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LETTER

Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects

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Abstract

Ambitious climate targets, such as the 2 °C target, are likely to require the removal of carbon dioxide from the atmosphere. Afforestation is one such mitigation option but could, through the competition for land, also lead to food prices hikes. In addition, afforestation often decreases land-surface albedo and the amount of short-wave radiation reflected back to space, which results in a warming effect. In particular in the boreal zone, such biophysical warming effects following from afforestation are estimated to offset the cooling effect from carbon sequestration. We assessed the food price response of afforestation, and considered the albedo effect with scenarios in which afforestation was restricted to certain latitudinal zones. In our study, afforestation was incentivized by a globally uniform reward for carbon uptake in the terrestrial biosphere. This resulted in large-scale afforestation (2580 Mha globally) and substantial carbon sequestration (860 $GtCO_2$) up to the end of the century. However, it was also associated with an increase in food prices of about 80% by 2050 and a more than fourfold increase by 2100. When afforestation was restricted to the tropics the food price response was substantially reduced, while still almost 60% cumulative carbon sequestration was achieved. In the medium term, the increase in prices was then lower than the increase in income underlying our scenario projections. Moreover, our results indicate that more liberalised trade in agricultural commodities could buffer the food price increases following from afforestation in tropical regions.

Introduction

To achieve ambitious climate targets, such as limiting global mean temperature increase to below 2 °C compared to preindustrial levels, a strong decline in global greenhouse gas (GHG) emissions is urgently needed (Clarke *et al* 2014). Yet simply reducing GHG emissions might not be sufficient, or might only be achievable at high cost, so that carbon dioxide removal from the atmosphere (CDR) could become necessary in the second half of the century. Accordingly, most scenarios of the fifth assessment report of the IPCC (AR5) that are consistent with the 2 °C target include negative net CO_2 emissions (Clarke *et al* 2014, Fuss *et al* 2014). This is also acknowledged in the recent Paris Agreement of the UNFCCC, in which parties agreed to aim for a balance between anthropogenic emissions and sinks of GHGs in the second half of the century (UNFCCC 2015). Land-based mitigation strategies such as afforestation and avoided deforestation could make important contributions to achieving this target (Smith *et al* 2014).

Afforestation offers a high carbon sequestration potential at moderate cost, and could therefore become an alternative to or could complement other mitigation options. Cost estimates for afforestation are lower than for other carbon removal technologies such as bioenergy with carbon capture and storage (BECCS) and by an order of magnitude lower than for direct air capture (Smith *et al* 2015). Strengers *et al* (2008) calculated supply curves of afforestation on abandoned agricultural land and found that in 2075 more than 50% of the overall potential could be supplied at costs of less than 200 $/tC, which is relatively cheap compared to other mitigation options. Edmonds *et al* (2013) showed that a 2 °C warming at the end of the century would be possible without BECCS, but would require substantial carbon sequestration through afforestation, especially if mitigation action is delayed in some countries. Calvin *et al* (2014) illustrated that afforestation is an economically attractive option. When in their study a carbon tax consistent with limiting radiative forcing to 3.7 W m^{-2} was applied to the energy and land-use system, global forest area increased by about 20%. Humpenöder *et al* (2014) found that a reward for terrestrial carbon uptake could provide an incentive for large-scale afforestation, resulting in cumulative removal of more than 700 Gt CO_2 by 2095. With such a huge potential, afforestation could play a considerable part in climate change mitigation efforts.

On the downside, large-scale afforestation might lead to a considerable increase in food prices through increasing competition for land between forest and agricultural production. Similar concerns have been raised in the past with regard to first-generation biofuel production, but the demand for biofuel was only one factor of many that contributed to food price hikes in recent years and its contribution was estimated to be rather modest (Mueller *et al* 2011, Persson 2015). Similarly, a model intercomparison study showed that second-generation bioenergy production consistent with the 2 °C target could result in rather moderate food price increases up to 2050 if the land available for the expansion of agriculture were not restricted and if necessary investments into technology and development (R&D) were anticipated (Lotze-Campen *et al* 2014). Afforestation, however, may need substantially more area to achieve a similar level of carbon dioxide removal to BECCS (Humpenöder *et al* 2014), and could therefore have a much stronger influence on land-use competition. Bioenergy crops are harvested regularly, while once established, forests need to be maintained also under declining carbon accumulation rates if the carbon is to remain stored. Wise *et al* (2009) found that a carbon tax on terrestrial and industrial emissions could lead to an expansion of managed forests but also to a more than doubling of corn prices. In a study by Reilly *et al* (2012) a price on land carbon emissions created an incentive to reforest but also increased food prices. Calvin *et al* (2014) assessed the effect of afforestation with the integrated assessment model GCAM and found that wheat prices increased to 320% in 2095 compared to 2005 values.

