

**A vital link: water
and vegetation in the
Anthropocene**

D. Gerten

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A vital link: water and vegetation in the Anthropocene

D. Gerten

Potsdam Institute for Climate Impact Research, Research Domain 1: Earth System Analysis,
14473 Potsdam, Germany

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Correspondence to: D. Gerten (gerten@pik-potsdam.de)

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Abstract

This paper argues that the interplay of water, carbon and vegetation dynamics is fundamental to some global trends in the current and conceivable future Anthropocene. Supported by simulations with a process-based biosphere model and a literature review, it demonstrates that the connectivity of freshwater and vegetation dynamics is vital for water security, food security and (terrestrial) ecosystem integrity alike. The water limitation of net primary production of both natural and agricultural plants – already pronounced in many regions – is shown to increase in many places under projected climate change, though this development is partially offset by water-saving direct CO₂ effects. Natural vegetation can to some degree adapt dynamically to higher water limitation, but agricultural crops require some form of active management to overcome it – among them irrigation, soil conservation and expansion into still uncultivated areas. While crucial to secure food production for a growing world population, such human interventions in water–vegetation systems have, as also shown, repercussions to the water cycle. Indeed, land use changes have been shown to be the second-most important influence on the terrestrial water balance in recent times. Furthermore, climate change regionally increases irrigation demand and decreases freshwater availability, impeding on rainfed and irrigated food production (if not CO₂ effects counterbalance this impact – which is unlikely at least in poorly managed systems). Drawing from these exemplary investigations, some research perspectives on how to further improve our quantitative knowledge of human-water-vegetation interactions in the Anthropocene are outlined.

1 Introduction

Plants need water to grow and survive – Ripl (2003) has for a reason characterised water as “the bloodstream of the biosphere”. In turn, vegetation growth and productivity are closely coupled with the water cycle via the carbon cycle, with feedbacks traceable

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at global scale (Hutjes et al., 1998; Peel et al., 2010; Ito and Inatomi, 2012). Hence, one may pose the question how important vegetation-water interactions actually are in the Anthropocene, i.e. the present era characterised by pervasive anthropogenic transformations of the Earth's climate, land surface and ecosystems (Crutzen, 2003; Steffen et al., 2011). Among the many, exponential upward trends that characterise the Anthropocene particularly since the 1950s are global warming (with impacts on vegetation dynamics and water cycles); the rapid increase in the land area taken into cultivation (Ellis et al., 2011); and the pronounced increase in withdrawal and consumption of freshwater (Vörösmarty et al., 2005), likely to further increase in the future and produce water stress in many regions (Arnell et al., 2011).

According to the vegetation-water coupling at process level, the trends in water and land use are interrelated. For example, expansion of cropland for the purpose of food production has often been accompanied by a promotion of water withdrawals for crop irrigation, especially in the course of the Green Revolution. Not only does irrigation improve plant growth and productivity, but also is water availability influenced by changes in evapotranspiration resulting from irrigation, and from land use change in general (deFries and Eshleman, 2004; Gordon et al., 2005; Scanlon et al., 2007). Adding to this, the spatio-temporal dynamics of the terrestrial water cycle is intermingled with anthropogenic climate change (Bates et al., 2008). Besides the radiative effects of increasing atmospheric CO₂ concentration, structural and physiological responses of (natural or agricultural) plants are likely to co-occur (as shown in numerous laboratory and field studies; e.g. Amthor, 1995; De Boer et al., 2011), with influences on water fluxes of potential significance at global scale (Gedney et al., 2006; Leipprand and Gerten, 2006). Hence, water-vegetation relationships underlying these complex feedbacks are crucial for major environmental and societal issues such as climate change impacts, ecosystem integrity, water security, and food security.

To avert potentially adverse developments, humankind can still opt for sustainable pathways that could, e.g. minimise the magnitude of global warming, of water scarcity and of related impacts. These “planetary opportunities” (deFries et al., 2012) include

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transitions to less water-intensive ways of production and consumption. Again, basic water-vegetation relationships are at the heart of many of those pathways – among them methods to increase plant water productivity, i.e. to boost crop production per unit of water either withdrawn from rivers, reservoirs or groundwater (“blue water” used in irrigated agriculture) or evapotranspiring directly or through plants from the soil (“green water” on which rainfed agriculture depends; Falkenmark and Rockström, 2004). Crop water productivity and its regional pattern also underlies the quite sizeable global water savings associated with “virtual water trade” – the blue and green water consumed in export countries (often characterised by water productivities higher than in import countries) and implicitly traded with agricultural and industrial commodities (Oki and Kanae, 2004).

