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NEGEM

Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways

Report on effects of climate extremes on NETP potentials and impacts

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Executive Summary

In light of the continuously rising anthropogenic greenhouse gas emissions, Negative Emission Technologies and Practices (NETPs) increasingly gain importance in climate change mitigation strategies. However, the capacities of NETPs for carbon dioxide removal are at the same time potentially affected by ongoing changing climate and the rising frequency and severity of concomitant climate extremes. Although the knowledge on the effects of climate extremes on NETPs is still rather limited, some parallels can be drawn from (observed or modelled) impacts of droughts, heatwaves as well as associated fires observed on the natural terrestrial carbon sink.

Based primarily on such evidence and new dedicated model analyses, this report explores some potential impacts of climate change and extreme events on NETPs, discussing their relevance for approaches enhancing the natural terrestrial carbon sink through re-/afforestation as well as biomass-based NETPs, such as BioCCS and biochar. We first synthesize existing literature pertaining to alterations in forest carbon sequestration capabilities in response to climate change and associated extreme events. We then discuss implications for future re-/afforestation endeavours, regarding both potential impacts on carbon storage as well as strategies for effective forest management (section 1). As opposed to the impacts of climate change and extreme events on forest ecosystems, the effects on biomass-based NETPs are less well-explored. Therefore, the second part of the report focuses on this aspect. We present a stylized simulation study, analyzing the effects of reduced precipitation on biomass plantation productivity and irrigation requirements applying the LPJmL biosphere model.

At a global scale, our simulations indicate a loss in biomass yields under reduced precipitation, with the extent of these yield losses increasing under higher precipitation reductions. However, the results reveal severe differences in regional vulnerabilities, in that arid and continental climate regions are exposed to significantly higher percentage losses in biomass harvest, whereas temperate and tropical regions show potential for higher absolute losses. While intensified management, including irrigation, offers potential to mitigate relative losses, the results also indicate that this would come along with substantial increases in irrigation water withdrawals, exacerbating pressure on already stressed systems. Our analysis therefore highlights that if Earth system resilience and risks of local water scarcity area to be simultaneously addressed, a careful consideration of compensating yield losses through intensified management on biomass plantations is of high importance.

However, there are also methods of NETP application that even enhance resilience of natural or anthropogenic systems to extreme events, exemplified in this report by measures of biochar sequestration and soil organic carbon build-up. Fully understanding the range of options and quantifying the co-benefits of NETPs in fostering resilience to climate extremes, is, however, outlined as one part of the larger research gap regarding the interactions between carbon sequestration capacity and various climate extremes across all types of NETPs.

Table of contents

List of figures

Introduction

In the face of continuously rising anthropogenic greenhouse gas emissions, Negative Emission Technologies and Practices (NETPs) increasingly gain importance in mitigating climate change, while their capacity for carbon sequestration is at the same time potentially impacted by the changing climate itself and particularly the increasing frequency and severity of climate extremes.

In this context, the natural terrestrial carbon sink serves as a reminder of the profound impacts that climate extremes can impose. Extreme events, such as droughts, storms, heatwaves and heavy precipitation, along with their associated disturbances have the potential to disrupt terrestrial carbon sequestration or even cause net losses in carbon stocks (Reichstein et al., 2013). Processes that are relevant in these dynamics involve interactions of heat and water stress, reduction in photosynthesis and plant growth, increase in fire damage and plant mortality as well as pathogen and pest outbreaks (Figure 1). The nonlinear dynamics of these effects underscore the susceptibility of carbon fluxes and stocks to even marginal shifts in the frequency or severity of climate extremes, thereby potentially engendering substantial reductions in carbon sinks and fostering significant positive feedbacks to climate warming. In essence, the dynamic and evolving nature of climate change presents nonstationary risks that imperil the integrity of the current (natural) land carbon sink and additionally pose challenges to CDR based on biospheric carbon, such as reforestation (Anderegg et al., 2020). The changing climate and particularly the increasing frequency and severity of extreme events therefore increase the risk of re-releasing carbon back into the atmosphere, posing challenges to accounting for carbon sequestration in the biosphere (see D6.3).

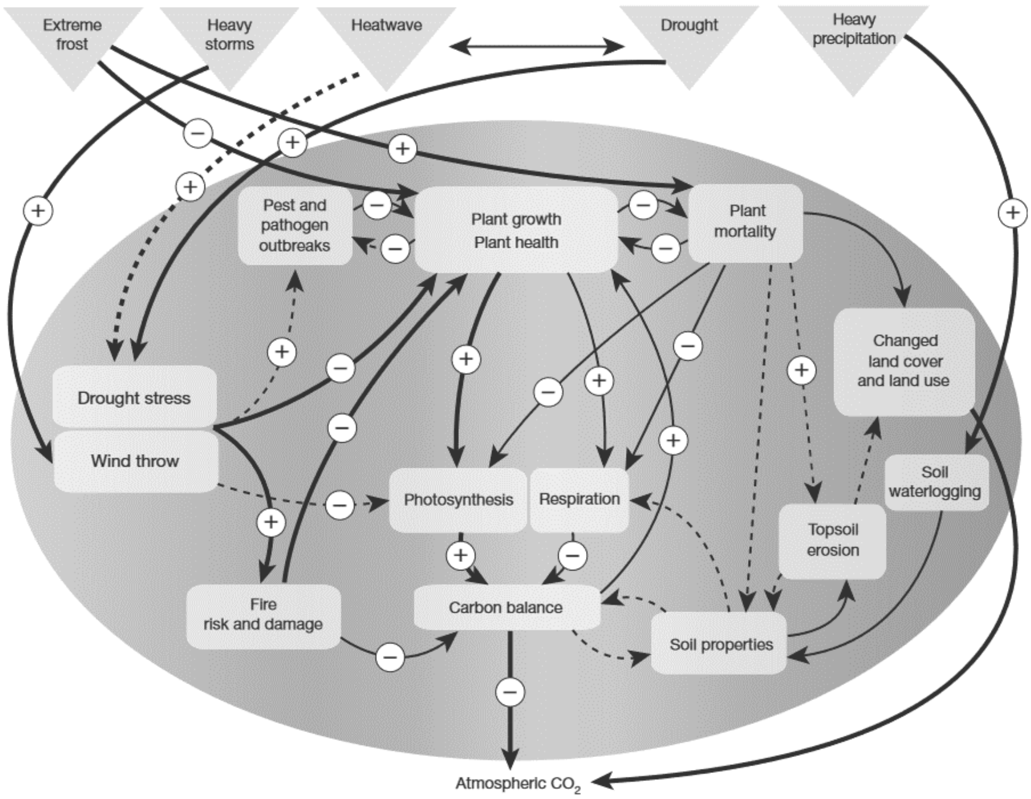

Figure 1. Processes and feedbacks triggered by extreme climate events in the terrestrial carbon cycle. Modified after Reichstein et al. (2013).