The effectiveness of afforestation for climate mitigation differs depending on the location, making its application unfavourable in some regions. This is because establishing forests leads to two effects that often have an opposing influence on the average global temperature. On the one hand, while growing, trees take up carbon from the atmosphere and store it in their biomass (biogeochemical effect). On the other hand, changing land-cover to trees also affects the amount of short-wave radiation reflected back to space (biogeophysical effect), directly by surface albedo and indirectly by the contribution to cloud formation. This biogeophysical effect varies as a function of latitude (Bonan 2008). Several studies with earth system models have shown that an expansion of forest in the tropics results in cooling, while afforestation in the boreal zone might have only a limited effect or might even result in global warming (Bala *et al* 2007, Bathiany *et al* 2010, Arora and Montenegro 2011). Bright (2015) and Bright *et al* (2015) provide a good overview over the biogeochemical and biophysical processes that affect global and local temperatures as a consequence of land-cover and management change.

In the study presented here, we assessed global and regional food price impacts of large-scale afforestation with the Model of Agricultural Production and its Impacts on the Environment (MAgPIE). Earlier studies, using similar methods, have assessed bioenergy potentials (van Vuuren *et al* 2009, Erb *et al* 2012), requirements for and consequences of forest and biodiversity protection (Kraxner *et al* 2013, Overmars *et al* 2014, Erb *et al* 2016) or estimated climate change impacts on food prices (Delincé *et al* 2015). Five scenarios were analysed, one in which a CO_2 price on land-use-change emissions avoids deforestation and three where the CO_2 price created an additional incentive for afforestation. In these cases afforestation was either unrestricted, prevented in the boreal zone, or limited to the tropical zone. These scenarios were compared to a business-as-usual case without emission pricing. As afforestation was expected to increase food prices, we furthermore assessed whether more liberalised trade conditions could have an alleviating effect on food prices.

Methods

The land-use model MAgPIE

Future land-use, carbon sequestration and food price development as affected by afforestation were modelled with the partial equilibrium model MAgPIE (Lotze-Campen *et al* 2008, Humpenöder *et al* 2014, 2015, Popp *et al* 2014). MAgPIE is an agro-economic land-use model that minimises the global costs of agricultural production for a given agricultural demand under a set of economic and biophysical constraints. By this it computes optimal, spatially explicit future land-use patterns in five-year time steps.

Agricultural demand in the model is based on projections of future population and gross domestic product (GDP) of the SSP2 scenario (KC and Lutz 2014, Dellink *et al* 2015, O'Neill *et al* 2015). This scenario assumes that global population peaks in 2070 at 9.4 billion people, while per capita GDP continues to increase until 2100. Future demand for calories and livestock share in consumption are derived through a regression model that has been estimated with historical data for calories consumed and GDP development (Bodirsky *et al* 2015) (see also figures S2 and S3). Feed demand for livestock production results from animal-specific feed baskets (Weindl *et al* 2010, 2015). Socio-economic parameters, such as the demand, are exogenously fed into the model at the level of ten geo-economic world regions.

The model considers the production of 17 different crop groups and 5 livestock commodities. Bioenergy production was not included in this study. Potential crop yields, carbon densities and water availabilities are derived by the Dynamic Global Vegetation Model LPJmL (Bondeau *et al* 2007, Fader *et al* 2010, Waha *et al* 2012, Müller and Robertson 2014) on a spatial resolution of 0.5°. For the starting year of the model (1995) crop yields were calibrated to match attained country yield levels and regional production areas reported by FAOSTAT. For an efficient, non-linear modelling under computational constraints, spatial input data were aggregated to 600 clusters with similar crop yields, hydrological conditions and market access (Dietrich *et al* 2013).

