

1 **Responses of drylands woody vegetation to elevated CO₂: review of**
2 **consequences and research needs.**

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24 **Abstract:**

25 Global changes such as elevated carbon dioxide [eCO₂] and warming have
26 been described as the most serious environmental threats to our planet.
27 Elevated CO₂ may have important consequences on forested ecosystems.
28 Although, the impact is worse in dryland ecosystems as atmospheric changes
29 increase aridity and change soil fertility, but it remains unknown. The study
30 aiming at understanding the effects of eCO₂ and its consequences on Hashab
31 (*Acacia senegal*) as a dryland C₃ tree species with substantial ecological and
32 economic roles. We quantitatively reviewed and discussed over 50 papers on
33 the literature about CO₂ elevation (eCO₂) effects on C₃ plant and ecosystems
34 to understand how eCO₂ will affect dryland C₃ species of sub-Saharan
35 Africa. We found in the literature that, for C₃ species generally eCO₂
36 increases photosynthesis rate and reduces stomatal conductance but with
37 increased plant leaves' area leading to release water. Water loss due to
38 stomatal conductance is unavoidable in dryland ecosystems. More seeds can
39 be produced in eCO₂ but with mostly correlated seed low quality which may
40 limit seedling recruitment. Seedlings, as the most responsive stage to eCO₂,
41 may respond by enhancing growth and biomass production or experience
42 photosynthesis down regulation and/or photorespiration. The results
43 suggested that *A. senegal*, as a C₃ and leguminous species will respond to

eCO₂ by two scenarios; 1) positively through enhancing growth and biomass or; 2) a negative photosynthetic acclimation that could be due to physiological dysfunction that resulted in metabolic compulsions. The responses need to be further investigated under different ecological conditions to feedback the global changes and ecosystem monitoring including changes of species composition is recommended.

Keywords:

Acacia senegal, climate change, drylands, elevated CO₂, Savanna, Sudan, Africa

1. Introduction:

Global climatic changes have been described as the most serious environmental threat to our planet due to massive anthropogenic activities (IPCC, 2014). Human activities are significant causing factor for increasing atmospheric pollution and concentrations of greenhouse gases (GHGs) that are considered a crucial indicator for climate change (Reynolds-Henn et al. 2010; IPCC, 2014).

Since the industrial era, CO₂, nitrous oxide and methane emissions have been raising up along with concomitant increasing in global mean temperature. Nowadays, CO₂ is at the highest levels worldwide (IEA, 2022).

The level has increased by about 40% since the industrial era to reach 390.5 ppm in 2011 and expected to rise up to 985 ppm during the upcoming 100 years (IPCC, 2013 and 2014). Despite the pandemic and its associated large scale & wide lockdown, it increased from 412 ppm in 2020 to reach 419 ppm in 2021 and additional increases (4.9%) are predicted in 2022, almost returning back to pre-pandemic level (during pandemic the decrease was 5.4%). These persistent increases are due to substantial rise in consumption of fossil fuel (Le Page, 2019).

The increase in CO₂ concentration of earth's atmosphere associated with predictions of global warming (IPCC, 2013) and water scarcity (ESCWA,

2011) have stimulated excellent reviews and growing body of knowledge about the consequences of high concentration of CO₂ on biodiversity in general and woody vegetation diversity in particular (Yeboah et al., 2016). However, impacts are worse in dryland ecosystems, particularly sub-Saharan Africa (IPCC 2014; Niang et al. 2014). For instance, recent studies have reported that impacts of climate change will have profound effect on vegetation composition and structure (e.g. Díaz et al., 2019) and ecosystem functions (e.g. USGCRP, 2018). Moreover, CO₂ concentrations on the atmosphere are likely to stimulate plant-microbes competition and increase soil fertility (Karhu et al., 2014). Globally, the above mentioned effect will increase C&N fixation rate in both above ground and below ground vegetations and by time will result in inefficient N in ecosystems (Luo et al., 2004). The enhanced vegetation accrual of N can explain the reduction in soil organic N (Gill *et al.*, 2006). According to Karhu et al. (2014), the consequences of elevated CO₂ will depend on the soil moisture and soil nutrient content, therefore the impact will be worse in dry areas of sub-Saharan and savannah regions due to severe drought and land degradation (Delgado-Baquerizo et al., 2014). Hu et al. (2016) reported that generally under elevated CO₂ interaction of woody vegetation and soil microbes are predicted to play a fundamental role in availing more nutrients,

109 although under limited nutrient conditions tree-microbes struggling for
110 nutrients will bear out the overall biomass dimensions.

111 Accounting for about 40% of the earth's area, dry lands are considered to be
112 most vulnerable spots for impacts of CO₂ concentrations accompanied with
113 global temperature increases (Stanley et al., 2000 and Cherlet et al., 2018).
114 According to White et al. (2002) about 50% of the world's countries are
115 completely or partially characterized by features of dry ecosystems. For
116 instance, in Africa as reported by Ffolliott et al. (2002), IUFRO (2004),
117 Yang et al. (2005) and Zeng and Yoon, (2009) dry ecosystems are spreading
118 out in 36 countries which is about 43% of the continental area. Even though,
119 the dry region is a habitat of near two fifth of the world's resident citizens
120 and it is inclined to enlarge because of population outgrowth and dry land
121 natural extension (Yang et al., 2005; Zeng and Yoon, 2009).

122 Hashab (*Acacia senegal*) is an important example of dryland forest tree, it is
123 a dry land's woody plant legume with substantial ecological and economic
124 roles for Africa's community livelihoods. Interconnecting Forests, Science
125 and People (IUFRO, 2004) has reported that the established intercropping *A.*
126 *senegal* resilient system that has been in Sub-Saharan Africa for handed
127 years, is to be exposed to many anthropogenic and ecological hazards.

Nevertheless, the tree is one of the most priority forest types in Sudan. It produces gum Arabic. Contributing to over 90% of global production, gum Arabic is of great socio-economic impacts. Agroforestry opportunity, animals' feed, shelter for shade, high quality charcoal, lumber and medicines are the other purposes of the tree (Fagg and Allison, 2004; Fadl and El Sheikh, 2010; Sprent et al., 2010; FAO, 2017).

Acacia senegal is a C₃ species (Sibret, 2018) hence, it may have physiological adaptations to CO₂ concentration on growth parameters, biomass accumulation and fitness. However our understanding to the mechanisms and magnitude of these effects is limited. Moreover, a better understanding of impacts of high CO₂ concentrations on the essential *A. senegal* is crucial (Sleen et al., 2015). On the other hand, many recent reports (e.g. Siddig, 2019; UNEP, 2020) have warned from ecological data-deficiency and information gap in Africa including impacts of CO₂ elevation on dryland woody vegetation. Accordingly, this study aims at exploring the impact of CO₂ raise on *A. senegal* and its consequences on dryland ecosystems' patterns by reviewing and discussing the responses of woody vegetation to CO₂ concentration. Finally, we also point out some needed research directions in this topic and recommended measurements.

