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LETTER

Accounting for local temperature effect substantially alters afforestation patterns

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Abstract

Human intervention in forested ecosystems is hoped to perform a fundamental shift within the next decade by reverting current forest loss—a major source of CO_2 emissions—to net forest gain taking up carbon and thus aiding climate change mitigation. The demanded extensive establishment of forests will change the local surface energy fluxes, and with it the local climate, in addition to competing with food and fiber production for land and water. Scenario building models encompass this competition for resources but have turned a blind eye to the biogeophysical (BGP) local surface energy flux disturbance so far. We combine the benefit of CO_2 sequestration of afforestation/reforestation (A/R) with the additional incentive or penalty of local BGP induced cooling or warming by translating the local BGP induced temperature change to a CO_2 equivalent. We then include this new aspect in the land-use model Model for Agricultural Production and their Impact on the Environment (MAgPIE) via modifying the application of the price on greenhouse gases (GHGs). This enables us to use MAgPIE to produce A/R scenarios that are optimized for both their potential CO_2 sequestration and the CO_2 equivalent local BGP effect, as well as the socio-economic trade-offs of A/R. Here we show that optimal A/R patterns are substantially altered by taking the local BGP effects into account. Considering local cooling benefits of establishing forests triples (+203.4%) the viable global A/R area in 2100 from 116 to 351 Mha under the conditions of the shared socioeconomic pathway 2 (SSP2) scenario driven by the same GHG price. Three quarters (76.0%, +179 Mha) of the additionally forested area is established in tropical climates alone. Therefore, a further neglect of BGP effects in scenario building models undervalues the benefit of tropical forests while simultaneously running the risk of proposing counterproductive measures at high latitudes. However, the induced focus on tropical forestation intensifies the competition with food production where forests contribute most to mitigation. A/R related trade-offs need to be considered alongside their climate benefit to inhibit unintentional harm of mitigation efforts.

1. Introduction

Forests are a major component of the global carbon cycle [1]. Loss in forest cover through deforestation and forest degradation is one of the main drivers of CO_2 emissions from the land sector and thus also of overall anthropogenic greenhouse emissions [2]. Afforestation, reforestation (A/R), and reduced deforestation are considered as essential tools for climate change mitigation [3]. This opportunity for binding CO_2 in forests is recognized by the scientific community in the special reports of the Intergovernmental Panel on Climate Change (IPCC) on global warming of 1.5 °C [4] and the special report on climate change and land [3]. In addition, policy also heavily relies on A/R as a climate change mitigation option written into the National Determined Contributions under the Paris Agreement [5, 6]. A/R is also frequently used in scenario building models that explore future societal and emission pathways. Especially scenarios that curb global temperature change below 2 °C or even 1.5 °C make strong use of land-based mitigation options like A/R [4, 7, 8]. The proposed policies and modeled pathways depend on the uptake of CO_2 from the atmosphere, a biogeochemical (BGC) effect. However, the impact of land-cover changes also has a biogeophysical (BGP) component. Altering the surface roughness, albedo and evapotranspirative capacity changes the surface energy balance [9]. The latter effect is mostly neglected by mitigation policy and is also absent in most scenario-building models. This is in contrast with studies exploring the importance of the combined BGC and BGP effect for local and regional climate for two decades [10–13], but also identified that in response to historical land-cover changes these two types of effects have had impacts of a similar magnitude on global mean temperature [14, 15]. Neglecting BGP effects risks underestimating the benefit of A/R in regions where local cooling is enhanced and, at the worst, could even lead to the proposal of measures counterproductive to mitigation efforts where a warming BGP effect supersedes the cooling of the CO_2 uptake [12–14]. Past studies have assessed the heterogeneous climate benefit of BGP and BGC effects of A/R highlighting the best suitable areas for mitigation efforts [10–13]. However, this prioritization based on physical impacts alone ignores the direct competition of A/R with food and fiber production for both water and suitable land-cover, whereas socioeconomic trade-offs emerge between the need for land-based mitigation and the demand for agricultural products [16]. First attempts to include BGP effects in scenario building models started by considering the radiative forcing (RF) of the albedo effect. Two notable approaches pursued either adding the RF of albedo effects to its global RF limit of burning fossil fuels [17] or restricting A/R completely to regions where the warming albedo change would not overpower the cooling of captured carbon by A/R [16]. The impact of BGP effects other than the albedo change is yet to be explored. Therefore, in this study we investigate A/R scenarios that consider agricultural demands and climate impacts including the overlooked, non-radiative, local BGP effects (i.e. driven by changes in surface evapotranspiration and roughness from land-cover change) and contrast them with pathways that are solely based on the BGC effect. To this end, we inform the land-use model Model for Agricultural Production and their Impact on the Environment (MAgPIE) [18] about local BGP effects. The model optimizes the global cost of production to match the demand of agricultural commodities such as food, fiber, and wood. A greenhouse gas (GHG) price provides the incentive for A/R with the purpose of mitigating climate change. MAgPIE has previously been used in providing such GHG price driven A/R and low emission scenarios highlighted in IPCC reports [16, 19]. The newly introduced estimates of the BGP effect are based on observation-based datasets [20, 21] which provide the local surface warming or cooling response to A/R. This local cooling or warming response, aiding or opposing mitigation, is translated to a CO_2 equivalent. Multiplied by the GHG price the CO_2 equivalent of the local BGP effect forms an incentive/disincentive to the cost optimizing decision process of the model and is added to the established mitigation incentive of A/R. Thus, we can produce A/R patterns that are optimized for both BGC and local BGP effects as well as the socioeconomic trade-offs emerging from A/R based mitigation efforts.