While findings on the terrestrial carbon cycle offer some insights into the implications for land-based NETPs, research on the effects of climate extremes on the capacities of chemical and marine NETPs is still limited. The IPCC AR6 on "Impacts, Adaptation and Vulnerability" highlights the risk of carbon removal reversal due to wildfires in re-/afforestation projects and due to drought in restored peatlands, but also emphasizes the lack of research assessing the prospective climate impacts on the mitigation capacity stemming from peatland restoration (IPCC, 2022). Furthermore, the IPCC report points to research gaps concerning the open ocean and blue carbon, as there is limited knowledge about blue carbon management and the consequences for marine carbon dioxide removal (CDR) if the sequestration capacity of marine ecosystems is damaged by climate change. In regard to biomass potentially supplying NETPs, like bioenergy with carbon capture and storage (BECCS), biochar sequestration and wood products, there is only a number of potential extremes-related drivers listed in the IPCC's AR6, including drought, precipitation and heat stress. For the impacts of climate extremes on chemical NETPs, like Direct Air Carbon Capture and Storage (DACCS) and enhanced weathering, there is, however, a lack of knowledge on affected and climate-sensitive processes. In total, there is thus a pressing need for further dedicated research to investigate the interactions between the carbon sequestration capacity of NETPs and climate extremes across all types of NETPs.

In this report we explore potential impacts of climate change and extreme events on NETPs, discussing their relevance for approaches enhancing the natural terrestrial carbon sink through re-/afforestation as well as biomass-based NETPs. These methods are prioritized due to their prevalence in current CDR initiatives, as indicated by the State of CDR report (Smith et al., 2023), and their prominence in future projections outlined in the IPCC AR6 WG3 scenarios (IPCC, 2022).

In the first section, we will synthesize existing literature pertaining to alterations in forest carbon sequestration capabilities in response to climate change and associated extreme events. This part will conclude with implications for future re-/afforestation endeavours, encompassing both potential impacts on carbon storage as well as strategies for mitigating adverse outcomes. Subsequently, the focus will shift to biomass-based NETPs in section 2, presenting a modelling exercise aimed at analysing the effects of reduced precipitation on biomass plantation productivity and irrigation requirements, as simulated within the LPJmL biosphere model. Finally, we will change the perspective for a brief overview exploring the potential of NETPs to enhance resilience towards climate extremes.

1 The forest sinks under climate change and climate extremes

Forest ecosystems play a pivotal role in terrestrial carbon uptake, representing the primary contributors to this process (Pan et al., 2011). However, the resilience of forest carbon sinks is increasingly jeopardized by climate extremes and associated risks (Anderegg et al., 2020; Seidl et al., 2017). Climatic conditions characterized by higher temperatures and increased aridity elevate the likelihood of disturbance agents like fire, drought, and insect outbreaks, while warmer and wetter climates heighten the risks associated with wind and pathogens (Seidl et al., 2017). Furthermore, the complexity of interactions among these agents is anticipated to intensify in the future, rendering forest ecosystems more vulnerable due to their relatively slow natural adaptation rates (Sohn et al., 2016).

Among climate-induced disturbances, droughts, in particular, have significant impacts on forest health and carbon storage, manifesting in leaf discoloration, canopy dieback, and the mortality of individual trees, groups, and stands (Schuldt et al., 2020). The primary cause of the mortality is often attributed to the failure of plant water transport (Choat et al., 2018) which is exacerbated if drought events increase in frequency, duration and severity (Field et al., 2020). The consequences of drought-induced tree mortality extend to declines in productivity and carbon losses (Allen et al., 2010; Hartmann et al., 2018; Reichstein et al., 2013). Hence, altered precipitation patterns, such as reductions, already significantly contribute to changes in carbon storage and aboveground biomass in forests (Khaine & Woo, 2015). In 2022, around 30% of the European continent (extending to nearly 3.0 million km^2) experienced a severe drought which strongly influenced European forests ecosystems. A recent study by van der Woude et al. (2023) found that this drought resulted in a reduction in net biospheric carbon uptake of 56-62 GtC (relative to 2019–2021) during the summer months. Especially areas in southern France showed a large-scale carbon release of >2.5 ppm excess CO_2 in the summer months relative to 2019–2021. Van der Woude et al. (2023) further conclude that due to climate change, such drought-induced reductions in carbon uptake will in the future no longer stand out as exceptional.

Drought-driven tree mortality often displays a broader and more diffuse pattern than mortality resulting from fires. These widespread effects make attributing impacts to drought events challenging, potentially leading to an underestimation of drought's overall impact on forests and their carbon sinks (Anderegg et al., 2020). Furthermore, the recovery phase from drought leaves forests highly vulnerable to subsequent attacks by insects or fungal pathogens, as evidenced by a study on Central European forests by Schuldt et al. (2020). The authors revealed unexpectedly strong drought-legacy effects in 2019, implying that the recovery of trees was hindered after the 2018 drought event, rendering them highly susceptible to subsequent drought impacts.

In addition to an increased occurrence and severity of droughts, also wildfires are driven by warmer climatic conditions, exhibiting escalated speed and intensity under climate change (Field et al., 2020). Fires have a twofold impact on carbon: In addition to the release of stored carbon into the atmosphere, fire-induced tree mortality compromises the carbon sequestration potential of forests. During 1997-2016, fires led to substantial global mean carbon emissions estimated at 2.2 Gt of carbon per year (van der Werf et al., 2017). Other consequences of fires are their negative impact on seedling density, with burned forests experiencing a 63% lower density compared to unburned forests in tropical moist deciduous environments (Khaine & Woo, 2015). Furthermore, fires highly influence biodiversity by affecting species distribution and migration (Khaine & Woo, 2015). While fires play a vital role in the natural carbon cycle, increases in frequency and extent under climate change will intensify the reductions in carbon storage and restoration capacities caused by the dynamics described.

Altered climatic conditions also influence the expansion of biotic agents such as insects and pathogens which can be accelerated significantly. Senf et al. (2016) for example identified a relationship between western spruce budworm outbreaks and regional-scale weather variability. Insect outbreaks can potentially even transform forest carbon sinks into carbon sources, as Kurz et al. (2008) further demonstrated with a study in British Colombia indicating a release of 17.6 Mt C per year.