2. Methodology:

This study focused on literature analysis and considering search of papers published in notable journals with focus on consequences that will face the dryland environments. In particular, a simple internet search have been begun by which keywords like drylands vegetation, acacia trees, global change, C₃ species, CO₂ increases based on searching procedure explained above plus looking at the titles, about fifty articles have been identified as relevant for further assessment. Therefore, in each article we looked at the title, abstract, keywords as well as skimming throughout the papers' results and discussions for collecting detailed evidences about the consequences that the drylands may face up to under elevated CO₂ and generally C₃ species responses and adaptation.

Specific information searched for were growth (e.g. photosynthesis, stomatal conductance, respiration, drought, soil, microbial activities, nutrition, seed production and seedling performance) and development (e.g. biomass production, dry weight) parameters.

3. Responses of woody vegetation to elevated CO₂:

Impact of increased CO₂ concentrations on plants is a long-standing research topic for plant ecologists. In particular, the responses of photosynthesis, stomatal conductance and respiration & transpiration, to elevated CO₂ as

well as their subsequent effects on plants' growth & health indicators, seed production and seedling performance are among the many research areas of recent works (Steinger et al., 2000; Katul, 2010). The literature of woody vegetation responses to elevated CO₂ have been well addressed (e.g. Yeboah, 2016). Considerable attention is growing on mechanisms and amount of carbon sequestration (Yeboah, 2016) and due to their extensive coverage, nearly one third of earth's surface and two thirds of gross biomass production, there are a growing interest in the consequences of CO₂ concentration on woody vegetation (Wisniewski and Neil, 2012; Bhargava et al., 2016) and in the following paragraphs we are discussing some of these responses.

3.1. Photosynthesis

Generally woody vegetations respond to CO₂ concentration by accelerating photosynthetic metabolic reactions and increasing allometry and biomass productivity with enhancement in litter quality and quantity and rhizodeposition as well (e.g. Knapp et al., 1996; Ainsworth and Long, 2005; Albert et al., 2011; de Graaff *et al.*, 2011). Accordingly, more detritus and root exudates with easy digested carbon are expected to be added into soil (Jones et al., 2009; Larsen et al., 2011).

189 According to Reddy et al. (2010), elevated CO₂ enhances photosynthesis
190 system and biomass production for many plant species, assuming that
191 growth limiting factors are available. It has long been known that, when C₃
192 tree species exposure to CO₂ for short term, this can intensify photosynthetic
193 process and ameliorate growth provided other resources are not seriously
194 limited (Haverd, 2019; Ainsworth and Rogers, 2007), whereas, for long time
195 the intensification usually counterbalanced by reduction in metabolic
196 synthesis (Long et al., 2004).

197 For the increase in relative growth rate and net assimilation rate that
198 accompanied with a decrease in specific leaf area that typically happens
199 under CO₂ concentration, the averages across the slow and fast-growing
200 *Acacia* species were increases of relative growth rate and net assimilation
201 rate with a decrease in foliage area per unit foliage dry mass (Poorter *et al.*,
202 1996). The greater enhancement of net assimilation rate by elevated CO₂ in
203 *Acacia* species, was offset by an equally large reduction of foliage area per
204 unit foliage mass. This can be attributed to *Acacia species* from semi-arid
205 environments which are inherently slower growing than those characteristic
206 of mesic environments (Atkin *et al.*, 1998). Slow growth in the semi-arid
207 species is not associated with lower net assimilation rate or less plant mass
208 allocated to foliage. Rather, their slow growth is associated with a smaller

foliage area per unit foliage mass compared to their faster-growing counterparts. Phyllode production reduces the relative growth rate because phyllodes have a smaller area per unit foliage mass than leaves (Atkin *et al.*, 1998). Not surprisingly, phyllode production is dominant in inherently slow-growing acacia species from semi-arid environments, with exclusive or dominant leaf production mainly occurring in faster-growing species from mesic environments (Atkin *et al.*, 1998).

3.2. Stomatal conductance:

Many studies (e.g. Gedney *et al.*, 2006 and Betts *et al.*, 2007) indicated that high CO₂ makes stomata to open less minimizing water loss resulting in greater surface running water. By this means and for instance in drylands, decreasing lost water may be prolonged growth period (Volk *et al.*, 2000). However, this effect can be counteracted by leaves' area that enlarged by CO₂ making no matter for water use efficiency (Ziska *et al.*, 1991). Nevertheless, stomata lesser opening releases the amount of CO₂ that would have absorbed by plant, into atmosphere (Shiren, 2013).

A possible beneficial effect of this increase in water use efficiency is a reduction in the rate of water consumption per unit leaf area, but the simultaneous increase in total leaf area as a result of CO₂ increase may partly offset this increase in WUE. Increase in WUE as a result of increasing

230 CO₂ concentration has been observed in a number of tropical pioneer and
231 climax tree species including *Acacia mangium* (Oberbauer *et al.*, 1985,
232 Reekie and Bazzaz, 1989; Ziska *et al.*, 1991).

233 Investigations of stomatal response to ecological changes has a dual
234 approaching models, the first one is depending on the effects of
235 environmental changes on stomatal through semi-empirical experiments and
236 photosynthetic performance (Jarvis, 1976; Leuning, 1995).

237 The other one, alternatively, depends on the plant- water requirements and
238 points out to organizing performance of stomata, consistent with these
239 approaches, when stoma opens to get carbon it concurrently releases water,
240 this evaporated water is respected as at expensive of plant water balance
241 (Makela *et al.*, 1996). This water loss due to stomatal conductance is even
242 more costly and unavoidable in dry land ecosystems.

243

244 **3.3. Respiration:**

245 Short-term elevation of CO₂ increases assimilation rate and decreases
246 transpiration rate in C₃ plants (Shiren *et al.*, 2013). Seemingly, elevated CO₂
247 has a retrogressive fitness to ecosystem transpiration, when CO₂ increases
248 transpiration rate entirely decreases (Ziska and Bunce, 1994; Gonzalez-
249 Meler, 2004). The mechanisms that reduced transpiration can be attributed

250 to increased rate of light independent reactions of carboxylation that
251 stabilize CO₂ (Gonzalez-Meler, 2004).

252 Transpiration per unit leaf area of *Acacia farnesiana* (L.) Willd. plants
253 grown at ambient CO₂ (concentration of 385 ppm) was about twice that of
254 plants grown at elevated CO₂ (980 ppm). However, when plants grown for
255 more than a year at elevated CO₂ were exposed to ambient CO₂ for 9 days,
256 they transpired at half the rate of those had been grown at ambient CO₂.
257 Similarly, plants grown at ambient CO₂, when exposed to elevated CO₂,
258 transpired at twice the rate of those grown at elevated CO₂ (Dugas *et al.*,
259 2001).

260 Concentration of CO₂ can improve plant growth and biomass production by
261 27% without changing in respiration rate, while in ambient the improvement
262 may reach 20% but associated with increases in whole plant community
263 respiration rate (Miquel *et al.*, 2004; Hamilton *et al.*, 2002).