2. Methods

We evaluate A/R patterns emerging from climate change mitigation policy measures but also considering their BGP effects, which may introduce local additional cooling or warming and thus aid or oppose the local benefits of mitigation. In previous studies, the modeled extent to which forests can contribute to mitigation has been driven by the GHG price which, multiplied by the potential carbon uptake of the future forest's biomass, produced a cost incentive for A/R. The extent of A/R that is viable as a mitigation option in a given region, thus, depends on the GHG price, the potential forest biomass, and the competition of other land use demands such as food and fiber production. To this decision process, we add the information of the local BGP effects of A/R. To this end, we translate the local BGP cooling or warming response of A/R into a CO_2 equivalent which then is added as an incentive or penalty to the GHG price driven establishment of forests. Hereafter, we first describe the MAgPIE model, the CO_2 equivalent metric, followed by the experiment setup, and the data we used, concluding with the uncertainties considered by our study.

2.1. The land-use model MAgPIE

MAgPIE is a global multi-regional land-use optimization model that incorporates spatially explicit information on biophysical constraints into an economic decision-making process [18]. It has previously been used in assessments of A/R and other land-based mitigation for IPCC assessments [8, 16, 19] and contributed to land-use scenario modeling within the framework of the shared socioeconomic pathways (SSPs) [22]. MAgPIE minimizes the global cost of production of agricultural goods to match the demand for food, feed, and fiber which are based on population growth and economic development. Means of production are constrained both by socio-economic factors like trade and policy, and biophysical factors like yields, carbon density and water availability. The latter are provided by the global hydrology and vegetation model "Lund-Potsdam-Jena managed Land" (LPJmL) [23]. Land-based mitigation like A/R is incentivized by the introduction of a GHG price which produces revenue from the removal of carbon dioxide from the atmosphere. The decision whether it is viable to establish a forest for mitigation purposes is based on a 50 years planning horizon. Within this time, it is assumed that the expected carbon accumulation as well as the rising GHG price are known. The future GHG price, however, is discounted according to the interest rate of 10% in low-income countries, 4% in high-income countries, and linearly interpolated in between in medium income countries. The expected carbon accumulation is based on sigmoidal growth curves for natural vegetation but can be changed to steeper curves of faster-growing plantation forests [24]. Only crop- and pastureland are viable options for mitigation driven A/R sites as their carbon density is lower than the one of the potential forest. Hence, higher food demand, i.e. by a larger population, limits the potential for A/R. The model can respond to this land scarcity by investing into technology that renders the cropland more productive, freeing up land for A/R, or by increasing trade with regions less affected by these limiting factors. Previous A/R studies conducted with MAgPIE yielded extensive A/R area in the range of ~2500 Mha [16, 19]. More recent versions of MAgPIE produce much more conservative A/R estimates due to two major changes: (a) A/R establishment was restricted to non-boreal or even just tropical climate zones to exclude A/R associated with considerable warming due to changing albedo. However, this change was reversed for this study to allow the assessment of the endogenous BGP effect in all climate zones. (b) The model can no longer directly invest in yield increasing technologies on grassland in the same way as it can on cropland. Most grassland areas are rangelands with natural vegetation. Thus, the same level of technical improvement as on heavily managed croplands is implausible. While crop yields can still be endogenously increased by investing in technological advancement, grassland yields only increase exogenously, and only by 25% of the croplands increase. This spillover effect approximates efficiency advancements possible on more heavily managed pasture. Compared to the previously used possibility to directly invest in yield improving tech on grassland, this change leads to lower grassland productivity reducing the area available to A/R. MAgPIE runs in timesteps of 5 years from 1995 until 2100 and can incorporate spatially explicit information at 0.5° resolution which get further aggregated into 200 clusters and 12 world regions.

2.2. Data and assumptions

Past studies compared the RF of BGP and BGC effects by studying earth system model experiments of global scale A/R or deforestation [12, 13]. However, a comparison between models showed a low agreement between the magnitude and even sign of the BGP effect produced by them [25]. Thus, we decided to use the observation-based datasets of the annual mean BGP surface temperature response to land-cover change produced by Bright *et al* [21] and Duveiller *et al* [20], which are respectively based on flux tower and satellite measurements. These datasets express the local surface temperature change produced by land cover changes instead of the more commonly used 2 m temperature. To be consistent, we therefore use the transient surface temperature response to produce the CO_2 equivalent. Due to the lack of literature on location-specific onset timing of the BGP effect after forest establishment we decided to implement a linear onset of the local temperature effect of A/R between the boundaries of previous research [26]. In this, any newly established A/R site starts to experience the BGP effect first after 10 years with a linear increase to the full BGP effect 30 years after the trees have been planted, reflecting the time needed for the local BGP parameters to change from a non-forested to a forested site.

