare ground and retain soil wetness. Bare ground declined from 30% under

192 conventional grazing to 1% in an AMP grassland with corresponding increases in soil water

193 holding capacity (SWHC) (Teague et al. 2010, 2011), thereby reducing water and nutrient runoff

194 by about 30% in AMP relative to conventional grazing (Park et al. 2017). These benefits of AMP

195 management along with increases in SOC (Fig. 1) can improve the resilience of AMP grasslands

196 against drought and flooding (Teague et al. 2010, 2011; FAO 2005). Increasing plant functional

197 diversity in AMP managed grasslands may stabilize or even increase productivity along with

198 productivity-dependent ecosystem functions by increasing grassland resilience (Fig. 2; Table S2)

199 (Craine et al. 2013; Isbell et al. 2015), and enhancing plant diversity promotes diversity of other

200 grassland organisms including pest predators and parasites, which could reduce the impact of

201 increased pest outbreaks predicted with climate change (Giulio et al. 2001).

202

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

204 The spatial and temporal efficiency of natural resources (land, light, nutrients, water) can

205 be optimized to increase the Land Equivalent ratio (LER), defined as the combined output of

206 yield, biomass production or electric power production per acre relative to a business-as-usual

207 managed grassland. In this section, we include 'agrivoltaics' (AV), defined as the combination of

208 solar photovoltaic panels and grasslands on the same land, and agroforestry with a reverse

209 phenology species, *Faidherbia (Acacia) albida,* as emerging strategies that can enhance the

210 productive efficiency of grasslands while enhancing their climate mitigation potential (Fig. S2).

211 AV combines standard agronomic systems with solar panels to meet both agricultural and

212 energy demands from a single field (Fig. S2), and differs from regular Photovoltaic systems (PV)

213 or solar farms that produce energy and compete with food production for land. There is an

214   increasing body of evidence that shows that AV can increase LER, especially when the

215   orientation of PV panels, tilt, size, distance, and design are optimized (n = 18; Table S6; Fig.

216   3A). Grasslands are ideal for AV adoption because they generally occupy areas with high solar

217   irradiance including temperate, subtropical, tropical, arid and semi-arid regions (Table 1), and

218   have minimal management, therefore causing minimal disturbance of farm operations (Adeh et

219   al. 2019).

220   AV can enhance LER as well as the productivity and photosynthesis of grasslands

221   through two mechanisms. The first is that AV has the potential to increase WUE enhancing

222   productivity of grasslands particularly in regions limited by water availability. It has been shown

223   that AV reduces ET of food crops grown under the shade of AV panels (Barron-Gafford et al.

224   2019). This shift away from latent heat flux could increase soil moisture and water use efficiency

225   (WUE; i.e. greater increased efficiency in C capture relative to water use) in AV grasslands

226   compared to conventionally managed grasslands. A recent study found that WUE of a temperate

227   AV grassland was 328% higher than of a conventional grassland with an associated 90%

228   increase in biomass (Adeh et al. 2018). AV panels also offer the possibility of a tighter regulation

229   of water if rainfall collected from the panels is routed to irrigated areas under or adjacent to the

230   panels, which together with improved WUE of AV systems could enhance drought and heat

231   wave resilience. The second mechanism by which AV can increase photosynthesis is by shading,

232   particularly in high irradiance regions (Adeh et al. 2019). Excess radiation, typically above ⅓ to

233   ½ of full sunlight, can potentially damage photosynthetic machinery, reducing quantum

234   efficiency and decreasing photosynthesis (Murata et al. 2007). Growing grasses under the partial

235   shade of solar panels can reduce this damage, particularly at midday when irradiance and

236   temperature are high.

237   We only found one study that investigated how PV panels impact CO_2 fluxes in a solar

238   park seeded with plant-rich grassland species. In that study, enhanced net CO_2 uptake of areas

239   between the panels were offset by decreased photosynthesis due to shading under panels

240   (Armstrong et al. 2016); however, photosynthesis of plants under the panels could be enhanced

241   by using PV systems with optimal design (panel placement, density and height; Table S6), with

242   high light transmission (>80%) (Husain et al. 2018) and built from materials with selective

243   wave-length technology that absorb some wavelengths of the solar spectrum but transmit

244   wavelengths used by photosynthesis (Loik et al. 2017).