1.1 Implications for re-/afforestation

At the same time that the carbon sink of the natural forest systems is jeopardized by the effects of climate change, reforestation and afforestation become increasingly relevant as negative emission technologies aimed at mitigating climate change. These techniques involve not only the transformation of areas previously used for different purposes (of less carbon storage) into forests but also serve as strategic approaches for rehabilitating forests and their storage capacity in the aftermath of disturbances. There was, for example, a pressing need for reforestation in European forests after a severe summer drought had affected large parts of Europe in 2018. According to the German Federal Ministry of Food and Agriculture, this drought caused significant damage, impacting millions of trees and necessitating afforestation efforts covering at least 2450 km^2 in Germany (BMEL, 2020).

Independent of whether re-/afforestation is implemented as new carbon sequestration project or restoration programme after disturbances: the increased risks of carbon storage losses in forests under climate change and extremes described above in principle hold true for afforested and reforested areas as well. Addressing these dynamics under changing climate and the impermanent nature of standing biomass (see D6.3), these increasing risks of releasing carbon back into the atmosphere need to be accounted for in CDR strategies of re-/afforestation.

Moreover, planning forests exclusively for maximizing the biomass stock may have additional trade-offs, such as decreasing the stand-level structural complexity and large emphasis on pure fast-growing stands, inducing risks for biodiversity and resilience to natural disasters (IPCC, 2022). Moreover, young trees involved in re-/afforestation efforts are even particularly vulnerable towards the previously mentioned disturbances. While they must compete with established trees for nutrients, light and water, they are more strongly impacted by disturbances like droughts due to their narrower climatic tolerance (Dobrowski et al., 2015; Khaine & Woo, 2015; Lalor et al., 2023). Dobrowski et al. (2015) for example investigated differences in the climatic tolerance of juvenile and adult western US tree species. They found that 74% of the species examined showed statistically significant differences in the mean of their distribution along at least one climatic axis. Thereby, especially the median values for minimum temperature and climatic water deficit were lower for juveniles. This narrower climatic tolerance has an impact on the positive population growth of the trees and renders juvenile trees more vulnerable to the increasing impacts of climate change.

1.2 Resilience-building measures and adaptation strategies for forests

With climate extremes and their detrimental impacts looming, effective forest management is increasingly recognized as imperative, serving a crucial role in building resilience and safeguarding the sustainability of forest ecosystems (FAO, 2012; Keenan, 2015). These strategies involve a combination of proactive planning (e.g. risk assessments and the implementation of new monitoring technologies), sustainable practices (e.g. wildlife conservation and water management), and adaptive measures (e.g. invasive species management and the selection of climate-adapted tree species). Anticipatory adaptation strategies aimed at enhancing the resistance and resilience of forest ecosystems against various disturbance agents involve altering the composition of future forest stands. Often, this includes the cultivation of more drought-resistant tree species or transforming monocultures into diverse mixed forests (Sohn et al., 2016). Multiple of these measures as well as combined approaches may qualify as emission reduction measure on the on hand (e.g. avoiding fires) and as CDR on the other hand, as the forest carbon sink may be enhanced through an increase in healthy standing biomass.

For existing forest stands, climate-adaptive silviculture plays a pivotal role. Selective thinning emerges as an effective strategy, contributing to higher soil water availability for residual trees, fostering more extensive individual root systems capable of extracting more water, and reducing competition (Manrique-Alba et al., 2022; Sohn et al., 2016). In addition, thinned forests may exhibit a significantly lower increase in canopy temperature and canopy water stress during drought periods compared to non-thinned forest stands, as shown for thinned Ponderosa pine forests by (Sankey & Tatum, 2022). These positive effects can lead to an increased forest growth after drought events, although the growth rates vary depending on tree species and region (Sohn et al., 2016).

Besides drought resilience, fire management practices play a crucial role in forest adaptation to climate change and extremes by mitigating the escalating risks of wildfires. Strategies include fuel removal through controlled burnings and enhanced fire suppression, but also monitoring practices, early fire detection and the enhancement of fire-fighting capacities (Khabarov et al., 2016; Molina-Pico et al., 2016). For planning and accounting in proactive fire management programmes, it is crucial to acknowledge that these practices do not only ensure safety from catastrophic fires of high carbon losses but also sustain essential ecosystem services (Khabarov et al., 2016; Sample et al., 2022).

Further integral components of forest adaptation strategies to climate change are community engagement and education. In this context, it is essential to empower local communities to actively participate in sustainable forest management. Informed communities contribute valuable traditional knowledge, playing a crucial role in implementing adaptive practices that enhance the resilience of forests to the challenges posed by a changing climate (Makondo & Thomas, 2018).

Beyond these strategies, additional forest management options include forest restoration/rehabilitation and fostering biodiversity, which can be closely connected to reforestation efforts as well as contributions to global restoration targets (e.g. Kunming-Montreal Global Biodiversity Framework). Further practices involve vegetation and pest management, the implementation of monitoring and early warning systems, and the adoption of water management practices (Field et al., 2020; Molina-Pico et al., 2016). Effectively increasing the resilience of forest systems will most likely require a portfolio of these measures. A comprehensive adoption of the measures tailored to local stressors will however always aim to fortify natural forest resilience to ensure their resistance against the multifaceted threats presented by a changing climate.

2 Impacts of climate change and climate extremes on biomass-based NETPs

Re/Afforestation and biomass-based NETPs share a dependence on photosynthesis as the primary mechanism for removing CO_2 from the atmosphere. The carbon sequestration potential of biomass-based NETPs hinges significantly on the availability of suitable feedstocks. While uncertainties persist regarding the scale and viability of biomass side streams as potential sources for NETs (e.g., agricultural residues, municipal waste, manure, etc., as outlined in D3.10), dedicated biomass plantations are widely regarded as dependable sources. However, there is only limited potential for the expansion of biomass plantations without further transgression of planetary boundaries, as shown in D3.2, D3.3 and D3.7. In addition, these plantations are also susceptible to adverse impacts stemming from climate change and extreme weather events.

Aligned with the discussion on declining plant health and productivity in forests attributed to droughts, floods, and storms, analogous trends are anticipated within biomass plantations, specifically those cultivating woody biomass. In the context of dedicated biomass crops it is moreover worth noting that water deficiency, particularly in the extreme form of drought, has been found to reduce crop yields more than any other environmental stress (Cattivelli et al., 2008). This stressor detrimentally affects all stages of plant development, as emphasized by Al Hassan et al. (2022). Correspondingly, several studies examining drought experiments with bioenergy crops such as miscanthus, giant reed or short-rotation poplar have demonstrated significant reductions in biomass yields as well as quality (Haworth et al., 2018; Tschaplinski et al., 2019; van der Weijde et al., 2017). However, it is important to acknowledge that these present isolated experiments, providing insights that are limited to specific regional conditions.