2.3. The CO_2 equivalent metric

Previous studies that compared the BGC and BGP effect made use of the RF concept [12, 13]. This well-established approach encompasses one aspect of BGP effects, the albedo change, but fails to consider non-radiative mechanisms such as changes to evapotranspiration and surface roughness relevant to the local climate [9, 27]. To include these non-radiative effects, we use a CO_2 equivalent metric proposed by Windisch *et al* [28] that represents the CO_2 emissions/removals that would theoretically induce the same local surface warming/cooling as the BGP effect, based on the data and assumptions presented in the previous section. To derive the cumulative CO_2 emission that produces that temperature change at any given location we use the transient climate response to cumulative emissions (TCREs) framework. The TCRE relates the occurring temperature response to cumulative emissions after a doubling of CO_2 content based on a +1% CO_2 per year increase (reached after 70 years) [29]. In contrast to studies that consider a global TCRE [30], we consider a local TCRE, which allows us to relate the local BGP effect of forest cover change to the local surface temperature impact of accumulated CO_2. We use the output and experiment setup of 21 earth system models that participated in the Climate Model Intercomparison Project 5 [29]. The BGP carbon dioxide equivalent at each grid cell's longitude and latitude (i,j) ($CO_{2\,eq}^{BGP}(i,j)$) is computed by dividing the local BGP induced temperature change ($\Delta°C^{BGP}(i,j)$) by the local climate sensitivity ($TCRE(i,j)$) to yield the amount of cumulative carbon emissions/removals that produce a warming/cooling of the same extent (figure 1). In line with previous assessments [12, 13],

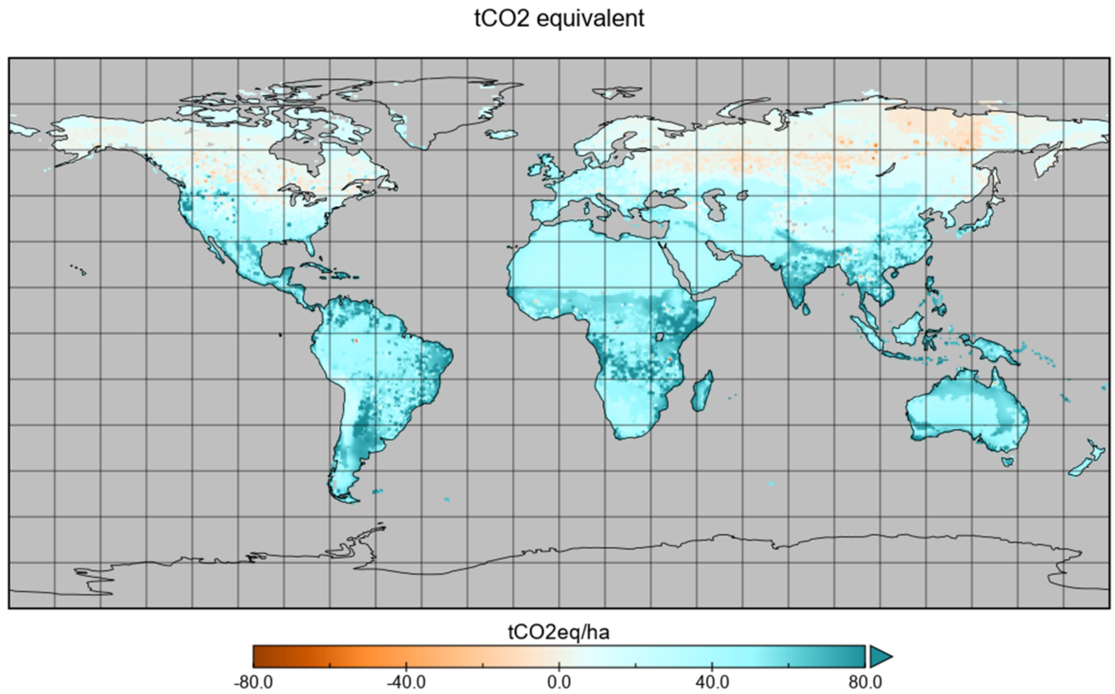

Figure 1. CO_2 equivalent of the observation based BGP effect of A/R produced by the transient ensemble mean response of earth system models to carbon emissions. Negative numbers indicate local BGP warming of A/R (e.g. boreal), positive numbers indicate cooling (e.g. tropics).

we further divide this CO_2 equivalent by the Earth's surface area (A_{SFC}) to obtain the local contribution as follows:

$$\mathrm{CO}_{2_{\mathrm{eq}}}^{\mathrm{BGP}}(i,j) = \frac{\Delta^{\circ}\mathrm{C}^{\mathrm{BGP}}(i,j)}{\mathrm{TCRE}(i,j)} \times \frac{1}{A_{\mathrm{SFC}}}.$$

I.e. a grid-cell might be cooled by the BGP effects of A/R by 1.1 °C ($\Delta^{\circ}\mathrm{C}^{\mathrm{BGP}}(i,j)$) and experiences a transient climate response ($\mathrm{TCRE}(i,j)$) of +2.3 °C to the doubling of the atmospheric carbon content (+4467 GtCO_2). The CO_2 equivalent of the local BGP effect corresponds in that case to 41.9 tCO_2 per ha after dividing by the Earth's surface area.

2.4. Experimental setup

We explore the impact of BGP effects on the attractiveness of A/R by endogenously considering them in the decision-making process. A/R is incentivized in MAgPIE by a fixed GHG price evolution (SI figure 7 available online at stacks.iop.org/ERL/17/024030/mmedia). In the control simulation this price only drives the benefit of storing carbon in the forest's biomass. We compare this to the experiment in which the GHG price additionally adds an incentive or penalty from the CO_2 equivalent of the BGP effects of A/R (see above). We choose to investigate the competition of A/R to other land-use demands such as food and fiber production in an intermediate socio economic pathway [22] (SSP2) in our main assessment but provide figures also for two pathways with lowered (SSP1) and higher challenges to mitigation (SSP3) in the supplementary material. Within the three SSPs, population growth and livestock share in diets are decisive parameters for land availability to A/R as they drive the extent of land occupied by pasture and crops. The explored range of population growth, diet, and resulting demand between SSPs is displayed in supplementary figures 8–10. In addition to the scenario assessment, we conduct a sensitivity analysis for two major assumptions. First, the assumption that the BGP induced local temperature change is most appropriately translated to its CO_2 equivalent by the local instead of the global temperature response to carbon emissions. The second is that A/R will be established by a native forest and not a more rapidly growing plantation. Results of the same control and experiment simulations described above are shown in the supplementary information for the applied global CO_2 equivalent translation (supplementary table 1) and the plantation driven A/R (supplementary table 2), with key findings highlighted in the sections 3 and 4.