245   Changes in the interactions between microclimate and vegetation due to AV

246   deployment will likely impact non-CO_2 GHGs and temperature at regional scales although

247   observations are limited. We speculate that increases in soil wetness under panels will stimulate

248   N_2O and CH_4 production. However, there is evidence that shading stimulates plant N uptake

249   (Cruz 1997; Andrew et al. 2021), improving NUE and suppressing N_2O emissions, which might

250   not support this prediction. While shading from PV panels in grasslands reduces leaf

251   temperature, AV grasslands could warm the atmosphere (0.4-1 Celsius) if albedo, the proportion

252   of incident radiation reflected by an ecosystem, decreases (Barron-Gafford et al. 2016; Lu et al.

253   2021).

254   Economic factors are critical in the decision-making process of adopting new

255   technologies including AV. Economic profits depend on multiple aspects including

256   establishment costs, profitability based on LER (including market fluctuations and national

257   policies on grid regulation), government incentives, and potentially on additional revenue

258   associated to C credits from reduced and avoided GHG emissions. While the deployment of PV

259   systems has increased dramatically worldwide, the economic benefits of combining PV systems

260   with grassland or crop production on the same land are yet to be fully analyzed (Miao and

261   Khanna 2020). AV systems could enhance the economic value of agricultural land as noted by

262   some authors (Dinesh and Pearce 2016; Proctor et al. 2021) but to fully realize their potential,

263   studies exploring how to maximize the land efficiency in the context of energy, water and GHG

264   emissions are urgently needed (Ravi et al. 2014). These studies must consider the life-cycle

265   analysis of solar installation, including logistic constraints, energy and materials used in the

266   manufacturing of PV modules, PV energy efficiency, and the recycling of panels (often projected

267   at 25 to 30 years) (Fthenakis and Kim 2011; Hsu et al. 2012).

268   *Faidherbia (Acacia) albida* is a reverse leaf phenology, N-fixing tree that thrives in hot

269   weather, and grows well in climates with precipitation ranging from 50 to 1800 mm (Table 1).

270   The natural distribution of this tree is Africa and South East Asia (Barnes and Fagg 2003), where

271   33% of grasslands are degraded and together make up 35% of global degraded grasslands (Kwon

272   et al. 2016). Managed grasslands in Africa and Asia contribute ~42% to the warming effect of

273   global grasslands (85.9 W m^{-2} of radiative forcing) (Chang et al. 2021). Agroforestry with

274   reverse phenology differs from regular agroforestry in that *F. albida* is photosynthetically active

275   when intercropped herbaceous or crops are dormant. Reverse phenology trait is unique to this

276   tree species (Barnes and Fagg 2003). Thus, this reverse phenology strategy could enhance not

277   only spatial productive efficiency of an ecosystem as a regular agroforestry system does but also

278   its temporal efficiency due to the temporal asynchrony of its growth and use of natural resources

279   (e.g. light, water and nutrients) compared with herbaceous plants (Fig. S2).

280   Current research seeks to identify conditions in which growing trees and crops together

281   yield more biomass than growing crops and grasses alone. *F. albida* sheds its leaves, ceasing

282   transpiration when grasses are active, which minimizes natural resource competition (i.e. light

12

283 and nutrients) (Roupsard et al. 1999). This as well as the additional N fixed that provides slow-

284 release N via decaying leaves, pods, and roots (Ndoye et al. 1995) enhances the productivity of

285 the integrated system compared to a crop or grassland alone (Barnes and Fagg 2003). Our

286 literature search showed that SOC consistently increased under the tree canopy compared to

287 open row crops or grasslands in a wide variety of soils and herbaceous species (41% increase; n

288 = 21; Fig 3A; Table S7) likely because of high tree biomass, stimulated C input from crops and

289 grasslands due to enhanced atmospheric N fixation, and enhanced proliferation of AMF in

290 intercropped plant species (Birhane et al. 2018).

291   An aspect that will likely influence C storage as well as the productivity of the integrated

292 system is tree planting density. A low tree planting density will not optimize the synergies

293 between *Faidherbia albida* and grasses, and a high planting density will likely enhance the

294 competition between species for water, nutrients and light and increase tree mortality (Barnes

295 and Fagg 2003; Sileshi et al. 2014). Based on observations, medium planting densities at the time

296 of tree establishment (i.e. 100 trees per hectare) and consequent thinning optimizes the use of site

297 resources and C storage, and enhances the productivity of this integrated system (Garrity et al.