264 More often than not, high CO₂ decreases leaves' transpiration rate and
265 increases plant leaves' area leading to release water. The water released is
266 balancing of that would be saved in low transpiration rate (Heath and
267 Kerstiens, 1997).

268 **3.4. Drought:**

World-wide and for upcoming hundred years, temperature is foreseeing to increase by 2 to 4.5°C on average, as a consequence of elevated CO₂, leading to change rainfall fluctuation pattern and increasing aridity (IPCC, 2013). The ecological changes alters biotic and abiotic factors that can change ecosystems composition and function (Beier, 2004; Santoyo, 2017). These anticipated climatic changes will have important consequences on ecosystem water availability (i.e. drought) specially in drylands of Africa (Lubica et al., 2010).

Many studies (e.g. Gessler et al., 2017; Escós et al., 2000; Blodner et al., 2005) reported that drought may decrease photo-assimilates by restricting stomatal opening, metabolic reactions and photosynthesis rate causing a substantial lack in biomass production and thus success in seedling establishment and plant competitiveness. Combined of increased aridity periods and temperature will amplify the consequences of drought by paced evaporation, minimized plant detritus and exudates, controlled soil microbes and fertility (Sowerby et al., 2008; van Meeteren et al., 2008; Selsted et al. 2012).

On the other hand, when soil moisture is not affected, increased temperature, at globe scale, will reversibly enhance soil microbes, nutrient minerals availability and soil fertility and so, enhance vegetation growth and

productivity (Jonasson et al., 2006; van Meeteren et al., 2007; Selsted et al., 2012).

3.4. Soil:

According to Keeling et al., (1995) and throughout the last ten years, there are two assumptions to describe the link between soil fertility and plant growth in the era of increasing CO₂ as the issue is of great consideration. Earliest for short-period, the increasing of soil fertility and microbes activity under carbon concentrations is continuous or whether for long-period, the fertilization enhancement will not continue because of reduction in nutrients of soil mainly N (Diaz et al., 1993).

The latest, plant soil interaction under CO₂ concentration will change soil C&N cycle that lead to either increases or decreases CO₂ emissions (Smith et al., 2000). The two assumptions are dealing with the changing in soil carbon & nitrogen and microbial activity because soil C&N cycle entirely correlates to microbial activity.

Large-scale pool of soil organic matter decomposition or synthesis reactions will result in considerable changes in the rate of CO₂ emission. Several investigations have concerned with this topic (e.g. Lichter et al., 2005 and 2008; Hoosbeek et al., 2006; Langley et al., 2009; Hoosbeek et al., 2006) as at large-scale pools, soil carbon responses to CO₂ concentration by two

309 variant approaches enhancement or detracting. Soil organic matter C&N can
310 increase or decrease under CO₂ concentrations, these two induced processes
311 are crucial and connected with pool C&N dynamics. In one hand, what let
312 researchers to suggest that CO₂ concentration will increase SOM is due to
313 raising plant exudates, detritus, soil microbial activity (Pritchard et al.,
314 2008).

315 On the other hand and according to Finzi et al. (2007) and Gill et al. (2006)
316 plant tissue gains more nutrient elements under CO₂ concentration making
317 litter is rich in N and detritus as well. However, such process is
318 demonstrating the changes in nitrogen content as it is lesser in tested soil
319 than control.

320 ***3.6. Microbial activity:***

321 Under CO₂ concentration 'priming effect' is one procedure that, probably,
322 affects soil carbon accumulation to increase this enhances soil microbial
323 activity and makes both original and newly added organic matter to soil
324 available for microbes to enlarge their mass and to improve their activity
325 (Kuzyakov et al., 2000; Fontaine et al., 2007; Patterson, 2009; Langley et al.,
326 2009). Nevertheless, the improvement of availing SOM seems to be not
327 sustainable, as some studies (e.g. Langley et al., 2009) concluded that

calculations of carbon added and depleted from soil result in reduction in carbon.

'Mine' procedure is another method under CO₂ concentration in which soil microbes have to search for more N from old organic matter, but the "mined" N usually removed by under stories growth making no enhancement in microbial biomass because of N inefficiency. Nonetheless, the new added organic matter can liberate CO₂ to atmosphere by amplified oxidation (Kuzyakov et al., 2000).

Estimation of such N increases is complicated due to need to understand why under CO₂ concentrations, plant demand more N than in the same amount of the decline one in the N cycle process (Reich et al., 2006). Nonetheless, the estimation of net N flows under CO₂ concentration in the environment at large is the key answer for the knowledge of N limitation in era of climatic changes (Sharon et al., 2010).

3.7. Nutrition

The increased demand of mineral nutrients in ecosystems often under elevated CO₂ may not be compensated because of limited mineral nitrogen supply. Nitrogen mineral supply is limited factor for potential growth of the individual plant and the community level under elevated CO₂ (Eamus & Jarvis, 1989). However, N₂-fixing species can compensate the shortages of

348 nitrogen and plant in nitrogen-limited conditions may depend on them for
349 nitrogen balances in the ecosystems (Hartwig et al., 2000; Soussana &
350 Hartwig, 1996).

351 Legumes can enhance their symbiotic nitrogen fixation under elevated
352 atmospheric CO₂. A higher biomass investment in tissues (e.g. nodules) is
353 one mechanism and the other is increasing nitrogenase activity (a greater
354 amount of N₂ fixed per unit nodule mass and time), but these mechanisms
355 can be additive, or cancel each other out. (Schortemeyer et al. 2002; Thomas
356 et al., 2000).

357 Rastetter et al. (1997) suggested that nutritional imbalances may limit effects
358 of CO₂ on plant due to changes in above-ground (C) and/or below-ground
359 required nutrients. Accordingly, decline in below-ground N constrains
360 effects of CO₂ elevation on woody vegetations (Poorter and Pérez-Soba,
361 2001). Furthermore, under CO₂ concentration soil poor in N content
362 produced N-limited leaves that resulted in reduced photosynthetic reactions
363 (Curtis et al., 2000).

364 According to Saxe et al. (1998) nitrogen limitation is often observed in high
365 CO₂ though, enhancement in woody vegetation growth could be reserved
366 merely with sustainable supply of nitrogen. Plant with ability of N₂-fixing is
367 proofed to enhance soil mineral N content in elevated CO₂, hence other

existing non-fixing species can assimilate more carbon as well. This interaction effect is considered as a 'positive effects' (Schortemeyer et al., 2002).

3.8. Seed production:

In era of high CO₂, reproductive traits such as flowering and seed production are vital features of the plant communities' future dynamics (Ibanez et al., 2006). Elevated CO₂ can alter tree population dynamics and ecosystem composition by affecting quality of seed bulks and then establishment of seedling (Caspersen and Saprunoff, 2005).

For instance, elevated CO₂ can increase seed production quantities (Jablonski et al., 2002) but are likely associated with decreasing features such as seed C/N, germination and biomass (He et al., 2005). Rather, leguminous tree can avoid reducing seed quality in high CO₂ by its N₂-fixing ability, provided that the compensated nutrients are balancing the gained carbon that being available at CO₂ elevation (He et al., 2005; Miyagi et al., 2007).