Thus, further research is needed to elucidate the response of lignocellulosic energy crops, crucial for supplying biomass-based NETPs like BECCS, biochar sequestration, and wood products, to extreme climatic stressors. Assessing the potential impact of climate extremes and shifting temperature and precipitation patterns on these crops at a global scale requires an evaluation of their spatially-explicit exposure to these changes within a cohesive assessment framework.

2.1 Simulating biomass plantations under reduced precipitation

To provide a first systematic analysis on this topic, we here use the biosphere model LPJmL5-NEGEM (refer to D3.1) to generate a database of simulated responses of biomass productivity to systematic reductions in precipitation of magnitudes that become increasingly likely under climate change. To achieve this, we simulate growth of herbaceous biomass plantations on rededicated pasture areas, as assumed under a full transition to the EAT Lancet planetary health diet, outlined in D3.7. Altering the baseline mid-century (2036-2065) climate input of a bias-corrected version of data from the GFDL-ESM4 model for RCP4.5-SSP2 (Lange & Büchner, 2021) that roughly reflects warming levels under NDC (Nationally Determined Contributions) fulfilment, we apply daily reductions in precipitation of 10%, 25%, and 50% in each grid cell. These values roughly align with precipitation losses simulated in the GGCMI Phase 2 protocol, selected to represent reasonable ranges for changes over the medium term (until 2100) under business-as-usual emissions (Franke et al., 2020).

For this simulation experiment, it is important to note that the precipitation perturbations represent potential deviations from historical climatology within the growing season only, treating each location (grid cell) separately. Therefore, our results should not be interpreted as a global scenario but rather as potential future states for individual grid cells or regions – while in reality, future changes in precipitation will vary temporally and spatially across the globe. Yet we think this sensitivity study is valid to demonstrate the principle vulnerability of biomass plantations to reduced rainfall, illustrating how yields and irrigation demands may change during a growing period with significantly lower rainfall.

Furthermore, we evaluate the extent of exposure under two management scenarios to assess how increased management intensity might mitigate some of the yield losses, albeit at the expense of additional irrigation withdrawals. A 'minimal management' scenario assumes rainfed conditions with no fertilizer application, whereas an 'intensified management' scenario involves irrigation on 30% of the plantation area and a high fertilization rate (2x nitrogen harvested on biomass plantations under unlimited conditions, as described in D3.7).

2.1.1 Biomass yield losses under reduced precipitation

The simulations indicate that significant reductions in precipitation during the growing season, such as a 50% decrease, potentially lead to substantial yield losses on herbaceous biomass plantations by ~47% globally under low management intensity (median effect across all cells and over the 30-year time period). Even a relatively modest reduction in precipitation, such as 10%, was found to result in decreased yields in most regions (median effect -4%). However, regions with more saturated soils, such as the tropics, are shown to exhibit some increases in yields due to a reduction in nitrogen leaching. Under more significant precipitation reductions of 25%, however, these potentially positive effects are simulated to be confined to isolated cases, resulting in a global median 17% yield loss. While these simulations aim to estimate yield losses for a single growing season of reduced precipitation, the overall hydrological and ecological shifts would be far more substantial, if precipitation was reduced on longer time frames eventually resulting in ecoregions shifting to more arid types.

In addition to global averages, Figure 2 and Figure 3 reveal that different climatic regions exhibit varying degrees of vulnerability to yield effects under reduced precipitation. Arid regions, for example, experience particularly high relative yield losses, with approximately 53% reduction under -50% precipitation, whereas tropical regions show comparatively lower losses of around 28% (median effect). Regions with temperate and continental climates, prevalent in Europe, also demonstrate substantial yield reductions of approximately 41% and 52% (median effect), respectively. This gradient from arid to tropical climates is evident across all scenarios of precipitation reduction, although it is less pronounced for smaller changes in precipitation. In absolute terms, the yield losses are simulated to be more pronounced in more productive regions with higher baseline yield levels: under minimal management, a reduction in precipitation by 50% is leading to losses of more than ~4 tonnes dry matter per hectare (tDM/ha) in continental, temperate and tropical climates, whereas arid regions loose only about 2.4 tDM/ha (median values, Figure 4). Yet, as expected, regions already facing water limitations (and with lower baseline yield levels) will experience more pronounced relative effects due to reduced rainwater availability, especially if not irrigated (Figure 3). This divergence of relative and absolute losses suggests that arid and continental regions are more exposed to experiencing larger relative losses in their own region – and thus local CDR capacity and local income generated by this –, while the potential losses in temperate and tropical regions have larger impacts on the global harvest and thus the overall CDR capacity.