298 2010; Sileshi et al. 2014).

299   In the absence of N_2O and CH_4 studies in grasslands-*F.albida* integrated systems we use

300 biogeochemical knowledge to hypothesize its potential. The N content in *Faidherbia albida*

301 biomass entering soils is comparable to fertilization of between 39 and 234 kg N ha^{-1} annually

302 depending on environmental conditions and tree density (Umar et al. 2012). Tropical,

303 subtropical, and semi-arid grasslands are typically fertilized at between 20 and 240 kg N ha^{-1} yr^{-1}

304 (Gomez-Casanovas et al. 2016), which suggests that grassland agroforestry with *Faidherbia*

305 *albida* would not require fossil-fuel based fertilizers. While fast-release soluble nitrogen

306 fertilizers (e.g. urea, ammonium sulfate) are particularly susceptible to loss (Snyder et al. 2009),

307 N-rich *Faidherbia albida* biomass may act as a slow-release fertilizer decreasing N_2O emissions

308 and N leaching, and enhancing NUE of integrated grasslands compared to conventionally

309 managed grasslands (Wang and Alva 1996; Fernández et al. 2015).

310 We hypothesize that integrating *Faidherbia albida* in grasslands might increase CH_4

311 emissions from subtropical and tropical pastures, especially during wetter periods, and increase

312 CH_4 uptake rates during drier times. *Faidherbia albida* roots go deeper (down to 7 meters)

313 (Roupsard et al. 1999) than roots of grasslands and CH_4 produced in deep soil layers could

314 bypass the top soil methanotrophic layer via root transport (Blanc-Betes et al. 2016). However,

315 this impact might be counterbalanced by an increase in net CH_4 uptake rates during the dry

316 season as ET in *Faidherbia albida* areas are larger than in the conventional grassland.

317 It has been suggested that agroforestry enhances the resilience of ecosystems to climate

318 change (Field et al. 2014). Based on this observation, we expect reverse phenology agroforestry

319 grasslands to be more resilient to changes in climate than conventional grasslands as agroforestry

320 protects grasses from wind stress (Böhm et al. 2014), stabilizes air and soil temperatures (Lin,

321 2007), increases soil water storage (Anderson et al., 2009; Siriri et al., 2013), and stratifies

322 rooting systems to better utilize water stored at depth. Given the vulnerability of subtropical, arid

323 and semi-arid grasslands to environmental changes, future research should examine the potential

324 of the adoption of this strategy under suitable conditions to reverse land degradation, decrease

325 GHG emissions and enhance the resilience of grasslands to changes in climate and extreme

326 weather events.

327

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 (Ca^{2+} and Mg^{2+}) and 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^oC to 1.6^oC 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; Burghelea et al. 2018; Porder 2019).

15

349   Few studies have investigated how basalt affects productivity in grasslands. However,

350   many studies have documented the benefits of applying Si slag on productivity in crops

351   including wheat, rice, corn and sugarcane as extensively reviewed with productivity

352   improvements over 40% (Tubana et al. 2016; Das et al. 2019). Basalt dust amendments can

353   improve the productivity of grasslands and stimulate biological C sequestration through three

354   mechanisms. First, fertilization, urine deposition, and sowing legumes cause the progressive

355   acidification of soil, slowing organic matter and root turnover and limiting plant nutrient uptake

356   and productivity (Neina 2019). Basalt-induced increases in soil pH may alleviate the limitation

357   of soil acidification on plant productivity. In fact, basalt dust is often prescribed as an

358   agricultural amendment on nutrient-poor acidic soils to counter soil degradation (Beerling et al.

359   2018). Second, the productivity of grasslands worldwide is constrained by P, K, Fe and silicate

360   (Si) as they become depleted through repeated harvest or grazing (Blecker et al. 2006; Elser et al.