In response to elevated CO₂ seed nitrogen reduced by 14% on average for 179 studied species while, there were significant variations between legumes

390 and non-legume species; legumes were not affected while in non-legume
391 species nitrogen was reduced (Jablonski *et al.*, 2002). When more N
392 available at elevated CO₂ concentrations seed biomass will increase without
393 reduction in seed quality. But even in N-reduction system, legume species
394 can invest more carbon that being available at elevated CO₂ for increasing
395 the N₂- fixation process (Allen *et al.*, 2000 and Hikosaka *et al.*, 2011).
396 Therefore under CO₂ concentration, legumes can increase their seed mass
397 without decreasing in seed N concentration while non-legumes can increase
398 their seed mass but with reduction in seed N concentration which may result
399 in seed quality and seedling future development (Fenner, 1991; Andalo *et*
400 *al.* 1996).

401 **3.9. Seedling's performance:**

402 Many studies (e.g. Radford & Cousens, 2000; Edwards *et al.*, 2001; Nguyen
403 *et al.*, 2017) reported that successful germination and well establishment of
404 new plantations are determining ecosystem's future composition and
405 services. Elevated CO₂ can increase relative growth rate of many species as
406 earlier stage of plant is more responsive to CO₂ (during a couple of days or
407 weeks) leading to advantage plant future growth (Norby *et al.*, 1996).
408 Ainsworth & Long (2005) and Ainsworth & Rogers (2007) in FACE
409 experimental studies of seedlings reported that soil N content is determining

the photosynthesis rate, as the rate in N-limited soil is lower than that of rich N. Since the limited growth factors rather than C seems to be limited or even decline under CO₂ lead to down-regulate growth enhancement. Soil fertility will play a vital role in establishing seedlings for community new generations.

The effect of elevated CO₂ on C₃ species' seedlings is transiently stimulated the Relative Growth Rate (RGR, increase in mass per unit mass per day) and likely the effect depends on the inherent RGR of the species. Environmental conditions often determine this characteristics as unfavorable conditions have the species of low RGR (Chapin, 1980; Lambers and Poorter, 1992; Poorter, 1993; Lambers et al., 1998). In woody plant species, characteristics of RGR are often robustly associated with a lower foliage area per unit foliage dry mass and lower N concentrations (Atkin and Lambers 1998; Atkin et al. 1998).

4. Conclusions and future directions:

Despite the increase in atmospheric CO₂ concentrations at the global scale, elevation of CO₂ in temperate forests, thought to stimulate plant growth and eventually NPP. In contrary, drylands of Africa such as Savanna woodlands are reported to be most vulnerable and highly sensitive to impacts of associated climate changes at the local scale. Examples of serious impacts of

430 climatic changes in Savanna ecosystems can be on soil moisture availability
431 and soil microbial communities those of critical roles in nutrient cycling and
432 plant growth in dryland ecosystems, respectively. Consequently, these
433 changes in such important processes may directly influence fauna and flora
434 diversity and distribution as well as their associated ecosystem services
435 which eventually affect human livelihoods in these ecologically fragile
436 regions.

437 Nevertheless, impacts of climatic changes on woody vegetation are still
438 limited and many questions are yet to be answered. For instance,
439 understanding and predicting the effects of climate change on specific
440 important Savanna trees species and consequently their ecosystem services
441 is crucial and much needed research direction. Moreover, the responses and
442 adaptations of the most important C₃ tree species in dryland of Sudan like
443 *Acacias* (*e.g. A. senegal*, *A. nilotica*, *A. seyal* ...etc) to CO₂ elevation need to
444 be evaluated for short and long-term periods to draw a holistic picture of
445 their ecosystem dynamics. Nonetheless, other interacting factors with CO₂
446 such as water limitation, thermal stress, and nutrient deficiency should be
447 investigated for better understanding responses of plants to climatic changes.

448

449 On the other hand, for a proper adaptation planning for drylands vegetation
450 in the face of climatic changes there are few management interventions that
451 have to be in place. These measures may include;

452 1) Following suitable rain water harvesting practices.

453 2) Developing vegetation assessment and vulnerability mapping following
454 remote sensing technology, for example.

455 3) Given the predicted impacts on seed production, soil-plant-nutrition, and
456 seedlings' performance, some attention has to be devoted to vegetation
457 rehabilitation programs.

458 4) Adoption of a long-term ecosystem monitoring including changes of
459 species composition and diversity as well as net photosynthesis and stomatal
460 responses (i.e. Ecosystem productivity). Important values for a such
461 proposed monitoring will not only provides ability to detect changes in CO₂
462 concentrations at the ecosystem level or allow better understanding of
463 relation between CO₂ elevation and up-regulation or down-regulation of
464 photosynthesis but also show plants stomatal response to elevated CO₂ and
465 under which conditions this occurs.

466 Overall, an impact of CO₂ elevation is expected to be worse in tropical
467 dryland ecosystems and particularly in sub-Saharan Africa. Accordingly,
468 much attention should be devoted to understanding how elevated CO₂ will

affect dryland woody vegetations and subsequent ecological functions and services in sub-Saharan Africa.

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References:

Ainsworth, E. A., & Rogers, A. (2007). The response of photosynthesis and stomatal conductance to rising [CO₂]: Mechanisms and environmental interactions. *Plant, Cell & Environment*, 30, 258–270.

Ainsworth, E.A. & Long, S.P. (2005). What have we learned from 15 years of free-air CO₂ enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO₂. *New Phytology*, 165, 351–372.

Albert, K. R., Ro-Poulsen, H., Mikkelsen, T. N., Michelsen, A., van der Linden, L. & Beier C. (2011). Interactive effects of elevated CO₂, warming, and drought on photosynthesis of *Deschampsia flexuosa* in a temperate heath ecosystem. *Journal of Experimental Botany*, 62, 12, 4253–4266.

Allen, L. H. & Boote, K. J. (2000). Crop ecosystem responses to climatic change: soybean. In *Climate Change and Global Crop Productivity* (Eds K. R. Reddy & H. F. Hodges), pp. 133–160. Wallingford, UK: CAB International.