2.5. Uncertainty

The uncertainties explored in this study are produced by (a) the conversion of BGP induced local temperature changes to their CO_2 equivalent and (b) the dependency of A/R scenarios on underlying socioeconomic conditions. To study the former, we use the spread of the 21 earth system models TCRE values to produce an upper and lower bound for the conversion of the BGP effect. A high/low climate sensitivity to cumulative carbon emissions (TCRE ensemble mean ± standard deviation) yields a lower/higher

CO_2 equivalent value since the same amount of warming induced by BGP effect would be achieved by less/more emitted CO_2. The latter, socioeconomic uncertainty, we explore by assessing A/R patterns with the same GHG price driver in three distinct socioeconomic conditions represented by the SSPs 1, 2, and 3. The two observation-based BGP estimates used in our study [20, 21] do not overlap in many grid cells due to their different methodology. Based on this, we decided not to produce an uncertainty range between the two datasets. We use the mean BGP value wherever they both produce an estimate at the same location. To study the uncertainties mentioned above we decided to keep the same evolution of the GHG price over time for all control and experiment runs regardless of SSP. A second area of uncertainty explored is the different socioeconomic challenges for mitigation motivated A/R between the intermediate challenges of SSP2 shown in the main manuscript and the lower/higher challenges of SSP1/3 highlighted in the supplementary material.

3. Results

Establishing forests warm or cool their local climate through BGP effects [9], depending on the region. In our experimental setup, the CO_2 equivalent of this induced temperature change multiplied by a GHG price becomes a penalty or added incentive to mitigation driven A/R efforts. Without BGP effects, A/R in MAgPIE is driven by the potential uptake of carbon in the vegetation's biomass. This already concentrates A/R to carbon dense, tropical forests and puts little incentive to higher latitude, boreal forests retaining less carbon in their biomass (figure 2(a)). In addition to the difference in carbon density low latitude, tropical forests excel at cooling their local environment due to their high evapotranspirative capacity while boreal ones can even induce a local warming particularly caused by albedo reduction in winter were forests shed the bright snow quickly compared to grass- or cropland where a closed snow cover is able to build [20, 21]. Thus, local BGP effects predominantly add more incentive and little if any penalty to a scenario where most A/R is established at low latitudes to begin with. In the SSP2 scenario the global GHG price driven A/R area established by the end of the century rises from 116 to 351 Mha storing an additional 18 gigatons of CO_2 ($GtCO_2$) if local BGP effects are endogenously considered (table 1). At the same driving GHG price, the global A/R area triples (+203.4%), adding 236 Mha of A/R (figure 3(a)).

The distinct increase of global A/R area induced by considering BGP effects is present in all explored socioeconomic scenarios. The relative area change is more pronounced if the control conditions (no BGP) show less initial A/R opportunity. While the 'middle of the road' SSP2 scenario roughly yields a tripling of A/R area in 2100, SSP1 conditions only yield a doubling (+91.4%), but the SSP3 setups sees more than a sevenfold (+660.4%) increase (table 1). Notably, the cumulative negative emissions are trailing behind the area gain as newly established A/R sites have yet to achieve their full mitigation potential. The performed sensitivity analysis only shows a minor difference between the two CO_2 equivalent approaches with −11.4% less additional A/R established between the results with and without BGP effects in SSP2 and −2.5%/−21.0% in SSP 1/3 (supplementary table 1). However, introducing more rapidly growing plantations increases the establishment of A/R under control conditions (no BGP) markedly adding +187.1% A/R area to the SSP2 control run without BGP effects and +58.4%/+558.5% to SSP 1/3. The higher initial A/R area induces the same effect of reducing the relative impact of BGP effects already observed between SSPs (supplementary table 2).

In line with the areas of most pronounced BGP induced cooling three quarters (76.0%, +179 Mha) of the additionally forested area is established in tropical climates (figure 2(b)). The remaining quarter is split to temperate (+29 Mha, 12.5%) and boreal regions (+27 Mha, 11.5%). A more extensive boreal A/R effort stands in contrast with the predominant BGP warming signal in the observation-based data. However, while most boreal regions experience this warming penalty to A/R efforts a few areas, like northern China, also see a local cooling benefit. Three of the 12 world regions in MAgPIE (Latin America, other Asia, and sub Saharan Africa) are solely responsible for more than half (+129 Mha, 55.0%) of the increase in A/R area when accounting for local temperature changes induced by the BGP effects of A/R (figure 3(b)). Almost a third (32.7%) of the additional area is established early on by 2050. Other notable world regions that experience an increased A/R area at the same driving GHG price are China (+34 Mha, 14.4% of total), the USA (+24 Mha, 10.0%), and Europe (+18 Mha, 7.7%) (figure 3(b)).