361   2007). Basalt contains varying levels of calcium, P, K and Fe and may provide a continued

362   supply to sustain plant and microbe growth (Hartmann et al. 2013; Basak et al. 2017). In

363   addition, basalt amendments, with 40-60% of Si content, could help restore soil Si levels and

364   sustain the productivity of grasslands, which are high Si accumulating systems (Carey and

365   Fulweiler 2012). Finally, albeit controversial, many studies report a negative correlation between

366   grazing intensity and the presence of AMF, plant P uptake, and productivity (Barto and Rillig

367   2010). Fast-reactive silicate rocks stimulate AMF proliferation (Porder 2019), which enhances

368   plant growth through a combination of high photosynthesis rate and improved nutrient and water

369   uptake by promoting an extended extraradical hyphae network (Bitterlich et al. 2018; Begum et

370   al. 2019).

371   With its positive impact on productivity and AMF proliferation, EW could increase SOC

372   sequestration in grasslands (Beerling et al. 2018). In addition, enhanced soil pH and cation

373   release from EW enhances the cation exchange capacity of soils and nutrient availability, which

374   could also increase SOC accumulation (Gillman et al. 2001). However, at the moment, the

375   impacts of EW on SOC of terrestrial ecosystems is unknown and requires further research.

376   While EW schemes are intended as a CO_2 removal strategy, these materials could impact

377   non-CO_2 GHG emissions from amended soils. We only found one study that documented the

378   impact of EW on N_2O fluxes (Blanc-Betes et al. 2020) (Table S8). In this study, the authors

379   found that the application of basalt decreased N_2O emissions by 16 and 8%, respectively, in a

380   temperate corn field and Miscanthus grassland used for bioenergy production; and they attributed

381   such decreases to pH-driven stimulations of the N_2O reductase, and to a lesser extent, to

382   enhanced NUE associated with basalt-induced increases in soil P content and availability.

383   Although few studies have investigated how basalt affects N_2O and CH_4, numerous

384   studies have documented the impact of applying Si and Fe slag on these gases (Tables S8 and

385   S9). We found that these slag materials decreased N_2O and CH_4 emissions by 32% and 21%,

386   respectively, and their response depended on slag type and application rate (Fig. 3B; Tables S8

387   and S9). The mechanisms explaining how EW, and Si and Fe slag decrease CH_4 fluxes are likely

388   similar. Under anaerobic conditions, Fe accepts electrons and Si enhances oxygen transport to

389   roots, which reduce methanogenic activity (Das et al. 2019). In aerobic soils, increasing pH and

390   P stimulate CH_4 uptake (Mosier et al. 1998).

391   Farming with crushed silicate rocks can improve the resilience of grasslands to changes

392   in climate through silicon and calcium-mediated mechanisms (e.g. increase in AMF

393   effectiveness) (Moradtalab et al. 2019) that can maximize WUE (Green et al. 2013), protect

394 plants against other biotic and abiotic stresses like heat, drought, and pathogens (Liang et al.

395 2007; Frew et al. 2017), and enhance water storage in agricultural watersheds (Green et al.

396 2013).

397   Overall, the beneficial impact of EW on productivity, GHG emissions, and on enhanced

398 resilience to climate change will likely depend on EW material, rate of application, and soil

399 properties including initial pH and soil buffering capacity, and Si and Fe levels of amended soils.

400 This suggests that more studies in response to EW material are needed across geographically

401 diverse grasslands at multiple rates and type of EW material. In addition, trade-offs related with

402 the large-scale deployment of basalt amendments need to be further assessed to characterizing its

403 potential for climate mitigation (Beerling et al. 2018).

404

405 **4. Outlook and future directions**

406   Achieving food and energy security will only be possible with a shift to ecologically and

407 environmentally sustainable management of agricultural systems that build resilience to climate

408 change. We conclude that environmental benefits vary between emerging management strategies

409 (Table 1), and that all of them have potential to enhance the resilience of grasslands to climate

410 change. The adoption of AMP, *F. albida* agroforestry, and EW could offer almost exclusively

411 positive impacts (Table 1). AV grasslands could enhance productivity per land area as evidenced

412 in other ecosystems while decreasing the land competition for food and energy but our

413 knowledge of its impact on climate regulating services of grasslands is limited (Table 1).

414   Some of these strategies are not mutually exclusive and their implementation in

415 grasslands to help slow climate change could be combined. For instance, EW could be combined

416 with AV to suppress the stimulation of N_2O emissions hypothesized in AV grasslands. However,

417   these novel strategies have yet to be fully evaluated in large scale field trails, 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.