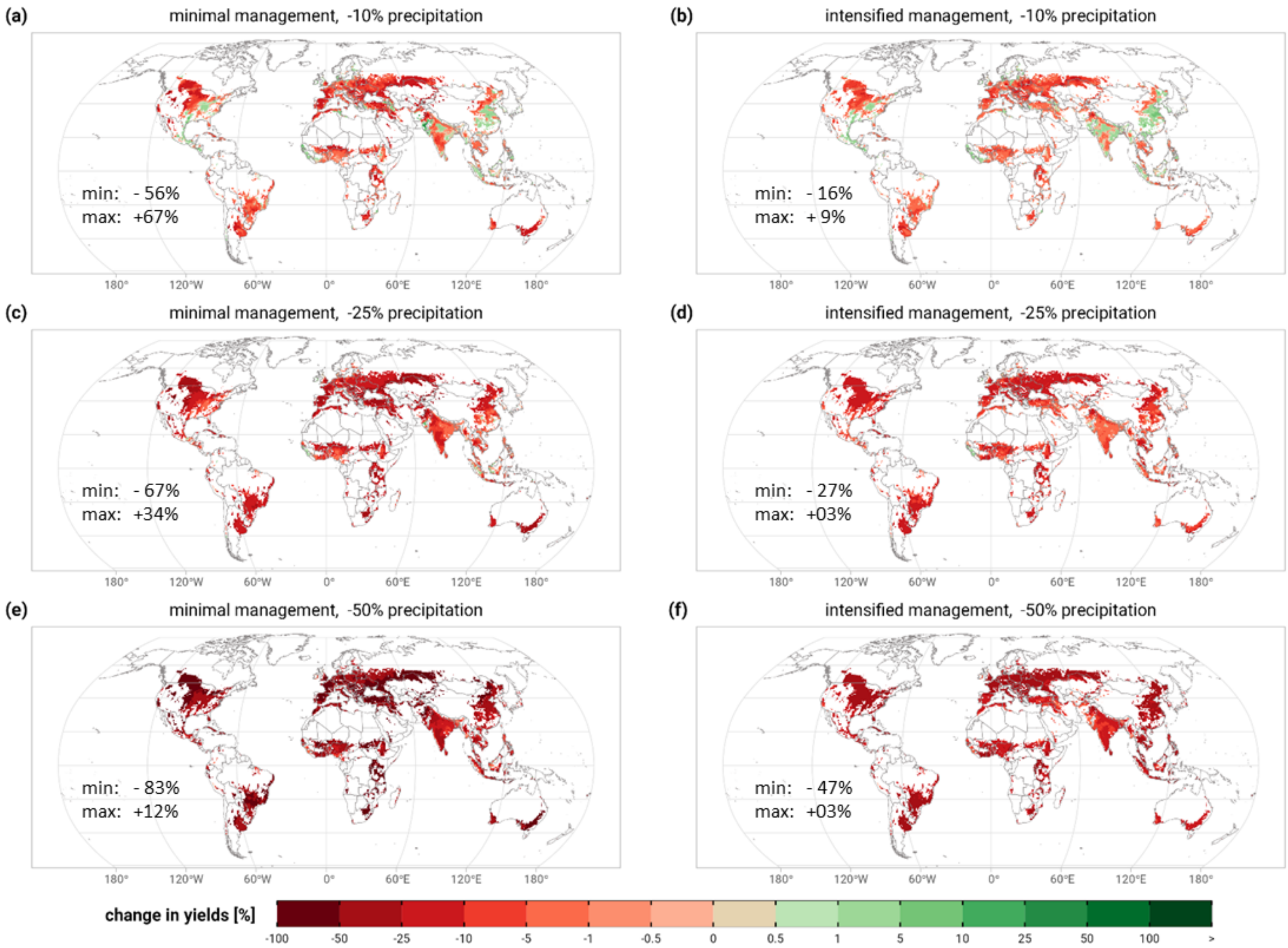

Figure 2. Global maps of percentage change in harvest on herbaceous biomass plantations simulated for mid-century (2036-2065) climate under different levels of precipitation reduction (-10/25/50%) combined with two distinct management intensities (marginal/intensified). The areas of biomass plantations correspond to a shift to the EAT Lancet planetary health diet and releasing pasture areas to biomass plantations as described in D3.7.

2.1.2 Lower yield losses on intensely managed plantations

On biomass plantations with higher management intensity, here represented by irrigating 30% of the plantation area and a high fertilizer rate, the relative harvest losses caused by precipitation reduction is compensated to some degree. Under conditions where the water demand of the plants is satisfied by irrigation systems on 30% of the area, the global median decline in yields amounts to only about 27% for the extreme case of 50% precipitation reduction, in contrast to a 47% reduction globally simulated under low management intensity. Comparing the scenario of high management intensity under 10% and 25% precipitation reduction to the same management assumption under default precipitation patterns (GFDL RCP4.5 SSP2) yields a response in biomass harvest reductions of 2% and 10%, respectively.

Higher management intensity on plantations is simulated to result in lower variability of yield responses to precipitation losses within climatic zones and a more coherent effect among areas with similar climatic conditions (see shorter violin symbols in Figure 3). In many regions this may be interpreted as less uncertainty in the effects and thus higher planning reliability for more intensely managed plantations. While the gradient of increasing relative harvest losses from tropical (-50% prec.: -23% yield) over temperate (-50% prec.: -27% yield) to continental climates (-50% prec.: -33% yield) is still visible in the scenario of high management intensity, the differences are less pronounced than under minimal management intensity. Absolute losses in harvest are simulated to be much higher under intensified management, with tropical climates showing the strongest effect of 10.4 tDM/ha yield losses (median effect) under 50% precipitation reduction, followed by temperate (8.7 tDM/ha), continental (6.2 tDM/ha) and arid (3.5 tDM/ha) climates (Figure 4).

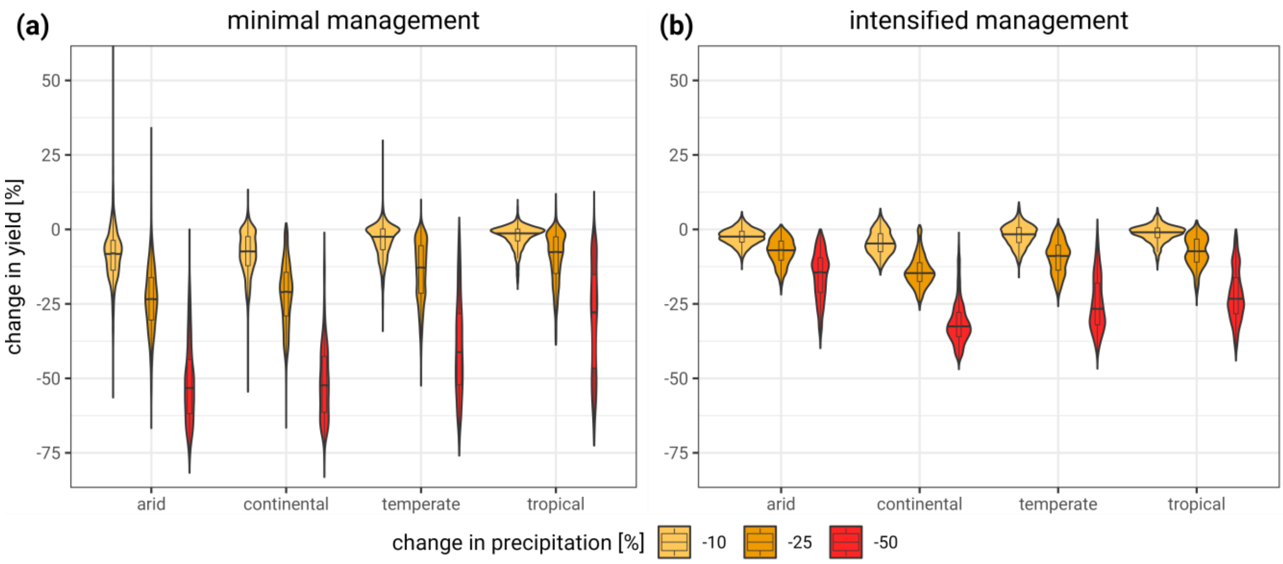

Figure 3. Percentage change in harvest on herbaceous biomass plantations simulated for mid-century (2036-2065) climate under different levels of precipitation reduction (-10/25/50%) for a) marginal management intensity and b) intensified management, grouped by Köppen-Geiger climate regions.