- Andalo, C., Godelle, B., Lefranc, M., Mousseau, M. & Tillbottraud, I. (1996).** Elevated CO₂ decreases seed germination in *Arabidopsis thaliana*. *Global Change Biology* 2, 129–135
- Atkin, O.K. & Lambers, H. (1998).** Slow-growing alpine and fast-growing lowland species: a case study of factors associated with variation in growth rate among herbaceous higher plants under natural and controlled conditions. In: Lambers H, Poorter H, Van Vuuren MMI (eds) *Inherent variation in plant growth: physiological mechanisms and ecological consequences*. Backhuys, Leiden, pp 259–288
- Atkin, O.K., Schortemeyer, M., McFarlane, N. & Evans, J.R. (1998).** Variation in the components of relative growth rate in ten *Acacia* species from contrasting environments. *Plant Cell Environ* 21, 1007–1017
- Beier, C. (2004).** Climate change and ecosystem function—full-scale manipulations of CO₂ and temperature. *New Phytol.*, 162, 243–251.
- Berry, J. & Bjrkman, O. (1980).** Photosynthetic response and adaptation totemperature. *Functional Ecology*, 31, 491–543.
- Betts R.A., Boucher, O. & Collins, M. (2007).** Projected increase in continental runoff due to plant responses to increasing carbon dioxide. *Nature*, 448, 1037–1041.
- Bhargava, R. N. V Rajaram, Keith Olson, and Lynn Tiede. (2016).** Ecology and Environment. Book, page 48. The Energy and Resources Institute. New Dlhi. ISBN 978-81-7993-410-4. www.teri.org. // bookstore.teri.res.in.
- Blodner, C., Skroppa T., Johnsen, O. & Polle, A. (2005).** Freezing tolerance in two Norway spruce (*Picea abies* [L] Karst.) progenies is physiologically correlated with drought tolerance. *J. Plant Physiol.*, 162, 549–558.
- Caspersen, J.P. & Saprunoff, M. (2005).** Seedling recruitment in a northern temperate forest: the relative importance of supply and establishment limitation. *Canadian Journal of Forest Research*, 35, 978–989.

Cherlet M., Hutchinson, C., Reynolds, J., Hill, J., Sommer, S. & von Maltitz, G. (2018). World Atlas of desertification: rethinking land degradation and sustainable land management. Luxembourg, Luxembourg: Publication Office of the European Union.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.L., Fichet, T., Friedlingstein, P., ... Booth, B.B. (2013). Long term climate change: Projections, commitments and irreversibility. In: Climate Change. The Physical Science Basis IPCC Working Group I Contribution to AR5 Cambridge University Press, Cambridge.

Curtis, P.S., Vogel, C.S., Wang, X.Z., Pregitzer, K.S., Zak, D.R., Lussenhop, J. ... Teeri, J.A. (2000). Gas exchange, leaf, nitrogen, and growth efficiency of *Populus tremuloides* in a CO₂- enriched atmosphere. *Ecol. Appl.*, 10, 3–17.

de Graaff, M., Schadt, C.W., Rula, K., Six, J., Schweitzer, J.A. & Classen, A.T. 2011. Elevated CO₂ and plant species diversity interact to slow root decomposition. *Soil Biol Biochem.*, 43, 2347–2354.

Delgado-Baquerizo, M., Maestre, F.T., Escolar, C., Gallardo, A., Ochoa, V. & Gozalo, B., (2014). Direct and indirect impacts of climate change on microbial and biocrust communities alter the resistance of the N cycle in a semiarid grassland. *Journal of Ecology* 102, 1592-1605.

Diaz, S., Grime, J.P., Harris, J. & McPherson, E. (1993). Evidence of a feedback mechanism limiting plant response to elevated carbon dioxide. *Nature*, 364, 616–617. doi:10.1111/gcb.12498.

Díaz, S., Settele, J., Brondízio, E., Ngo, H.T., Guèze, M., Agard ... Zayas, C., (2019). Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-policy Platform on Biodiversity and Ecosystem Services. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany.

Dugas, W.A., Polley, H.W., Mayeux, H.S. & Johnson, H.B. (2001). Acclimation of whole plant *Acacia farnesiana* transpiration to carbon dioxide concentration. *Tree Physiology*, 21, 771-773.

- Eamus, D. & Jarvis, P.G. (1989).** The direct effects of increase in the global atmospheric CO₂ concentration on natural and commercial temperate trees and forests. *Advances in Ecological Research* 19, 1-55.
- Edwards GR, Clark H & Newton PCD. (2001).** The effects of elevated CO₂ on seed production and seedling recruitment in a sheep-grazed pasture. *Oecologia* 127, 383–394.
- Escós, J., Alados, C.L., Pugnaire, F.I., Puigdefábregas, J. & Elmen, J. (2000).** Stress resistance strategy in an arid land shrub: interaction between developmental instability and fractal dimension. *Arid Environ.*, 45, 325-336.
- ESCWA, Economic & Social Commission for Western Asia, (2011).** Draft Legal Framework for Shared Groundwater Resources in the Arab Region, Second Intergovernmental Consultative Meeting. Beirut, 3 report. E/ESCWA/SDPD/2011/IC.2/3Report.
- Fadl, K.E.M., & Sheikh, S.E. (2010).** Effect of *Acacia senegal* on growth and yield of groundnut, sesame and roselle in an agroforestry system in North Kordofan state, Sudan. *Agrofor Syst*, 78, 243–252.
- Fagg, C.W. & Allison, G.E. (2004).** *Acacia senegal* and the Gum Arabic Trade: Monograph and Annotated Bibliography. Oxford Forestry Institute, Department of Plant Sciences, University of Oxford, Oxford.
- Ffolliott, P.F., Jeffrey, O.D., James, T.F., Itshack, M., Timothy, E.F., Abdullah, A.M., ... Paul, V. (2002).** Assessing capabilities of soil and water resources in drylands: The role of information retrieval and dissemination technologies IALC Conference. *Arid Lands Newsletter*, 52.
- Finzi, A.C., Norby, R.J., Calfapietra, C., Gallet-Budynek, A., Gielen, B., Holmes, W.E., ... Ceulemans, R. (2007).** Increases in nitrogen uptake rather than nitrogen-use efficiency support higher rates of temperate forest productivity under elevated CO₂. Proceedings of the *National Academy of Sciences of the United States of America*, 104, 14014 -14019.
- Fontaine, S., Barot, S., Barre, P., Bdioui, N., Mary, B. & Rumpel, C. (2007).** Stability of organic carbon in deep soil layers controlled by fresh carbon supply. *Nature*, 450, 277-280.