The objective of this paper is to reveal, and provide quantifications of, some core processes that link terrestrial vegetation and freshwater dynamics and that appear to be relevant for the potential future evolution of the Earth’s bio- and hydrosphere. A focus is on the following topics. (1) The current and potential future water limitation of terrestrial vegetation (natural and agricultural, rainfed and irrigated), as controlled by global climate and its anticipated future changes; (2) the potential of water management options to increase crop production by reducing this water limitation to some extent; and (3) the effect of human land cover/land use changes and water withdrawals on freshwater flows and resources. For each of these topics, some needs for future research (modelling studies in particular) are identified. I address the topics primarily from a global perspective, partly drawing from simulations with the LPJ and LPJmL Dynamic Global Vegetation Model (DGVM) published in earlier studies but revised, synthesised and expanded upon here. LPJmL is a process-based numerical simulation model that couples vegetation, carbon and water dynamics for both the natural biosphere and human land use systems consistently in a single framework. It has been validated in terms of its hydrological, vegetation dynamical and biogeochemical features (e.g. Sitch et al., 2003; Gerten et al., 2004; Bondeau et al., 2007; Rost et al., 2008a; Biemans et al., 2009; Fader et al., 2010).

2 Water limitation of natural vegetation

While it is generally known that plant growth and productivity depend on the availability and accessibility of freshwater, the detailed physiological and ecohydrological mechanisms of plant water limitation are very complex (Rodríguez-Iturbe and Porporato, 2007). Globally, as assessed by Nemani et al. (2003), soil moisture is a main factor limiting terrestrial photosynthesis and net primary production (NPP). However, the severity and regional pattern of NPP water limitation depends on the co-limitation by temperature or radiation. Furthermore, it is controlled not solely by soil moisture but by the balance between soil moisture and atmospheric moisture deficit (determined by temperature, radiation and wind speed, and in turn determining potential transpiration). To capture these co-limitations, NPP water limitation can be defined as the ratio of actual (limited by soil moisture and plant hydraulic features) and potential canopy conductance (controlled by atmospheric conditions and photosynthesis rate, unlimited by soil moisture) of water and CO₂ in the process of photosynthesis, as in Gerten et al. (2005, 2007).

Figure 1 illustrates that soil moisture and NPP water limitation are more or less decoupled in many regions. For example, NPP at high latitudes is hardly water-limited despite relatively low soil moisture, as in these regions temperature and/or radiation limit NPP stronger than does water. Correspondingly, climate change would affect the two variables differently. Increases (or declines) in soil moisture in response to projected future climate change do not necessarily mean that the productivity of concurrently existing vegetation becomes less (or more) water-limited. At high latitudes, for instance, the modelled increase in soil moisture hardly affects the water limitation of plants. The net physiological and structural CO₂ effect is found to modify, or even cancel out, effects of temperature and precipitation on plant water limitation. Furthermore, the altered hydroclimatic conditions induce shifts in the geographical distribution, composition and phenology of plants. For instance, in regions with decreasing soil moisture, vegetation will successively adapt to the drier conditions and on average display a weaker

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NPP water limitation than would the replaced vegetation (died back due to this very aggravation of water stress).

Gerten et al. (2005) thus hypothesised a resilient behaviour of the terrestrial biosphere – “resilient” defined as the capacity of vegetation to dynamically adapt to climatic and hydrologic change. Findings from plot-scale simulations and manipulation experiments combining different environmental change factors tend to support this conclusion. They show that manipulation of single factors (such as temperature, rainfall, CO₂ concentration, nutrient supply) often provoke rather strong responses in key ecosystem features such as NPP, whilst multi-factor experiments can yield weaker responses as a net result of complex, nonlinear process interactions (Zhou et al., 2006; Luo et al., 2008).