In the model there are several options to respond to future changes in demand or other pressures on the land-use system, such as afforestation. The land-use pattern can react flexibly so that one land-use class can be extended at the expense of others, e.g. cropland can be expanded onto former pasture areas, or afforestation might take place on present-day croplands. The model can also reallocate production to locations that are more productive, domestically within a region or via international trade. Another option implemented is the use of irrigation. Finally, agricultural production can be intensified by endogenous investment decisions in yield-increasing technological change.

Agricultural production and all options to increase production are associated with costs. Factor costs account for costs related to capital, labour and fertilizer use and were derived from the GTAP database (Narayanan and Walmsley 2008). The change from one land-use class to another is subject to regionally differing land conversion costs (Schmitz 2012). Yield increases induced by technological change are endogenous in MAgPIE and are connected to additional investment costs for Research & Development (R&D). These costs were derived through a regression between historical investments and observed yield increases (Dietrich *et al* 2014). An investment horizon of 30 years and a discount rate of 7% are assumed for all investment decisions. Starting from the present distribution of areas equipped for irrigation (Siebert *et al* 2007), the model can increase irrigated areas at investment costs for the creation of the infrastructure and costs for operation and maintenance (Bonsch *et al* 2016). The cost effectiveness of production is also influenced by intraregional transport costs which make production at locations far from markets more expensive.

Food commodities can be traded between the world regions. Two trade pools are implemented in the model. Within the first trade pool, trade flows are fixed to fulfil regional, historically observed self-sufficiency rates calculated from FAOSTAT (2010). For the following time steps, the influence of this first trade pool is reduced depending on the scenario, and food commodities are to a larger share traded according to regional comparative advantages (Schmitz *et al* 2012) (figure S4).

Afforestation and avoided deforestation are incentivized by a price on CO_2 emissions from the land system. While the CO_2 price renders deforestation and the conversion of pasture to cropland more costly, carbon dioxide removal through afforestation is rewarded and lowers the costs in the objective function of the model. Afforestation is implemented as induced regrowth of natural vegetation. Carbon accumulation in living biomass follows sigmoidal tree growth curves where the upper limit is defined by carbon densities from the LPJmL model. Soil and litter carbon densities are assumed to increase linearly over 20 years, starting from the weighted average carbon density of cropland and pasture (Humpenöder *et al* 2014, 2015). For this study we assumed a CO_2 price that starts at 30 US$ per tonne of CO_2 in 2020 and increases by 5% each year (similar to Calvin *et al* 2012 and Kriegler *et al* 2013).

Scenarios

Afforestation is considered to be most effective in the tropical zone because the combined effect of carbon sequestration and albedo change are assumed to lead to a net cooling, while for the boreal and temperate zones the effect is presumably much lower. To assess the food price effects of afforestation under differing levels of ability to decrease global temperatures, we considered three scenarios where afforestation was limited to certain latitudinal zones. Within these areas the decision to afforest was based on its cost-effectiveness under a CO_2 price on land-use emissions. The effect of albedo was not included directly in the model, but scenarios with different influence on albedo-induced radiative forcing were assessed. In the first scenario afforestation was not restricted at all (*unrestricted aff*), in the second not allowed in the boreal zone north of 50°N (*no boreal aff*), and finally it was limited to the tropical zone between 20°S and 20°N (*only tropical aff*). The definition of tropical and boreal zones thereby follows Bala *et al* (2007). These afforestation scenarios were compared to a scenario of *avoided deforestation*, where terrestrial CO_2 emissions were also priced but no afforestation was considered, and to a *business as usual* (*BAU*) case without any emissions pricing (see also table 1).

While limiting large-scale afforestation to the tropics seems plausible from a climate mitigation

Table 1. Scenario description and resulting afforested area, cumulative land-use emissions, food prices indices and technological change rates. Reference year for the figures is 2010.