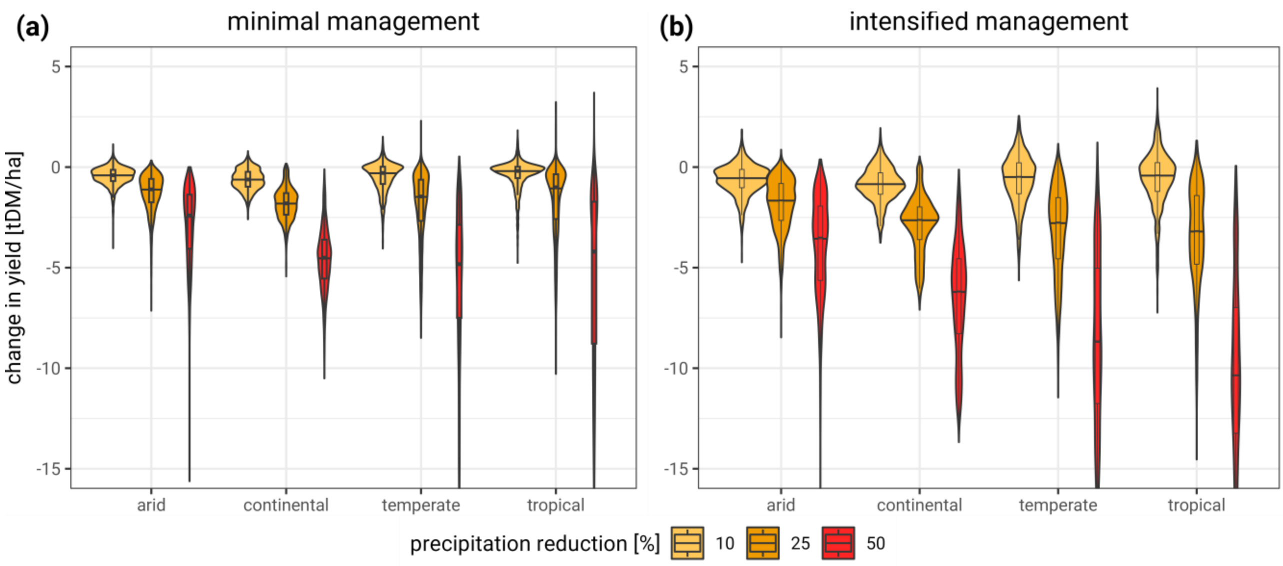

Figure 4. Absolute change in yields on herbaceous biomass plantations in tDM/ha simulated for mid-century (2036-2065) climate under different levels of precipitation reduction (-10/25/50%) for a) marginal management intensity and b) intensified management, grouped by Köppen-Geiger climate regions.

A particularly substantial reduction in relative harvest losses in the intensified management scenario (compared to minimal intensity) can be identified for arid climate zones, i.e. from -53% to -14% in the -50% precipitation scenario. This is due to fact that irrigated harvests constitute the predominant portion of total harvests in these regions of pronounced water limitations. Rainfed yields tend to be notably low, while the effect of irrigation on plant productivity is considerably high. Despite precipitation losses affecting the majority of plantation area (70%), the resultant yield reductions do not significantly influence the overall yield response, as the 30% irrigated area contributes the bulk of the harvest. The irrigated portion remains unaffected by precipitation reductions, assuming an unlimited water supply from river and groundwater systems, as simulated here. However, in reality, substantial reductions in precipitation would directly diminish water availability from rivers, reservoirs, and ultimately groundwater recharge.

2.1.3 Increased water demand of intensely managed plantations

While biomass plantations of higher management intensity and particularly irrigation are less prone to production losses under precipitation reductions, the withdrawal demand will increase significantly (**Error! Reference source not found.**) at the same time as water availabilities are further reduced in river systems and reservoirs.

Arid regions stand out as the climatic zone with the lowest relative change in withdrawals due to reduction in precipitation (10% at -50% precipitation, median effect, Figure 6). This can be attributed to the already substantial withdrawals necessary for irrigated systems under the baseline climate scenario, which do not experience significant relative augmentation even under a decrease in already limited rainfall. While continental climate features higher precipitation levels than arid regions, it is also characterized by strong seasonality. This leads to pronounced water constraints during drier periods of the growing seasons and considerable reliance on precipitation for agricultural productivity in wetter seasons, the latter of which diminishes under scenarios of reduced precipitation. Consequently, areas of continental climate conditions demonstrate the most pronounced response to decreases in precipitation, reflected in a 48% median increase in irrigation water withdrawals under the -50% precipitation scenario.

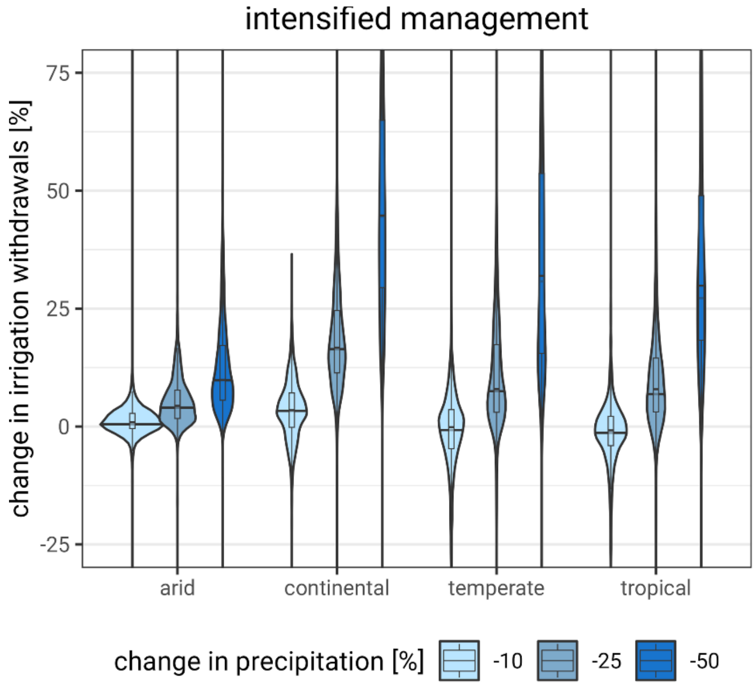

Figure 5. Global maps of change in irrigation water withdrawals for biomass plantations simulated for mid-century (2036-2065) climate under different levels of precipitation reduction (-10/25/50%) and intensified management.

Cells showing reduced irrigation withdrawals (**Error! Reference source not found.**), particularly evident in the -10% precipitation scenario, predominantly correspond to regions experiencing increased productivity (Figure 2). These effects in the simulations can best be explained by reduced nitrogen leaching, resulting in larger plants that require more energy for interception, consequently reducing the availability of energy for soil evaporation. This leads to wetter soils that necessitate less irrigation to achieve soil saturation and optimal water supply. However, further assessments are necessary to determine if these effects, in terms of direction and magnitude, are applicable to real-world plantation settings. Similar to the patterns of enhanced yield under precipitation losses, instances of reduced withdrawals are confined to isolated occurrences in more substantial shifts in precipitation, such as the -25 and -50% precipitation scenarios.