Notwithstanding these possible equilibrating processes, satellite data show potentially strong and large-scale declines in NPP in response to lower soil moisture and increasing water limitation. Zhao and Running (2010) demonstrate that recent droughts and southern hemispheric drying trends have slowed down an increase in global terrestrial NPP that otherwise would be expected in response to temperature and CO₂ rise, which happens to disagree with the hypothesised resilient behaviour. This is probably due to the fact that current atmospheric CO₂ concentration is still below a level that would buffer impacts of heatwaves or droughts. Moreover, adaptive ecosystem changes may occur only at longer time scales. Indeed, while there is (local) evidence for tree mortality and alterations to ecosystem structure in response to droughts (Anderegg et al., 2013) – sometimes even with multi-annual time lags due to complex processes related to vegetation architecture (Saatchi et al., 2013) – biomes seem to differ significantly with respect to their capacity and time scale to adapt to drought (Vicente-Serrano et al., 2012). Overall, spatially and temporally more detailed analyses of the interrelations of soil moisture, plant water stress, NPP and associated ecosystem changes in a changing global climate – including feedbacks between land cover/land use changes and the atmosphere (Betts et al., 2007; Port et al., 2012) examinable

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with coupled vegetation-climate models (Strengers et al., 2010) – are a desideratum for future research.

3 Water limitation of agricultural crops – and ways to overcome it

Agricultural vegetation is governed by the same physiological and ecohydrological mechanisms than natural vegetation, thus it is similarly prone to hydroclimatic changes. There is an important difference, though. On the one hand, farmers can and do, by purpose, influence the distribution, structure, seasonality, water productivity and water limitation of crops through various forms of management, in order to maximise their production. On the other hand, cultivated crops can adapt less dynamically to climatic changes than natural vegetation, i.e. it is unlikely that their composition and distribution adapts to climatic and hydrologic changes without direct human intervention (altered crop varieties, cropping patterns, irrigation, etc.).

The global modelling study by Rost et al. (2009) quantifies the water limitation of agricultural crops, the extent to which this limitation is presently overcome by irrigation, and by how much it could be diminished further through specific on-farm management practices (see Fig. 2). These practices account for avoidance of soil evaporation and for “harvesting” of water and its use during dry-spells. Present irrigation evidently minimises crop water limitation in a number of countries, while crop yields could be boosted even further if the considered management options were actually implemented (Fig. 2b, c). The LPJmL simulations suggest that avoidance of 25 % of soil evaporation and harvesting and later use of 25 % of (sub)surface runoff on the world’s cropland would increase global crop production by nearly a fifth (Rost et al., 2009). In some regions, gains of similar magnitude could be achieved through expansion of irrigation areas and/or increased irrigation efficiency.

However, these yield increases would probably be too small to meet the requirements for a prospective world population of 9 or 10 billion people. Along these lines, Gerten et al. (2011) and Fader et al. (2013) find that many countries will not be able

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to produce with their domestic arable land and water resources the food required for a balanced diet under conditions of climate and demographic change. This will be the case even if the green water resource (soil water on cropland) is accounted for – a resource that adds substantially to the blue water usable for crop irrigation (Rost et al., 2008; Rockström et al., 2009a). Note that these studies considered spatial and temporal differences in crop water productivity as controlled by climate and crop management, which determine how much calories can be produced in the different regions with the available water resources. The productivity patterns also underlie the quantities of water “virtually” traded internationally along with crop-based and other products (Hanasaki et al., 2010; Siebert and Döll, 2010; Fader et al., 2011; Hoekstra and Mekonnen, 2012). Eventually, water-vegetation linkages in export countries relative to those in import countries determine whether and how much water can be “saved” globally through trade. An optimised virtual water trade can thus reduce water withdrawal in water-scarce regions and avoid cropland expansion that might otherwise be necessary to access more blue and green water, respectively. Studies exploring possible changes in future global trade and their effects on global water savings are still pending.

The above and other studies also clearly demonstrate that (green) water availability and land use are closely connected, complicating trade-offs in land use and water use, respectively (Beringer et al., 2011). Accordingly, the “planetary boundaries” of freshwater use and land use are tightly linked as well – their provisional definition and quantification (Rockström et al., 2009b) thus requires refinement by means of spatially explicit calculation of local water and land limits and opportunities of use.

4 Effects of climate and CO₂ change on irrigation

As noted above, climate change is likely to affect the water limitation of natural and agricultural vegetation via impacts on soil moisture and atmospheric water demand, complicated by direct plant responses to rising atmospheric CO₂ concentration. Rost et al. (2009) find for three climate scenarios that climate change alone would increase

water limitation and decrease global crop production. They also show that this impact could be balanced by the direct beneficial CO₂ effects on crop water use efficiency and production (as in the case of natural vegetation). Analogously, Konzmann et al. (2013) show that the irrigation requirement – defined as the amount of (blue) water needed to ease NPP water limitation of crops – on present irrigation areas will increase in many regions and globally in response to climate change, according to LPJmL simulations. In contrast, global irrigation demand would decrease by 9–19 % (range from 19 climate scenarios) if the crop responses to elevated CO₂ were accounted for (Fig. 3).