This focusing of the global A/R area to tropical regions is a product of the combined favorable conditions of both the BGC and BGP effect of establishing forests. The high potential carbon uptake of carbon dense tropical forests and their strong local cooling via BGP effects make the tropics the most area efficient A/R option in our setup. Thus, the GHG price driven A/R in MAgPIE predominantly establishes mitigation incentivized forests in the tropics. However, this unbalanced distribution of global A/R efforts concentrates the trade-offs of large-scale forest establishment to the tropics as well. The price for agricultural commodities markedly increases under the burden of the added forest area established as a result of the added incentive of local BGP effects. Latin America suffers from this trade-off more heavily than all other world regions, experiencing a marked hike in prices of agricultural commodities to 160% of its value in the no BGP scenario at the end of the

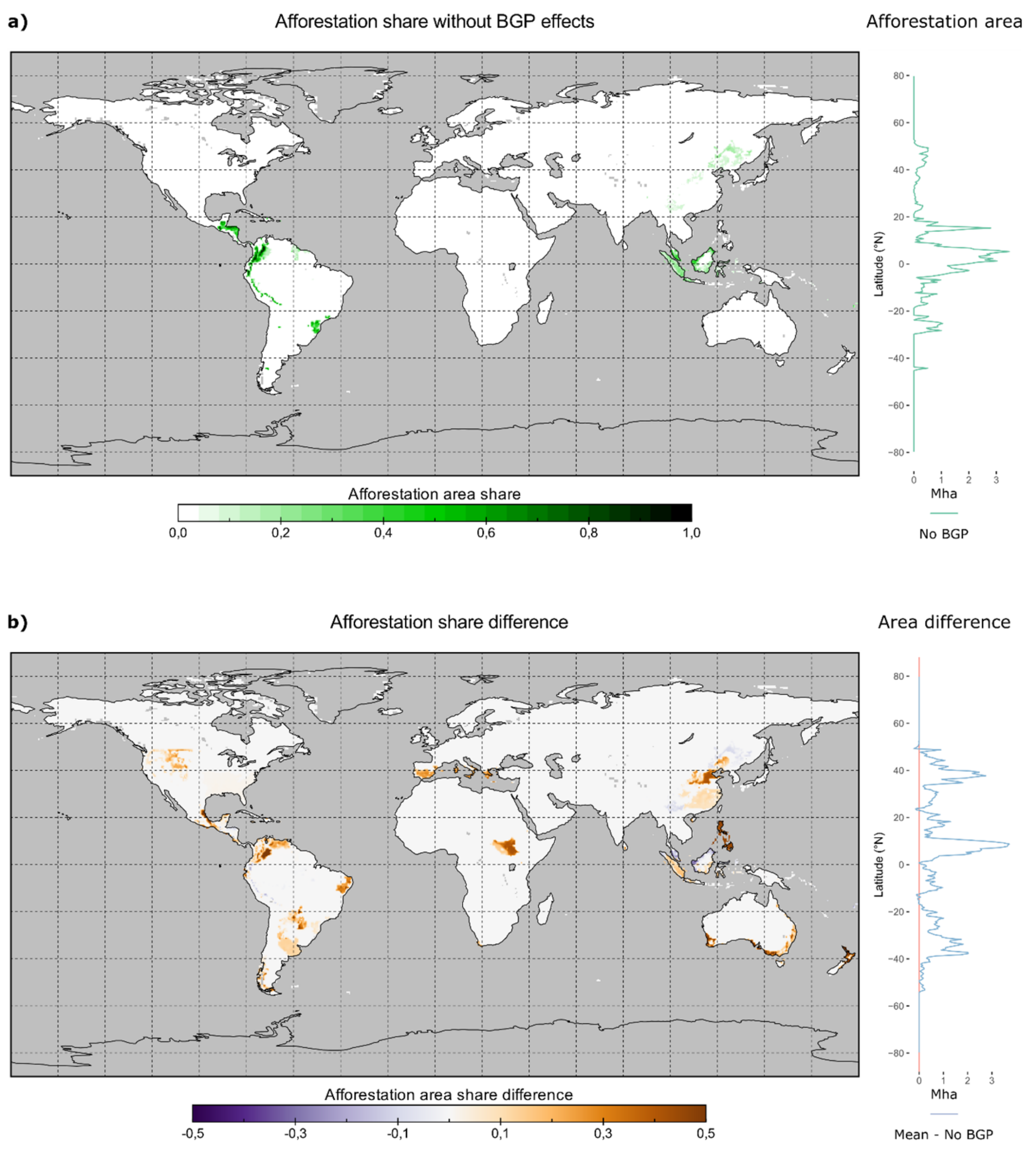

Figure 2. (a) Grid-cell A/R share in percent (1 = 100%) driven by the GHG price in an SSP2 scenario without BGP effects considered. Latitudinal sums of the established A/R area are shown in Mha on the right. (b) Difference in A/R share between the same SSP2 scenario and GHG price with BGP incentives and penalties established and the BGP effect turned off. Adding the base A/R distribution (a) to the difference (b) yields the A/R distribution realized by endogenously considering BGP effects. Latitudinal sums of this area difference in Mha are depicted on the right.

Table 1. Global area (top) and cumulative, negative emission (bottom) established by the GHG price-driven A/R in three SSPs in 2050 and 2100 expressed in million hectares (Mha) and gigatons CO_2 ($GtCO_2$). Columns correspond to the results without BGP effects considered (no BGP), the results established with the incentive of mean BGP effects (BGP), and the upper and lower boundary produced by the BGPs uncertainty (bound).