The significant rise in simulated irrigation withdrawals observed in the -25% and -50% precipitation scenarios extends beyond mere resource demand, also impacting local water stress levels. A comparison between the distribution of increased withdrawals in scenarios of reduced precipitation and the distribution of water stress under baseline climate conditions, as detailed in D3.7, highlights markedly heightened pressure on river systems in regions already experiencing considerable water stress due to the establishment of biomass plantations with high management intensity. Additionally, it is essential to acknowledge that at the same time as meeting the water demands of biomass crops would necessitate increased withdrawals under reduced precipitation, the replenishment rates of river systems, reservoirs, and groundwater sources would decrease significantly.

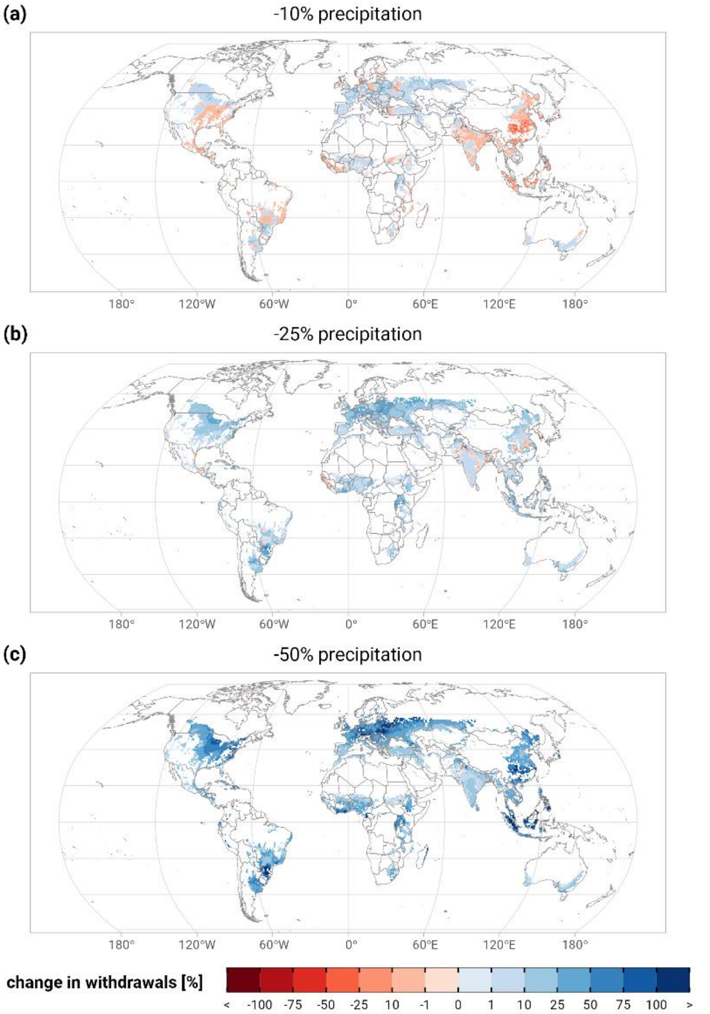

Figure 6. Change in irrigation water withdrawals for biomass plantations simulated for mid-century (2036-2065) climate under different levels of precipitation reduction (-10/25/50%) and intensified management, grouped by Köppen-Geiger climate regions.

3 NETPs fostering resilience to climate extremes

Sections 1.2 and 2.1.2 discussed reduced extreme-induced impacts through management options for forests and biomass plantations. This suggests that implementation pathways for some NETPs need climate change adaption strategies in order to reach full sequestration capacity. Other NETPs, such as biochar sequestration in soils and soil carbon sequestration measures, may in contrast play the role of the adaptation practice themselves. Here we shortly summarize the role of these NETPs for enhancing soil health and resilience to climate extreme events.

This underscores the necessity for integrating climate change adaptation strategies into the implementation pathways of certain NETPs to optimize their sequestration potential. In contrast to that, other NETPs like biochar sequestration in soils and soil carbon sequestration measures may inherently function as adaptation practices. Here, we shortly summarize the contribution of these NETPs to enhancing resilience against climate extreme events.

3.1 Biochar sequestration in soils

Biochar applications to soil offer numerous agronomic benefits, some of which enhance the resilience of agricultural soils to extreme events like droughts. Research indicates that applying biochar can stimulate root growth, leading to improved plant performance. For instance, Xiang et al. (2017) conducted a comprehensive meta-analysis showing that biochar applications significantly increase root biomass (32%), root volume (29%), and root surface area (39%). These effects are attributed to biochar expanding the rhizosphere, thereby enabling roots to access a larger volume of water and nutrients (Prendergast-Miller et al., 2014).

Additionally, biochar amendments have been found to enhance the water use efficiency of plants, as reported in a meta-analysis by Gao et al. (2020), where an average increase of 19% was observed. Moreover, biochar improves the water holding capacity of soils, with a grand mean increase of 8% reported in the meta-analysis by Omondi et al. (2016). Further meta-analyses by Edeh et al. (2020) showed significant improvements in available water content (29%), field capacity (20%), permanent wilting point (17%), and total porosity (9%) with biochar applications.

The combined effects of increased water holding capacity and enhanced root growth resulting from biochar applications can greatly enhance the resilience of plants to extreme weather events (Koide et al., 2015; Schmidt et al., 2021). These processes extend the period before potential wilting and are particularly beneficial for soils prone to droughts.

3.2 Soil carbon sequestration

Enhancing the soil carbon sequestration is another NETP that is closely interlinked with soil resilience to extreme climate events. Practices aimed at elevating soil organic carbon (SOC) content encompass various strategies, such as:

a) Management of vegetation, which involves implementing practices with high carbon input, such as utilizing improved crop varieties, implementing diverse crop rotations, integrating cover crops into agricultural systems, adopting perennial cropping systems, and leveraging biotechnology to augment inputs and enhance the recalcitrance of below-ground carbon.

b) Nutrient management and organic material supplementation to augment carbon input into the soil, which includes optimizing the application rate, type, timing, and precision of fertilizers and organic materials.

c) Adoption of reduced tillage intensity and retention of crop residues to minimize soil disturbance and enhance carbon retention.

d) Enhancement of water management practices, particularly through the implementation of irrigation schemes in arid or semi-arid environments (Smith et al., 2019).