Hence, CO₂ effects are potentially a major factor for future vegetation productivity, water availability and water stress. Unfortunately, however, it is highly uncertain whether they can be fully realised in the field, as they can be suppressed by many factors. Debates are ongoing on the strength of the net CO₂ effect and the subsequent effects on the global water cycle and climate (e.g. Tubiello et al., 2007; Cao et al., 2009; Friend, 2010). DGVMs such as LPJmL reproduce well the plant responses observed in open-field Free Air CO₂ Enrichment (FACE) experiments (Hickler et al., 2008), and the implemented conductance and transpiration schemes are in line with accepted theory for stomatal behaviour under CO₂-enriched conditions (Medlyn et al., 2011). Nevertheless, more work is required on the modelling of processes that might constrain the CO₂ response in the future – first and foremost on herbivory and on nutrient limitation in both natural ecosystems (Zaehle and Dalmonech, 2011) and agricultural systems (Long et al., 2006). For example, it is perplexing that crops appear to be significantly less responsive to CO₂ enrichment in FACE experiments than in chambers (based on which models are usually parameterised). Understanding why major crops fail to achieve yield improvements as high as those observed in chambers is of immediate importance for future food supply, as many millions of people might depend on whether or not these improvements can be attained in a warming climate (Leakey et al., 2009).

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5 Role of vegetation changes in the global water balance

If actually required to increase global food production in the future (see above), expansion of cropland – either rainfed or irrigated – is likely to bring about changes in the water cycle, as can be concluded from past evidence. Gordon et al. (2005), Piao et al. (2007) and Rost et al. (2008a,b) demonstrate that land cover conversions and water withdrawals have already noticeably changed the partitioning of terrestrial precipitation into evapotranspiration and runoff. Compared to a situation without any human land use, current global river discharge is estimated to be 5 % lower (due, e.g. to deeper roots, higher interception losses and longer growing periods, altogether resulting in higher evapotranspiration). Moreover, in the absence of irrigation, discharge to the world oceans would be at least 0.6 % higher according to LPJmL simulations (Rost et al., 2008b), and possibly even higher – in which case a contribution to sea level rise cannot be ruled out (Pokhrel et al., 2012; but see Konikow, 2012). Similarly, Gerten et al. (2008) suggest that the collective effect of land cover and land use changes over the past century was an increase in global discharge by $\sim 6 \text{ km}^3 \text{ yr}^{-2}$; this impact ranks second after the predominant impact of precipitation fluctuations and trends.

Since transpiration – which makes up almost two third of total land evapotranspiration – occurs through the stomata of plants which, in turn, are regulated by atmospheric CO_2 concentration (see above), Gedney et al. (2006) suggest that the recent rise in CO_2 has already left a discernible impact on global river discharge. Their hypothesis is that reduced transpiration due to the physiological CO_2 effect was the main cause of a supposed increase in global discharge. While other authors (Peel and McMahon, 2006) point to data issues regarding this conclusion, Gerten et al. (2008) are in principle supportive of Gedney et al.'s (2006) conclusion. However, the magnitude of this increase is rather small in the underlying LPJmL simulations ($\sim 4 \text{ km}^3 \text{ yr}^{-2}$). An explanation is that the structural CO_2 effect – an increase in biomass and evapotranspiration seen in some semiarid regions where vegetation cover slightly expands – partly outweighs the physiological effect that reduces transpiration due to stomatal closure. The

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balance between physiological and structural CO₂ effects requires a more systematic investigation, though – also in the light of findings by Piao et al. (2007), who find with another DGVM that the net effect is a small decrease in global discharge.