- Fraser, E.D.G., Dougill, A.J., Hubacek, K., Quinn, C.H., Sendzimir, J. & Termansen, M. (2011). Assessing vulnerability to climate change in dryland livelihood systems: conceptual challenges and interdisciplinary solutions. *Ecology and Society* 16,3.
- Gedney, N., Cox, P.M., Betts, R.A., Boucher, O., Huntingford, C. & Stott, P.A. (2006). Detection of a direct carbon dioxide effect in continental river runoff records. *Nature*, 439, 835-838.
- Gill, R.A., Anderson, L.J., Polley, H.W., Johnson, H.B. & Jackson, R.B. (2006). Potential nitrogen constraints of soil carbon sequestration under low and elevated atmospheric CO₂. *Ecology*, 87, 41-52.
- Gonzalez-Meler, M.A., Taneva L. & Trueman, R.J. (2004). Plant respiration and elevated atmospheric CO₂ concentration: cellular responses and global significance. *Ann Bot.* 94(5):647-656. doi:10.1093/aob/mch189.
- Hamilton, J.G., DeLucia, E.H., George, K., Naidu, S., Finzi, A.C. & Schlesinger, W. H. (2002). Forest carbon balance under CO₂. *Oecologia* 131: 250–260.
- Hartwig, U.A., Luscher, A., Daepp, M., Blum, H., Soussana, J.F. & Nosberger, J. (2000). Due to symbiotic N₂-fixation, five years of elevated atmospheric CO₂ had no effect on the N concentration of plant litter in fertile, mixed grassland. *Plant and Soil*, 224, 43 -50.
- Hartwig, U.A., Luscher, A., Daepp, M., Blum, H., Soussana, J.F. & Nosberger, J. (2000). Due to symbiotic N₂-fixation, five years of elevated atmospheric CO₂ had no effect on the N concentration of plant litter in fertile, mixed grassland. *Plant and Soil*, 224, 43-50.
- Haverd, V., Smith, B., Canadell, J. G., Cuntz, M., Mikaloff-Fletcher, S., Farquhar, G., ... Trudinger, C. M. (2020). Higher than expected CO₂ fertilization inferred from leaf to global observations. *Glob Change Biol.* 2020;00:1–13. <https://doi.org/10.1111/gcb.14950>
- He, J.S., Flynn, D.F.B., Wolfe-Bellin, K., Fang, J. & Bazzaz, F.A. (2005). CO₂ and nitrogen, but not population density, alter the size and C/N ratio of *Phytolacca americana* seeds. *Functional Ecology*, 19, 437–444.

- Heath, J. & Kerstiens, G. (1997).** Effects of elevated CO₂ on leaf gas exchange in beech and oak at two levels of nutrient supply: consequences for sensitivity to drought in beech. *Plant, Cell and Environment*, 20, 57-67.
- Hikosaka, K., Kinugasa, T., Oikawa, S., Onoda, Y. & Hirose, T. (2011).** Effects of elevated CO₂ concentration on seed production in C₃ annual plants. *Journal of Experimental Botany* 62, 1523–1530.
- Hofmockel, K.S. & Schlesinger, W.H. (2007).** Carbon dioxide effects on heterotrophic dinitrogen fixation in a temperate pine forest. *Soil Science Society of America*, 71, 140 -144.
- Hoosbeek, M.R., Yongtao, L. & Scarascia-Mugnozza, G.E. (2006).** Free atmospheric CO₂ enrichment (FACE) increased labile and total carbon in the mineral soil of a short rotation poplar plantation. *Plant and Soil*, 281, 247-254.<https://doi.org/10.5424/sjar/2017151-9990>.
- Hu, H.W., Macdonald, C.A., Trivedi, P., Anderson, I. C., Zheng, Y. , Holmes, B., ... Brajesh, K.S. (2016).** Effects of climate warming and elevated CO₂ on autotrophic nitrification. and nitrifiers in dryland ecosystems. *Soil Biology & Biochemistry* 92, 1-15.
- Hungate, B.A., Johnson, D.W., Dijkstra, P., Hymus, G., Stiling, P., Magonigal, P., ... Bert G. D. (2006).** Nitrogen cycling during seven years of atmospheric CO₂ enrichment in a scrub oak woodland. *Ecology*, 87, 26 -40.
- Ibanez, I., Clark, J.S., Dietze, M.C., Feeley, K., Hersh, M., LaDeau, S., ... Wolosin, M.S. (2006).** Predicting biodiversity change: outside the climate envelope, beyond the species-area curve. *Ecology*, 8, 1896–1906.
- IEA (International Energy Agency, 2022).** Global Energy Review: CO₂ emissions in 2021.
- IPCC, (2014).** Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

- IPCC. (2013).** Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, USA.
- IUFRO. (2004).** Trees, Agroforestry and Global Change in Dryland Africa (TACCDA) Brinkman, W., Whyte, E. and Maas, J., eds. Proceedings from VITRI/ ETRN/ IUFRO workshop, 31 July-4 August 2003, Hyytiälä, Finland. www.etfrn.org.
- Jablonski, L.M., Wang, X.Z. and Curtis, P.S. (2002).** Plant reproduction under elevated CO₂ conditions: a meta-analysis of reports on 79 crop and wild species. *New Phytologist*, 156, 9-26.
- Jarvis, P.G. (1976).** The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. *Philosophical Transactions of the Royal Society of London. Series B. Biological Sciences*, 273, 593–610.
- Jonasson, S., Castro, J. & Michelsen, A. (2006).** Interactions between plants, litter and microbes in cycling of nitrogen and phosphorus in the arctic. *Soil Biol Biochem.*, 38, 526–532.
- Karhu, K., Auffret, M.D., Dungait, J.A.J., Hopkins, D.W., Prosser, J.I. & Singh, B.K. (2014).** Temperature sensitivity of soil respiration rates enhanced by microbial community response. *Nature* 513, 81e84.
- Katul, Gabriel, Stefano Manzoni, Sari Palmroth & Ram Oren. (2010).** A stomatal optimization theory to describe the effects of atmospheric CO₂ on leaf photosynthesis and transpiration. *Annals of Botany* 105: 431 –442, 2010. doi:10.1093/aob/mcp292, www.aob.oxfordjournals.org.
- Keeling, C.D., Whorf, T.P., Wahlen, M. & Vanderplicht, J. (1995).** Inter annual extremes in the rate of rise of atmospheric carbon dioxide since 1980. *Nature*, 375, 666-670.
- Knapp, A. & Smith, M.D. (2001).** Variation among biomes in temporal dynamics of aboveground primary production. *Science*, 291, 481-484. Doi:10.1126/science.291.5503.481.

- 738 **Kuzyakov, Y., Friedel, J.K. & Stahr, K. (2000).** Review of mechanisms
739 and quantification of priming effects. *Soil Biology and Biochemistry*, 32,
740 1485 -1498.
- 741 **Lambers, H., Poorter, H. & Van Vuuren, M.M.I. (eds) (1998).** Inherent
742 variation in plant growth: physiological mechanisms and ecological
743 consequences. Backhuys, Leiden
- 744 **Langley, J.A., McKinley, D.C., Wolf, A.A., Hungate, B.A., Drake, B.G.**
745 **& Megonigal, J.P. (2009).** Priming depletes soil carbon and releases
746 nitrogen in a scrub-oak ecosystem exposed to elevated CO₂. *Soil Biology*
747 *and Biochemistry*, 41, 54 -60.
- 748
749 **Le Page, M. (2019).** Carbon dioxide levels will soar past the 410 ppm
750 milestone in 2019. *Environment, The Daily Newsletter*.
- 751 **Leuning, R. (1995).** A critical-appraisal of a combined stomatal
752 photosynthesis model for C₃ plants. *Plant, Cell and Environment*, 18, 339–
753 355.
- 754 **Lichter, J., Barron, S.H., Bevacqua, C.E., Finzi, A.C., Irving, K.F.,**
755 **Stemmler, E.A. & Schlesinger, W.H. (2005).** Soil carbon sequestration and
756 turnover in a pine forest after six years of atmospheric CO₂ enrichment.
757 *Ecology*, 86, 1835-1847.
- 758 **Lichter, J., Billings, S.A., Ziegler, S.E., Gaindh, D., Ryals, R., Finzi,**
759 **A.C., Schlesinger, W.H (2008).** Soil carbon sequestration in a pine forest
760 after nine years of atmospheric CO₂ enrichment. *Global Change Biology*, 14,
761 2910-2922.
- 762 **Long, S.P., Ainsworth, E.A., Rogers, A. & Ort, D.R. (2004).** Rising
763 atmospheric carbon dioxide: plants FACE the future. *Annual Review Plant*
764 *Biology*, 55, 591–628.
- 765 **Lubica, D., Daniel, K., Sari, P., Jaroslav, K. & Katarina, S. (2010).**
766 Physiological responses of Norway spruce (*Picea abies*) seedlings to
767 drought stress. *Tree Physiology*, 30, 205–213.
- 768
769 **Luo, Y., Su, B., Currie, W.S., Dukes, J.S., Finzi, A. & Hartwig, U.**
770 **(2004).** Progressive nitrogen limitation of ecosystem responses to rising
771 atmospheric carbon dioxide. *Bioscience* 54, 731-739.