	SSP1			SSP2			SSP3		
	No BGP	BGP	Bound	No BGP	BGP	Bound	No BGP	BGP	Bound
A/R 2050 in Mha	170	238	213 474	52	103	95 239	8	45	27 185
A/R 2100 in Mha	664	1271	1130 1485	116	351	235 545	53	403	150 553
CO_2 2050 in $GtCO_2$	−4	−8	−7 −16	−1	−3	−3 −10	<−1	−1	−1 −7
CO_2 2100 in $GtCO_2$	−88	−117	−111 −138	−23	−41	−34 −60	−10	−27	−19 −47

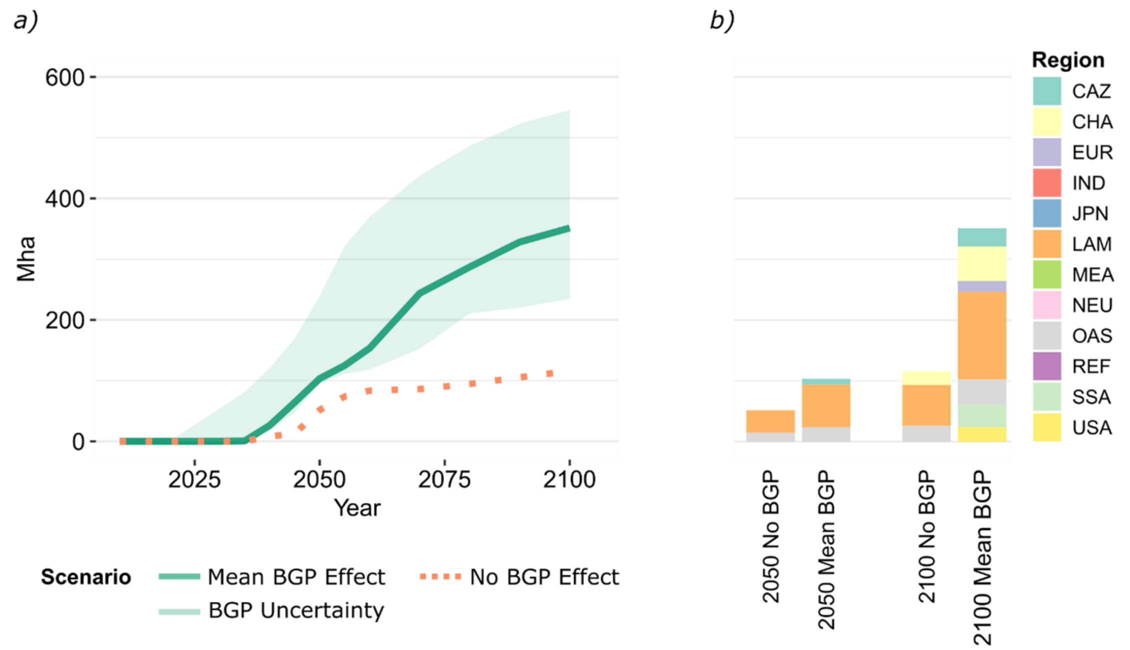

Figure 3. (a) Evolution of global A/R area driven by the same GHG price in the SSP2 scenario until the end of the century. The baseline established A/R area with no BGP effects considered is shown in orange dots. Dark green depicts the area with mean BGP effects endogenously considered which is also the basis for figures 2(b) and 4. The spread in A/R area produced by the uncertainty in translating the BGP effect into its CO_2 equivalent is highlighted in the light green envelope. (b) A/R area divided by contributions of world regions in 2050 and 2100 without BGP effects considered on the left versus mean BGP effects considered on the right. (Region abbreviations: Canada, Australia and New Zealand: CAZ; China: CHA; European Union: EUR; India: IND; Japan: JPN; Latin America: LAM; Middle East and North Africa: MEA; non-EU member states: NEU; other Asia: OAS; reforming countries: REF; sub-Saharan Africa: SSA; United States: USA).

century (figure 4). Other world regions that accommodate tropical climates are not as strongly affected by the land scarcity driven price hike of agricultural commodities under the socioeconomic conditions of the SSP2 scenario. In sub Saharan Africa and other Asia the price index is only marginally increased to 106.5% and 109.2% of its value when BGP effects are considered.

4. Discussion

Accounting for local BGP effects predominantly encourages the establishment of more forests in low latitude, tropical areas where both their carbon uptake and local cooling potential is high. An increased focus on tropical A/R to fulfill the land-based mitigation needs of the world would, however, shift the issues of competing land demand of A/R with food production to these world regions. Curbing this trade-off between mitigation by A/R and the price for other agricultural goods could be achieved by setting a limit to the established A/R restricting their mitigation benefit in turn. However, existing assessments that provide an upper boundary usually do so for a global or inter-regional limit which will fail to prohibit regional trade-offs as found in Latin America in this study [31]. A reduced livestock share in human diets, the intensification of free trade, and the closing of yield gaps also has the potential to mitigate trade-offs between A/R and the price of agricultural production without reducing the amount of carbon removed from the atmosphere [16, 32–34]. In contrast to tropical sites, where more A/R is encouraged, considering local BGP effects at high latitude boreal areas theoretically has the potential to prohibit counterproductive A/R measures. However, this was not observed as no A/R was established in boreal areas by MAgPIE under the tested conditions in SSP2. Other modeling efforts and studies that neglect BGP effects still commonly rely on boreal A/R to achieve mitigation goals risking warming BGP effects [35]. This risk could be mitigated by introducing the penalty to local warming introduced here.