Table 1. Potential effect of emerging strategies on productivity, biodiversity, C sequestration, non-CO_2 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_2 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_2 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_2O 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 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_2O and CH_4 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_2O fluxes; n = 7 for CH_4 fluxes; Tables S1, S2, S3 and S4). The % change refers to the relative increase or decrease of SOC, productivity, N_2O and CH_4 emissions of AMP versus Continuous Grazing (CG). For N_2O and CH_4 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_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.

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_2 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 Abioth 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 N2O 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 bioclimosequence. 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

Burghelea 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

Frąc M, Hannula SE, Bełka M, Jędryczka 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 11015 5999-6003 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'Donoughue 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

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.bbabio.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 15N 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
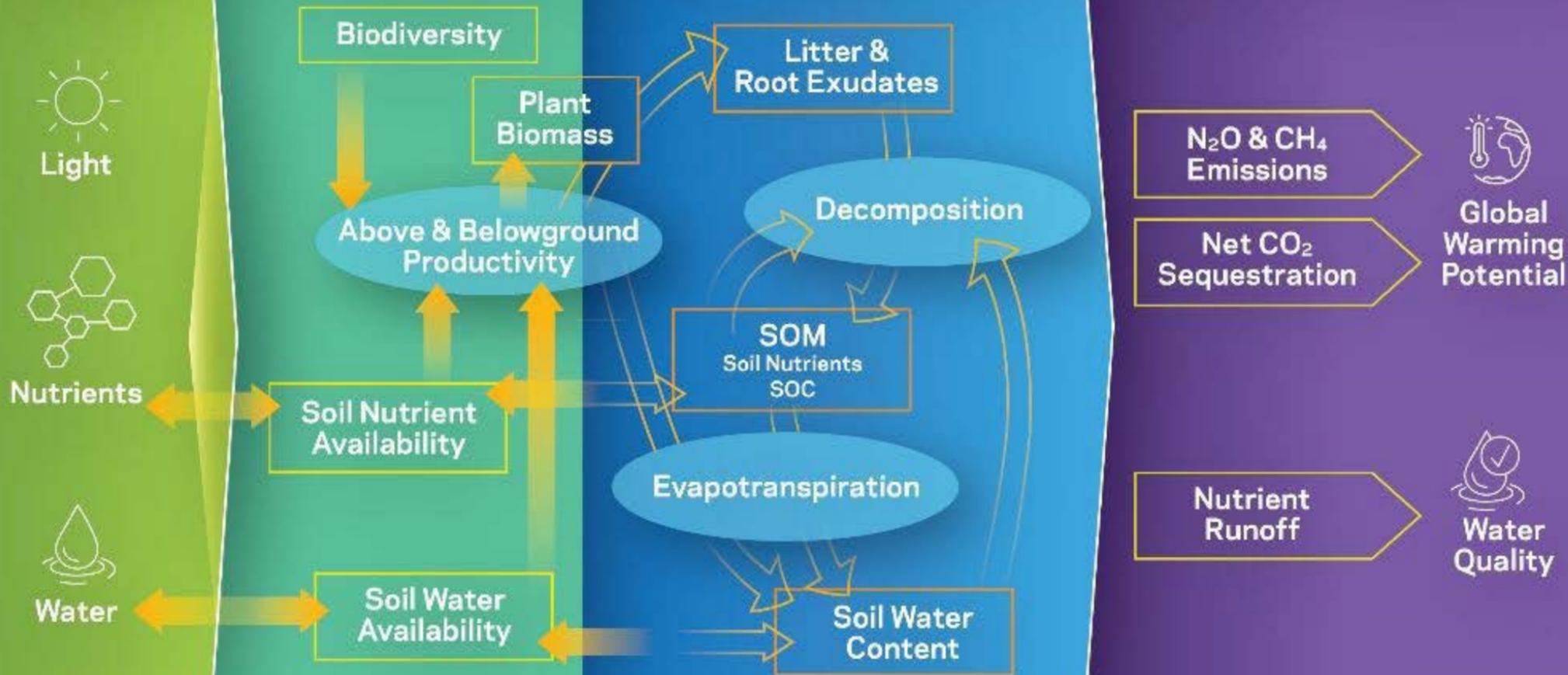
Teague R, Dowhower SL, Baker SA, et al (2011) Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. Agric Ecosyst Environ 141:310–322. https://doi.org/10.1016/j.agee.2011.03.009