- Lüscher, A., Hartwig, U.A., Suter, D. & Nosberger, J. (2000).** Direct evidence that symbiotic N₂-fixation in fertile grassland is an important trait for a strong response of plants to elevated atmospheric CO₂. *Global Change Biology*, 6, 655-662.
- Miquel, A.G., Taneva, L. & Rebecca, J.T. (2004).** Plant Respiration and Elevated Atmospheric CO₂ Concentration: Cellular Responses and Global Significance. *Annals of Botany*, 94, 647–656. Doi:10.1093/aob/mch189, available online at www.aob.oupjournals.org
- Miyagi, K.M., Kinugasa, T., Hikosaka, K. & Hirose, T. (2007).** Elevated CO₂ concentration, nitrogen use, and seed production in annual plants. *Global Change Biology*, 13, 2161–2170.
- Morgan, J.A., LeCain, D.R. & Pendall, E. (2011).** C₄ grasses prosper as carbon dioxide eliminates desiccation in warmed semi-arid grassland. *Nature*, 476, 202–205. Doi:10.1038/nature10274.
- Munson, S.M., Belnap, J. & Schelz, C.D. (2011).** On the brink of change: Plant responses to climate on the Colorado Plateau. *Ecosphere*, 2, 6, art68. Doi:10.1890/ES11-00059.1.
- Nguyen C., Thinh, E., Kumagai, H. S. & Michio K. (2017).** Effects of elevated CO₂ concentration on bulbil germination and early seedling growth in Chinese yam under different air temperatures. *Plant Production Science*, 20:3, 313-322, DOI: 10.1080/1343943X.2017.1346477.
- Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J. & Urquhart, P. (2014).** Africa. In: Climate change 2014: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.
- Norby, R.J., Wullschleger, S.D. & Gunderson, C.A. (1996).** Tree responses to elevated CO₂ and implications for forests. In: Koch, G.W., Mooney, H.A., eds. Carbon Dioxide and Terrestrial Ecosystems. San Diego, CA, USA, Academic Press, 1-21.
- Oberbauer, S.T., Strain, B.R. & Fetcher, N. (1985).** Effect of CO₂ enrichment on seedling physiology and growth of two tropical tree species. *Physiologia Plantarum*, 65, 352-356.

- Patterson, E., (2009).** Comments on the regulatory gate hypothesis and implications for C-cycling in soil. *Soil Biology and Biochemistry*, 41, 1352-1354.
- Poorter, H. & Pérez-Soba, M. (2001).** The growth response of plants to elevated CO₂ under non-optimal environmental conditions. *Oecologia*, 129, 1–20.
- Poorter, H., Roumet, C. & Campbell, B.D. (1996).** Interspecific variation in the growth response of plants to elevated CO₂: a search for functional types. In: Körner C, Bazzaz FA (eds) carbon dioxide, populations, and communities. Academic Press, San Diego, pp 375-412.
- Pritchard, S.G., Strand, A.E., McCormack, M.L., Davis, M.A. & Oren, R. (2008).** Mycorrhizal and rhizomorph dynamics in a loblolly pine forest during five years of Free-Air CO₂-enrichment (FACE). *Glob Change Biol.*, 14, 1252–1264.
- Radford IJ & Cousens RD. 2000.** Invasiveness and comparative life-history traits of exotic and indigenous *Senecio* species in Australia. *Oecologia* 125: 531–542.
- Rastetter, E.B., Agren, G.I. & Shaver, G.R. (1997).** Responses of N-limited ecosystems to increased CO₂: a balanced-nutrition coupled element-cycles model. *Ecological Applications*, 7, 444-460.
- Reddy A. R., Girish K. R. & Agepati S. R. (2010).** The impact of global elevated CO₂ concentration on photosynthesis and plant productivity. *Current Science*, 99, 46-57.
- Reekie, E.G. & Bazzaz, F.A. (1989).** Competition and patterns of resource use among seedlings of five trees grown at ambient and elevated CO₂. *Oecologia*, 79, 212-222.
- Reich, P.B., Hungate, B.A. & Luo, Y. (2006).** Carbon-nitrogen interactions in terrestrial ecosystems in response to rising atmospheric carbon dioxide. *Annual Review of Ecology and Systematic*, 37, 611- 636.

- Sage, R.F., Sage, T.L. & Kocacinar, F. (2012).** Photorespiration and the evolution of C₄ photosynthesis. *Annu Rev Plant Biol*, 63, 19–47. doi:10.1146/annurev-arplant-042811-105511.
- Santoyo, G., Hernández-Pacheco, C., Hernández-Salmerón, J. & Hernández-León, R. (2017).** The role of abiotic factors modulating the plant-microbe-soil interactions: toward sustainable agriculture. A review. *Spanish Journal of Agricultural Research*, 15, 1, e03R01.
- Saxe, H., Ellsworth, D.S. & Heath, J. (1998).** Tree and forest functioning in an enriched CO₂ atmosphere. *New Phytol.*, 139, 395–436.
- Schortemeyer, M., Atkin, O.K., McFarlane, N. & Evans, J.R. (2002).** N₂ fixation by *Acacia* species increases under elevated atmospheric CO₂. *Plant Cell Environ.*, 25, 567–579.
- Selsted, M.B., van., der Linden, L., Ibrom, A., Michelsen, A., Larsen, K.S., Pedersen, J.K., ... Ambus, P. (2012).** Soil respiration is stimulated by elevated CO₂ and reduced by summer drought: three years of measurements in a multifactor ecosystem manipulation experiment in a temperate heathland (CLIMAITÉ). *Glob Chang Biol.*, 18, 1216–1230.
- Sharon, A.B., Lichter, J., Ziegler, S.E., Hungate, B.A. & Richter D.B. (2010).** A call to investigate drivers of soil organic matter retention vs. mineralization in a high CO₂ world. *Soil Biology and Biochemistry*, 42, 665 - 668.
- Shiren, M., Anita, J., & Michael, F. (2013).** Positive effects of elevated CO₂ and its interaction with nitrogen on safflower physiology and growth. *Agronomy for Sustainable Development*. Springer Verlag/EDP Sciences/INRA, 33, 3, 497-505. 10.1007/s13593-013-0137-x.hal-01201388
- Sibret, T. (2018).** The Sahelian Drylands Under Pressure: Studying The Impact of Environmental Factors on Vegetation in Dahra, Senegal. Ghent University, M.Sc. dissertation. Schimel, D.S., 2010. Drylands in the earth system. *Science* 327, 418-419.
- Siddig, A. A. H. (2019).** Why is biodiversity data-deficiency an ongoing dilemma in Africa? *Journal for Nature Conservation*. Volume 50: 125719. doi.org/10.1016/j.jnc.2019.125719.