While the attribution of drivers of past changes in discharge has been refined more recently (e.g. Dai et al., 2009; Alkama et al., 2010, 2011), it appears that the precise contribution of natural vs. anthropogenic drivers, and of changes in vegetation, to variations and trends in global discharge currently cannot be quantified on solid grounds. Even the existence of an upward global trend is hardly detectable with confidence. The main reason is – besides uncertainties in other drivers – that the uncertainty in global precipitation and also discharge data is so high (due to incomplete observation networks and time series) that different datasets disagree not only in terms of the magnitude but even in terms of the signs of the global trend (range in 20th century global discharge trend from four precipitation datasets: -4 to $+8$ km³ yr⁻²; Gerten et al., 2008). Similarly, estimates of long-term average global runoff and evapotranspiration computed by global hydrological, land surface and vegetation models exhibit a very large spread in the order of ± 20 % (Haddeland et al., 2011). This calls for systematic model intercomparisons, including identification of model structural differences and knowledge gaps. Also needed are efforts to better reconcile differences between model results and observations (Dai et al., 2009; Jung et al., 2010; Dai, 2012; Sterling et al., 2013; Douville et al., 2013) and to constrain model results by hydrological, meteorological and biogeochemical data (Milly and Dunne, 2002; Beer et al., 2007; Döll et al., 2012). However, calibration and tuning of individual variables is problematic in coupled vegetation-water models such as LPJmL, as this may compromise the simulation quality of other, un-tuned hydrological, biogeochemical and vegetation-related variables. Detailed, meso-scale inspection of forces of hydrologic changes, their uncertainty, and the role of vegetation-water interactions are required as well to complement coarser-scale global-scale assessments (Destouni et al., 2012; Immerzeel and Bierkens, 2012).

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Notwithstanding the uncertainties associated with the past and present global water balance, many studies clearly indicate a rise in *future* global discharge in response to the radiative (intensification of the hydrological cycle along with global warming) and physiological vs. structural effects of further increasing atmospheric CO₂ content (see Bates et al., 2008). As anthropogenic land use changes and water withdrawals are very likely to continue, they will additionally affect the future global water cycle. Hence, the natural and human influences on water fluxes and the Earth's vegetation can be expected to further intensify, diversify, and interact with each other.

6 Conclusions

The exemplary findings reviewed and discussed herein demonstrate that vegetation, water, climate and human activities are closely linked, and that these links underlie some of the global trends characteristic for the Anthropocene. It is shown that vegetation dynamics and productivity is in many regions controlled by water availability; that this water limitation is likely to change in response to anthropogenic climate change (via complex interactions, e.g. involving plant responses to CO₂); that part of the water limitation of agricultural plants can be overcome by more efficient water use whereas expansion of irrigated or rainfed cropland appears to be inevitable as an additional measure to meet future food requirements; and that such irrigation, land use and land cover change feeds back significantly to water resources and water cycles. The two latter points demonstrate that wise management of green and blue water is needed, including increases in crop water productivity – a water-vegetation link that is key to meeting the challenge of water and food security in the Anthropocene. Indeed, implementation and revitalisation of such “more crop per drop” practices in the context of a current paradigm shift towards “soft-path” strategies is gaining increasing importance for global water and food security (Gleick, 2000; Molden, 2007; McIntyre et al., 2008). Eventually, new and old ways of sustainable water management are to be further explored in the modern Anthropocene – there was and still is a diversity of alternative

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perceptions and modes of water use, which altogether could enrich the dominating contemporary focus on quantifiable material aspects of water (Gerten, 2010; Linton, 2011). Such new perspectives account for co-benefits across the water-food-energy nexus (Hoff, 2011) and are ideally informed by a new water ethos that values water and its many functions more comprehensively than in previous decades (Falkenmark and Folke, 2002; Groenfeldt and Schmidt, 2013). Systematic exploration of such opportunities in both theory and practice would help frame climatic, ecologic and hydrologic changes within their wider cultural dimensions (Adger et al., 2012), and acknowledge the crucial role of water and vegetation for the well-being and survival of human societies (Folke et al., 2011).

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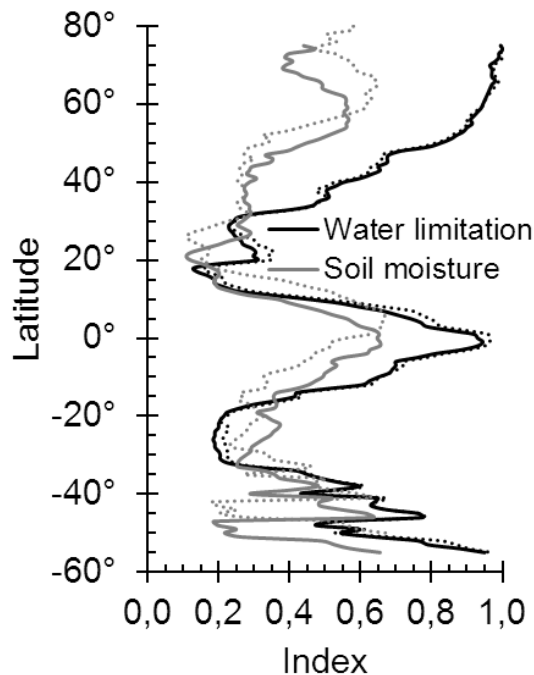


Fig. 1. Latitudinal pattern of present (1971–2000 annual average) and potential future (2071–2100) soil moisture and NPP water limitation, simulated with the LPJ DGVM for potential natural vegetation. Future changes are the median obtained under climate scenarios from five General Circulation Models, including direct CO₂ effects on plants. Both variables are plotted as indices scaled between 0 and 1: soil moisture relative to maximum water holding capacity, water limitation relative to potential canopy conductance attainable under water-unlimited conditions. Modified after Gerten et al. (2005, 2007).