The realized A/R area and carbon dioxide removal (CDR) potential under SSP2 conditions in this study is considerably lower than the maximum potential found by ‘bottom-up’ studies assessing the limits of land-based mitigation attainable with current knowledge and technology [35–37]. Based on this maximum potential a cost-effective estimate is often deduced. Limiting the feasible mitigation below a certain cost threshold (e.g. \$100 per tCO_2) [36, 37]. However, the economic potential studied ‘top-down’ with integrated assessment models (IAMs), as is done here, commonly is even lower than the feasible, cost-effective limit as shown by Roe *et al* [37]. Based on an extensive literature review and 131 scenarios of six IAMs, Roe *et al* [37] found a median A/R CDR rate of 475 $MtCO_2\ yr^{-1}$ (min./max. 27/4′136 $MtCO_2\ yr^{-1}$) in 2050 in the six

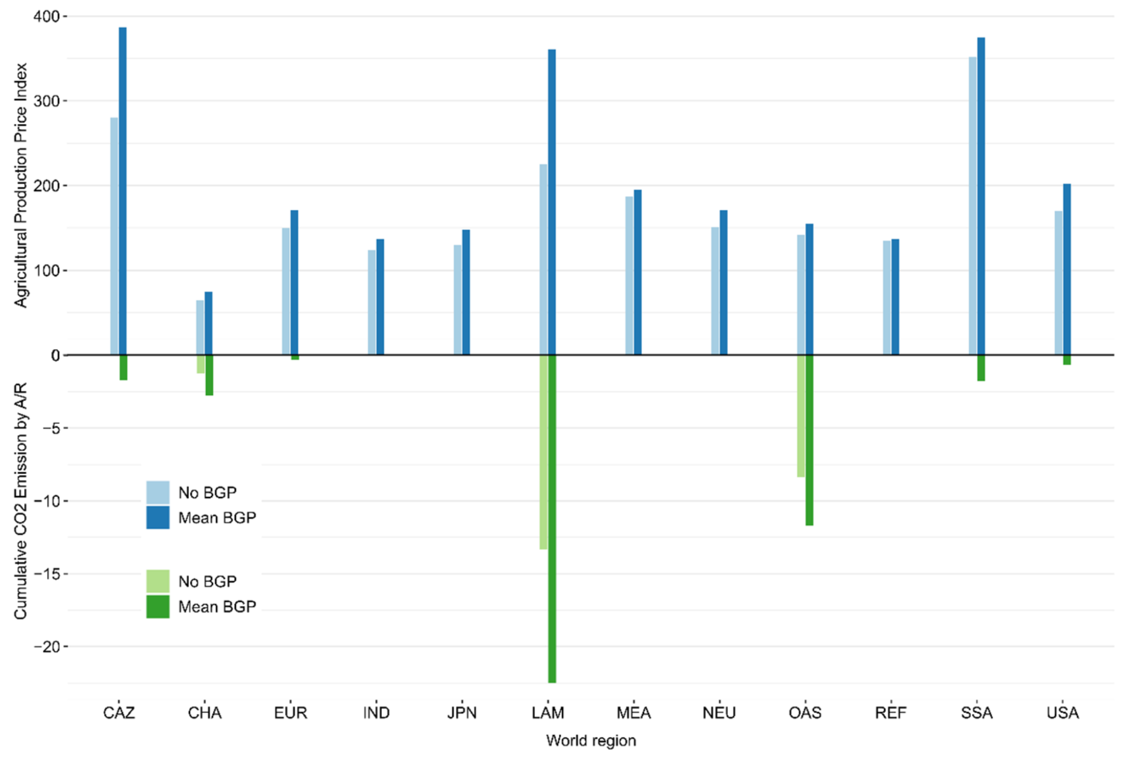

Figure 4. Agricultural commodity price index versus the cumulative negative CO_2 emissions induced by A/R by world regions at the end of the century. The price index tracks the price of agricultural commodities relative to its value in 2010 which is set to 100. Light blue/green depicts the SSP2 scenario that disregards BGP effects. Dark blue/green shows the same SSP2 scenario with BGP effects endogenously considered. (Region abbreviations: Canada, Australia and New Zealand: CAZ; China: CHA; European Union: EUR; India: IND; Japan: JPN; Latin America: LAM; Middle East and North Africa: MEA; non-EU member states: NEU; other Asia: OAS; reforming countries: REF; sub-Saharan Africa: SSA; United States: USA).

IAMs. In comparison, the cost-effective ‘bottom-up’ literature is higher averaging 1′208 $MtCO_2$ yr^{-1} (min./max. 891/1′526 $MtCO_2$ yr^{-1}) with the maximum potential studies reaching an average rate of CDR in 2050 of 8′472 $MtCO_2$ yr^{-1} (min./max. 5′513/11′431 $MtCO_2$ yr^{-1}). The A/R CDR rate of the scenarios presented here lie well within the range of scenarios produced by other IAMs albeit on the lower end of the 131 assessed scenarios in Roe *et al* [37]. Without the introduced BGP effects A/R in MAgPIE yields 159 $MtCO_2$ yr^{-1} in 2050 in the SSP2 scenario and 40/479 $MtCO_2$ yr^{-1} in SSP 3 and 1 respectively. Incentivized by BGP effects, MAgPIE’s estimates are considerably higher but still well within the previously explored limits. The scenario with mean BGP effects in SSP2 conditions reaching a CDR rate of 327 $MtCO_2$ yr^{-1} and 133/774 $MtCO_2$ yr^{-1} in SSP 3 and 1. Comparable to yearly mitigation rates, the economically viable A/R area varies considerably between models, their specific implementation of A/R and competing land-uses, socioeconomic boundary conditions, and level of carbon price incentive. Again, the combination of underlying assumptions made here result in a proposed A/R extent at the conservative end of existing analyses. Previous studies range between 231 [38] and 2800 Mha [19] of A/R at the end of the century compared to the 116 and 351 Mha resulting in scenarios produced here under SSP 2 conditions without and with BGP incentives implemented.