Smith, P., Powlson, D.S., Smith, J.U., Falloon, P. & Coleman, K. (2000). Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture. *Global Change Biology*, 6, 525–539.

Soussana, J.F. & Hartwig, U.A. (1996). The effects of elevated CO₂ on symbiotic N₂ fixation: a link between the carbon and nitrogen cycles in grassland ecosystems. *Plant Soil*, 187, 321–332.

Sowerby, A., Emmett, B.A., Tietma, A. & Beier, C. (2008). Contrasting effects of repeated summer drought on soil carbon efflux in hydric and mesic heathland soils. *Glob Chang Biol*, 14, 2388-2404.

Sprent, J.I., Odee, D.W. & Dakora, F.D. (2010). African legumes: a vital but under-utilized resource. *J Exp Bot*, 61, 1257-1265/.

Stanley, D.S., Travis, E.H., Stephen, F.Z., Therese, N.C., David, C.H., James S.C. ... Robert, S.N. (2000). Elevated CO₂ increases productivity and invasive species success in an arid ecosystem. *Nature*, 408, 79-82. www.nature.com

Steinger, T., Gall, R. & Schmid, B. (2000). Maternal and direct effects of elevated CO₂ on seed provisioning, germination and seedling growth in *Bromus erectus*. *Oecologia*, 123, 4, 475-480.

Thomas, R.B., Bashkin, M.A. & Richter, D.D. (2000). Nitrogen inhibition of nodulation and N₂ fixation of a tropical N₂-fixing tree (*Gliricidia sepium*) grown in elevated atmospheric CO₂. *New Phytol.*, 145, 233-243.

UNEP. (2020). United Nations Environment Programme 2020. Emissions Gap Report - Executive summary. Nairobi.

Upreti, D.C., Garg, S.C., Bisht, B.S., Maini, H.K., Dwivedi, N., Paswan G., ... Saxena, D.C. (2006). Carbon dioxide enrichment technologies for crop response studies. *Scientific and industrial research.*, 65, 859-866.

USGCRP, (2018). (U.S. Global Change Research Program) Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment. II. U.S. Global Change Research Program, Washington, D.C., USA.

- 941 **van der Sleen P, Groenendijk P, Vlam M, Anten, N., Boom, A.,**
 942 **Bongers, F., ... Zuidema, P (2015).** No growth stimulation of tropical trees
 943 by 150 years of CO₂ fertilization but water-use efficiency increased. *Nature*
 944 *Geoscience* 8: 24-28.
- 945
 946 **van Meeteren, M.M., Tietema, A., van Loon, E.E. & Verstraten, J.M.**
 947 **(2008).** Microbial dynamics & litter decomposition under a changed climate
 948 in a Dutch heathland. *Appl Soil Ecol.*, 38, 119–127.
- 949
 950
 951 **Volk, M., Niklaus, P.A. & Korner, C. (2000).** Soil moisture effects
 952 determine CO₂ responses of grassland species. *Oecologia.*, 125, 380–388.
- 953
 954 **Way, D.A. & Oren, R. (2010).** Differential responses to changes in growth
 955 temperature between trees from different functional groups and biomes: a
 956 review and synthesis of data. *Tree Physiol.*, 30, 669–688. doi:10.1093/ tree
 957 phys/ tpq015.
- 958
 959 **Wertin, T.M., Mcguire, M.A. & Teskey, R.O. (2010).** The influence of
 960 elevated temperature, elevated atmospheric CO₂ concentration and water
 961 stress on net photosynthesis of loblolly pine (*Pinus taeda* L.) at northern,
 962 central and southern sites in its native range. *Glob Chang Biol*, 16, 2089-
 963 2103.
- 964
 965 **White, R.P., Tunstall, D. & Henninger, N. (2002).** An ecosystem approach
 966 to drylands: Building support for new development policies. Information
 967 Policy Brief 1. Washington, DC: World Resources Institute.
- 968
 969 **Wisniewski, J. & Neil, S.R. (2012).** Terrestrial Biospheric Carbon Fluxes
 970 Quantification of Sinks and Sources of CO₂. *Water, Air and Soil pollution*,
 971 70, 1-4, 1993.
- 972
 973 **Wu, Z., Dijkstra, P., Koch, G.W. & Hungate, B.A. (2012).**
 974 Biogeochemical and ecological feedbacks in grassland responses to
 975 warming. *Nature Climate Change*, 2, 458–461. doi:10.1038/nclimate1486.
- 976
 977 **Yang, X., Zhang, K., Jia, B. & Ci, L. (2005).** Desertification assessment in
 978 China. *Journal of Arid Environments*, 63, 2, 517-531.
- 979

- Yeboah, S., Zhang, R., Cai, L., Song, M., Li, L., Xie, J., Luo, Z., Wu, J. & Zhang, J. (2016).** Greenhouse gas emissions in a spring wheat–field pea sequence under different tillage practices in semi-arid Northwest China. *Agroecosystem*, 106, 77–91. DOI 10.1007/s10705-016-9790-1
- Zak, D.R., Holmes, W.E., Finzi, A.C., Norby, R.J. & Schlesinger, W.H. (2003).** Soil nitrogen cycling under elevated CO₂; a synthesis of forest FACE experiments. *Ecological Applications*, 13, 1508-1514.
- Zavaleta, E., Shaw, M.R. and Chiariello, N.R. (2003).** Grassland responses to 3 years of elevated temperature, CO₂, precipitation and N deposition. *Ecol Monogr.*, 73, 585–604.
- Zeng, N. & Yoon, J. (2009).** Expansion of the world’s deserts due to vegetation- albedo feedback under global warming. *Geophys Res Lett.*, 36, 17401. Doi:10.1029/2009GL039699.
- Ziska, L.H. & Bunce, J.A. (1994).** Direct and indirect inhibition of single leaf respiration by elevated CO₂ concentrations: interactions with temperature. *Physiol. Plant*, 90, 130-138.
- Ziska, L.H., Hogan, K.P., Smith, A.P. & Drake, B.G. (1991).** Growth and photosynthetic response on nine tropical species with long-term exposure to elevated carbon dioxide. *Oecologia*, 86, 383-389.