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

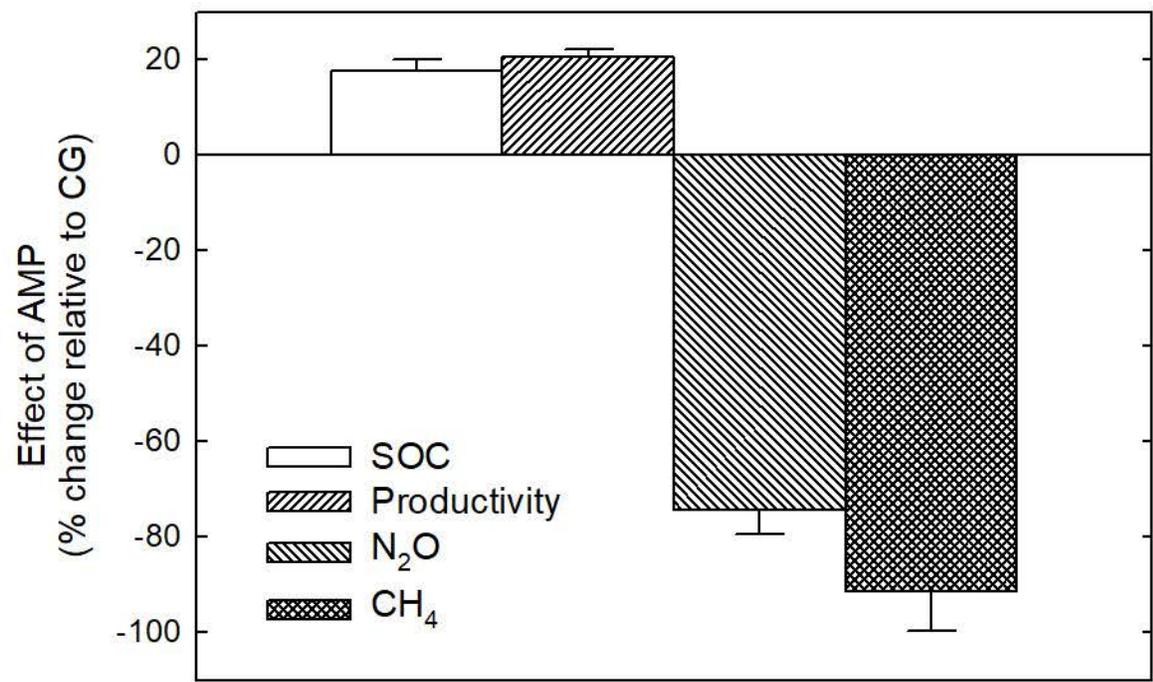Wang FL, Alva AK (1996) Leaching of Nitrogen from Slow-Release Urea Sources in Sandy Soils. Soil Sci Soc Am J 60:1454–1458. https://doi.org/10.2136/sssaj1996.03615995006000050024x
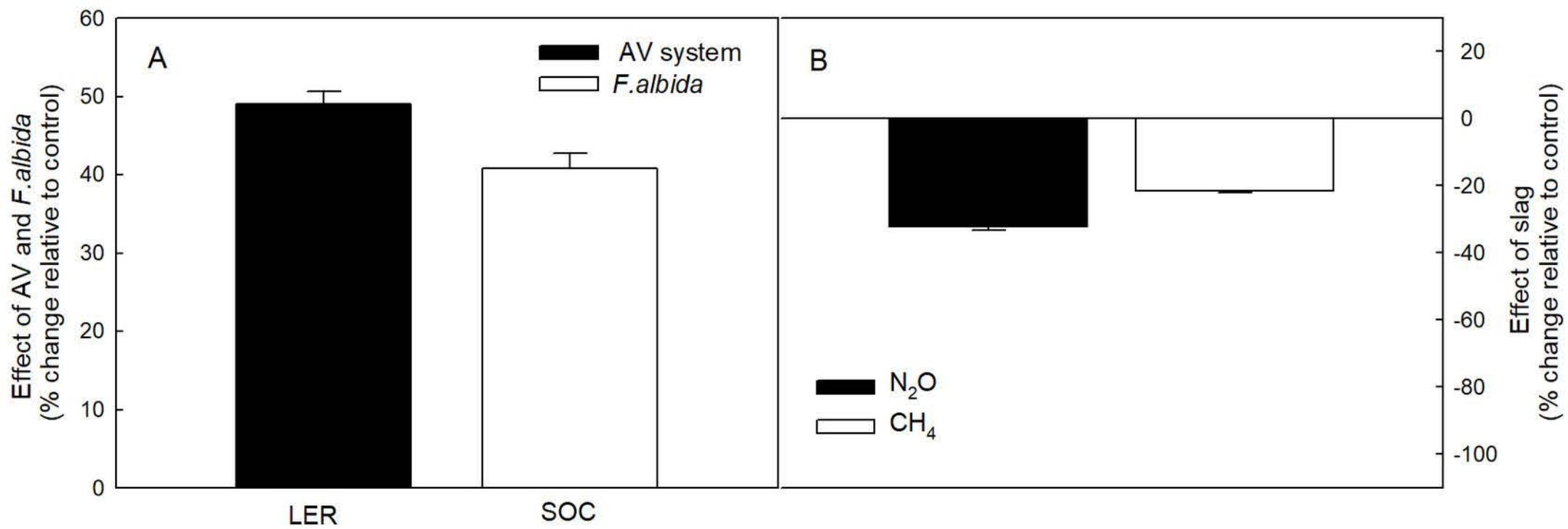
| RESOURCES | PROVISIONING SERVICES | SUPPORTING SERVICES | REGULATING SERVICES |