The IPCC Special Report on Climate Change and Land Management highlights that increasing soil carbon stocks can enhance soil water retention capacity, thereby mitigating the impacts of droughts and enhancing ecosystem resilience to water scarcity (Smith et al., 2019). This is supported by Lal (2016) who underscores the variety of soil functions and ecosystem services that depend on SOC. The overall soil health fostered by high levels of SOC, but particularly improved water and nutrient availability, increase the soil's resilience to extreme climate events, such as droughts and floods (Lal, 2016).

A case study by Pan et al. (2009) examining the Chinese National Soil Survey showed that in the agricultural sector, which grapples with yield reductions due to climate extremes, the adoption of soil carbon sequestration

(SCS) measures could present a mutually beneficial strategy. The SCS practices in China increased crop productivity and stabilized yields, while leading to significant carbon sequestration in the soils (Pan et al., 2009). In line with that, Hijbeek et al. (2017) showed in a meta-analysis that the yields in Europe increased for root and tuber crops, spring sown cereals, and for very sandy soils or wet climates. Yet, the additional yield effect on other crops, soil types and climates was surprisingly not significant. Thus, application areas of highest co-benefits should be prioritized for SCS implementation. Particularly in developing countries where continuous soil degradation interferes critically with food production, elevating the soil organic carbon content could enhance available water holding capacity, cation exchange capacity, soil aggregation and susceptibility to crusting and erosion (Lal, 2006). Despite different regional needs for restoring soil health, SCS could become a pivotal tool for addressing food security and climate change mitigation in a synergistic manner.

4 Key findings and policy relevant messages

While CDR strategies are becoming increasingly relevant under continuously rising greenhouse gas emissions, our understanding of how climate change and particularly climate extremes will impact the storage capacities of the different NETPs is limited. For terrestrial NETPs, such as reforestation, peatland restoration, and biomass-based approaches, evidence from observations and model simulations increases that suggests severe risk of experiencing significant reductions in uptake rates and even carbon storage reversal due to extreme weather events. Yet, questions on spatially-explicit and globally aggregated effects remain for the specific stressors. In regard to impacts of climate extremes on chemical NETPs, CDR in the open ocean and blue carbon ecosystems, there is a lack of knowledge on affected processes and management options (IPCC, 2022).

Besides revealing these knowledge gaps regarding the interactions of NETPs and climate extremes, the report also informs the research field about impacts on feedstock production for biomass-based NETPs through simulations of plantation productivity in response to systematic reductions in precipitation, reflecting magnitudes increasingly likely under climate change.

On a global scale, biomass yields are here simulated to decrease under reduced precipitation, with the extent of these yield losses increasing under higher precipitation reductions. However, the results reveal severe differences in regional vulnerabilities: arid and continental regions face greater vulnerability to experiencing proportionally larger losses, thereby impacting local CDR capacity and associated income, whereas temperate and tropical regions show potential for higher absolute losses exerting broader repercussions on global biomass harvests and consequently overall CDR capacity. Relative losses can be reduced significantly under enhanced management intensity, most importantly irrigation. However, in D3.3/3.7, we have identified the minimal management scenarios as the most suitable approach for addressing Earth system stability holistically, although their implementation necessitates profound transformations and extensive regulatory measures. Yet, the findings of the study in this report indicate a particularly high vulnerability of biomass plantations under minimal management to relative yield losses under precipitation reductions. While intensified management, including irrigation, offers potential to mitigate these losses, our assessment also reveals substantial increases in water withdrawals, exacerbating pressure on already stressed systems. This will consequently diminish local water availability, impacting blue water resources, i.e. environmental flow requirements in streams, groundwater levels and reservoirs, potentially even triggering conflicts with other water use sectors, as it becomes difficult to reconcile water uses for both food production and carbon sequestration (Rockström et al., 2012). Therefore, prioritizing Earth system resilience as a whole would entail a careful consideration of compensating yield losses through intensified management on biomass plantations and would lead to the exclusion of large regions where disruptions to biosphere integrity, natural nitrogen and water cycles already transgress planetary boundaries, as demonstrated in D3.3/3.7.

Aligned with Earth system stewardship, NETP implementation strategies should prioritize methods that enhance the resilience of nature and/or anthropogenic systems, like agriculture, towards extreme events. Biochar applications to soils and soil carbon sequestration measures provide promising examples in this field, as described in section 4. However, more research is needed to outline the array of options and quantify the potential co-benefits of NETPs fostering resilience to climate extremes.

5 Conclusions and further steps

This report suggests substantial risks to the CDR potentials of NETPs resulting from the impacts of ongoing climate change and associated extreme events. The examination of literature regarding risks to forest carbon sinks and their implications for re-/afforestation efforts draws from observed phenomena in diverse forest ecosystems globally. As our understanding of the impacts on biomass-based NETPs, particularly productivity on biomass plantations, remains limited, our preliminary and stylised modelling study investigates the response of such plantations to significant reductions in precipitation. This analysis still elucidates the magnitude and geographical distribution of vulnerabilities associated with yield losses under shifting precipitation regimes. However, our assessment does not specifically address drought dynamics (e.g. rainfall reductions of >10–50%, possibly intensifying in the course of the growing period), which could induce more severe consequences, potentially leading to complete crop failure. Hence, further dedicated research is required to evaluate the future resilience of biomass plantations to droughts and other extreme weather events such as heatwaves in particular (directly damaging crops). Such efforts may entail simulations involving prolonged periods of rainfall deficiency, the timing and duration of which may vary across different regions. Capturing these regional characteristics – and thus creating more realistic scenarios than the sensitivity experiment employed here –, the generation of input data for such simulations could potentially involve the derivation of drought patterns from historical data, with particular focus on amplified Rossby waves, i.e. so-called wave 5 and wave 7 events (Kornhuber et al., 2020).

Beyond the research on stressors for biomass productivity, there is a pressing need for further dedicated research to investigate the interactions between the carbon sequestration capacity of NETPs and climate extremes across all types of NETPs. This is particularly relevant in face of continued emission increases, as higher greenhouse gas concentrations in the atmosphere amplify both the importance of CDR efforts and the vulnerability of their storage capacities to extreme weather events.

For preparing this report, the following deliverable/s have been taken into consideration:

D#	Deliverable title	Lead Beneficiary	Type	Dissemination level	Due date (in MM)
D3.2	Global NETP biogeochemical potential and impact analysis constrained by interacting planetary boundaries	PIK	R	PU	M24
D3.3	Global NETP assessment of impacts utilising concepts of biosphere integrity	PIK	R	PU	M36
D3.7	Global impacts of NETP potentials on food security and freshwater availability, scenario analysis of options and management choices	PIK	R	PU	M36
D6.3	Global governance of NETPs – global supply chains and coherent accounting	BELLONA	R	PU	M30

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