The CO_2 equivalent of the local BGP effect is calculated by the local as opposed to the global temperature response to cumulative emissions. This aims at reflecting the local relief or further harm caused by the local cooling or warming induced by BGP effects of A/R as compared to the temperature response to carbon removal or emission produced by BGC effects. A CO_2 equivalent metric using the global temperature response to cumulative emissions could also be applicable. Instead of the local relief or harm, it would reflect the local temperature change’s fraction of the global mean temperature change. Using the global instead of the local value to form the CO_2 equivalent would increase/decrease the BGP incentive or penalty in areas that experience a stronger-/weaker local response to cumulative emissions than the global mean response since more/less CO_2 is necessary to produce the same response by switching to the global value. Thus, areas at high latitudes experiencing a strong local response to emissions would see their BGP CO_2 equivalent increased while tropical areas with a predominantly weak local response would see a lower benefit from BGP effects if the alternative CO_2 equivalent would be used. However, the resulting A/R area is projected to be only slightly different if the BGP effect is translated by the local

TCRE compared to the global TCRE. In SSP2 conditions, the A/R area in 2100 incentivized by the BGP effect translated with the global TCRE is 11% smaller than in the locally translated scenario (SI table 1). This minor difference is to be expected as the surface temperature response to cumulative emissions strongly deviates from the global mean only at very high latitudes due to the polar amplification effect [28].

The rate of carbon uptake by A/R is determined by the steepness and shape of growth curves. With future value being discounted, faster-growing plantations are of higher value to an economic decision-maker than native forests that accumulate carbon more slowly [24]. Thus, using plantations instead of native forests can increase GHG price motivated A/R area. The difference in A/R area produced between scenarios with plantations and native forests is of similar magnitude as the BGP effect explored here (SI table 2). However, plantations are associated with reducing biodiversity while native forests can aid the loss of species [39, 40].

4.1. Limitations

Not only A/R but all land-cover changes modulate the energy flux at the land surface. In this study we focus on A/R as an important mitigation tool only. BGP induced penalties or benefits were not assigned to any other land-use decisions like food production. We argue that this reflects a likely scenario of a GHG price established in the agricultural sector were only mitigation motived land-use, but not food production, is driven by the GHG price. Using observation-based assessments of the local BGP effect has the advantage of avoiding the large disagreement between models highlighted by previous studies [41]. They are limited, however, to the current climatic conditions under which the observations were made. Thus, we likely overestimate the penalty induced by high latitude A/R in a future where we fail to address rising temperatures since the annual mean warming BGP effect of A/R is heavily influenced by the winter snowcover. A decrease in precipitation, as predicted for the Amazon in a warming climate, might also limit the cooling evapotranspirative effect in the South American tropics. However, tropical forests in Africa and Southeast Asia might even increase their cooling effect due to climate change [42, 43]. The more we limit future warming, the less pronounced this issue will be. Observation-based data on surface effects that solely rely on remote sensing is biased towards days without overcast conditions. We aim to alleviate this limitation by pairing the remote sensing study of Duveiller *et al* [20] with the assessment of Bright *et al* [21]. The latter includes station data which does not suffer from the described overcast bias. Further, non-local BGP effects are not considered although they have been shown to impact global mean temperature by at least the same magnitude, and potentially by the opposite sign, as the local effects considered in this study quantified by the observation-based datasets [44, 45]. This calls for a consideration of these non-local BGP effects in future, more comprehensive assessments of the overall climate impact of land-based mitigation. However, the limited understanding and availability of quantified estimates of these effects have so far prevented this from happening. Further, the lack of forest-specific evaluations of the onset of BGP effects after planting new forests holds the potential to substantially alter the incentive or penalty of BGP effects in models that consider the discounting of future value. The use of carbon growth curves of forests might be an adequate proxy for the BGP effect's progression over time. However, the relation between the establishment of BGP effects and carbon accumulation has yet to be quantified. If a connection is found in upcoming assessments it would likely heighten the benefit of fast growing, tropical forests since the value of the BGP cooling benefits could be expected earlier and, therefore, would experience less discounting.

Including BGP effects in scenarios and policy recommendations has the potential to end the proposal of forest-based mitigation where their establishment is counterproductive to their goal of cooling climate. At the same time, BGP effects exacerbate A/R trade-offs by concentrating land-use competition with food production to a much narrower area. Thus, including BGP effects increases the necessity to exercise greater care in proposing A/R efforts that do not come at the cost of local livelihood.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.5902955 [46].

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Code availability

Documentation of the model can be found at https://rse.pik-potsdam.de/doc/magpie/4.3.1/. The model's source code is openly available at https://github.com/magpiemodel/magpie with the specific model version used here at https://github.com/magpiemodel/magpie/tree/v4.3.1-BGP. The figures were created with ggplot and Panoply 4.10.11.

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