Light

Nutrients

Water

Biodiversity

Plant Biomass

Above & Belowground Productivity

Soil Nutrient Availability

Soil Water Availability

Litter & Root Exudates

Decomposition

SOM
Soil Nutrients
SOC

Evapotranspiration

Soil Water Content

N₂O & CH₄ Emissions

Net CO₂ Sequestration

Global Warming Potential

Nutrient Runoff

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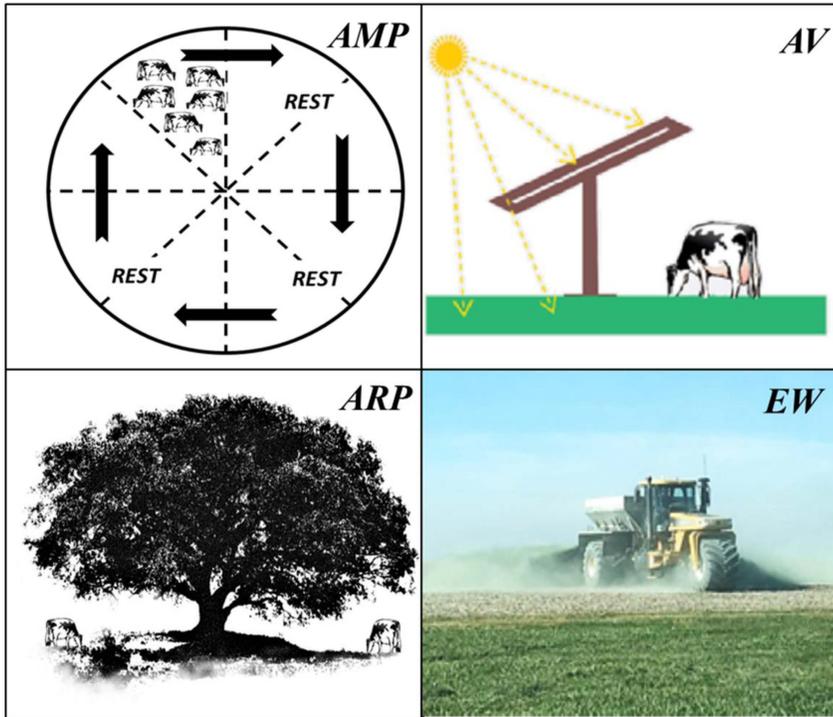
Emerging strategies to enhance environmental benefits of grasslands: Adaptive Multi-paddock grazing (AMP), Agrivoltaics (AV), Agroforestry with Reverse Phenology tree species (ARP), Enhanced Weathering (EW)

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_2 sequestration, non-CO_2 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.