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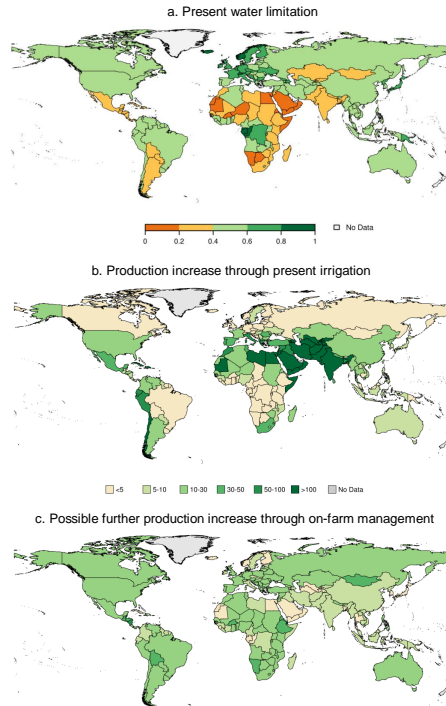


Fig. 2. (a) Country average NPP water limitation during the growing season on current cropland (1971–2000), analogous to the index in, computed by LPJmL. (b) Increase in crop production currently achieved through irrigation (assuming unlimited water supply to fulfil irrigation demand). (c) Potential further increase in crop production through harvesting of 25% of runoff from cropland and avoiding 25% of soil evaporation. For calculation procedure and more detailed maps see Rost et al. (2009).

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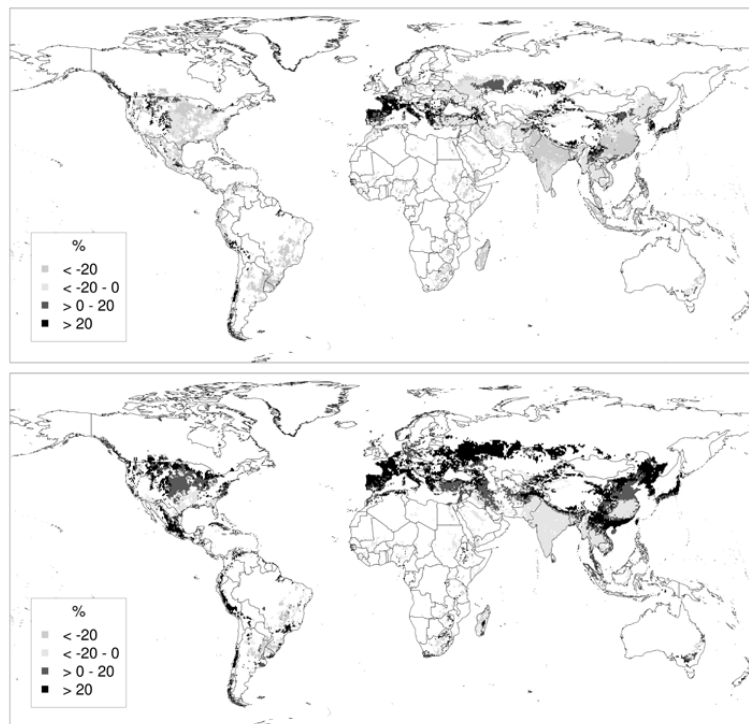


Fig. 3. Areas currently equipped for irrigation that are simulated to experience an increase or a decrease in irrigation demand by the 2080s. Shown is the percentage change in irrigation requirements relative to 1971–2000, portrayed as the median across 19 GCMs used to force the LPJmL model. Top: including effects of rising atmospheric CO_2 content; bottom: excluding these effects. The CO_2 effect will be fully realised only if unconstrained by factors such as nutrient limitation – hence, the lower panel represents an optimistic scenario assuming absence of such limitations, possibly achievable through intensive management. Maps modified after Fig. 2 in Konzmann et al. (2013).

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