Scenario	Afforestation	CO_2 price	Afforested area (Mha)		Cumulative emissions (Gt CO_2)		Food price index (2010 = 100)		Average annual yield-increasing technological change rate	
			2050	2100	2050	2100	2050	2100	2050	2100
BAU	No	No	0	0	88	91	103	92	0.76%	0.44%
Avoided defor	No	Yes	0	0	8	2	128	95	1.09%	0.61%
Unrestricted aff	Allowed globally	Yes	1614	2577	−356	−860	186	442	1.66%	1.34%
No boreal aff	Allowed <50°N	Yes	1351	2240	−330	−791	180	402	1.60%	1.29%
Only tropical aff	Allowed 20°S–20°N	Yes	921	1235	−266	−525	152	138	1.38%	0.81%

perspective, it could still result in severe food price hikes in tropical regions. Enhanced international trade of agricultural commodities could be one option to buffer these price increases in tropical regions. For the *only tropical aff* case we therefore assessed how more liberalised trade influenced food prices (*only tropical aff tradelib*). In this scenario, trade departed more quickly from historical agricultural trade patterns towards more international trade based on comparative advantages. While in our default setting the influence of historical trade patterns decreased by 0.5% per year, in this scenario it was reduced by 1% per year (see also figure S4).

For these scenarios we calculated Laspeyres food price indices that comprise vegetable and livestock products. The Laspeyres formula weights prices according to base year quantities and is also the common approach used, for instance, by The World Bank (2015) to calculate its consumer price index. Food prices derived from MAgPIE reflect the marginal costs of food production (shadow prices), i.e. the costs that would arise for the production of one additional commodity unit. They are formed as a consequence of altered demand and production costs and therefore show the relative long-term commodity price development. Food prices in the *BAU* scenario are driven by the increasing demand for food from a growing and wealthier population. In the *avoided deforestation* scenario food prices additionally reflect the pricing of land-use-change emissions, the thus reduced attractiveness to reduce the area of forest or convert pastures to cropland, and the increased need to invest into yield-increasing technology. Food prices in the afforestation scenarios are the result of all these factors and an additional reward on carbon uptake through afforestation which leads to decreasing agricultural areas.

Results

Land demand and required technological change

The growing demand for food (figure S2) leads to an expansion of croplands in the *BAU* scenario. Globally, cropland area increases by 360 million hectares (Mha) until 2100, leading to a reduction of the area of pasture by 275 Mha and of forests and other natural vegetation by about 85 Mha. The introduction of a price on CO_2 emissions from land-use change stops the net conversion of forest to agricultural areas on a global level. In the *avoided deforestation* scenario, cropland expands by 77 Mha, with most of the change happening in Africa (40 Mha) at the expense of pasture (17 Mha) and forest (13 Mha), while in Europe there is some regrowth of forests (14 Mha).

In the afforestation scenarios the CO_2 price provides an incentive for afforestation so that forest area increases substantially in all regions where this option was given considering the latitudinal restrictions. Under *unrestricted* afforestation, more than 2500 million ha are newly afforested globally between 2010 and 2100, which is equivalent to an increase of global forest area by more than 60%. The largest areas of afforestation in absolute terms are in Africa (630 Mha) and Latin America (600 Mha), but afforestation is also substantial in all other regions when compared to their total land areas (figure 1). While in most regions afforestation leads mainly to a reduction in pasture, in Europe and Pacific Asia more croplands are converted to grow forests.

The restriction to *no boreal* afforestation reduces the afforested area by about 13% globally, but hardly changes the amount of land conversion in tropical regions. In the *only tropical* afforestation scenario, in contrast, the area of forest establishment is cut by half (table 1). While it remains at comparable levels in the tropical regions Africa and Pacific Asia it is lower in Latin America (435 Mha), because areas in the south (>20°S) were not considered for afforestation (figure S9).

While in the *BAU* scenario investments into yield-increasing R&D are rather modest, the introduction of a price on CO_2 emissions prevents further agricultural expansion and necessitates higher yields in the *avoided deforestation* scenario. In the afforestation scenarios, pasture and cropland area decrease globally, which results in even more substantial yield increases needed to fulfil food demands (table 1). Throughout the afforestation scenarios, the highest rates of yield-increasing technological change are seen in 2020, when the

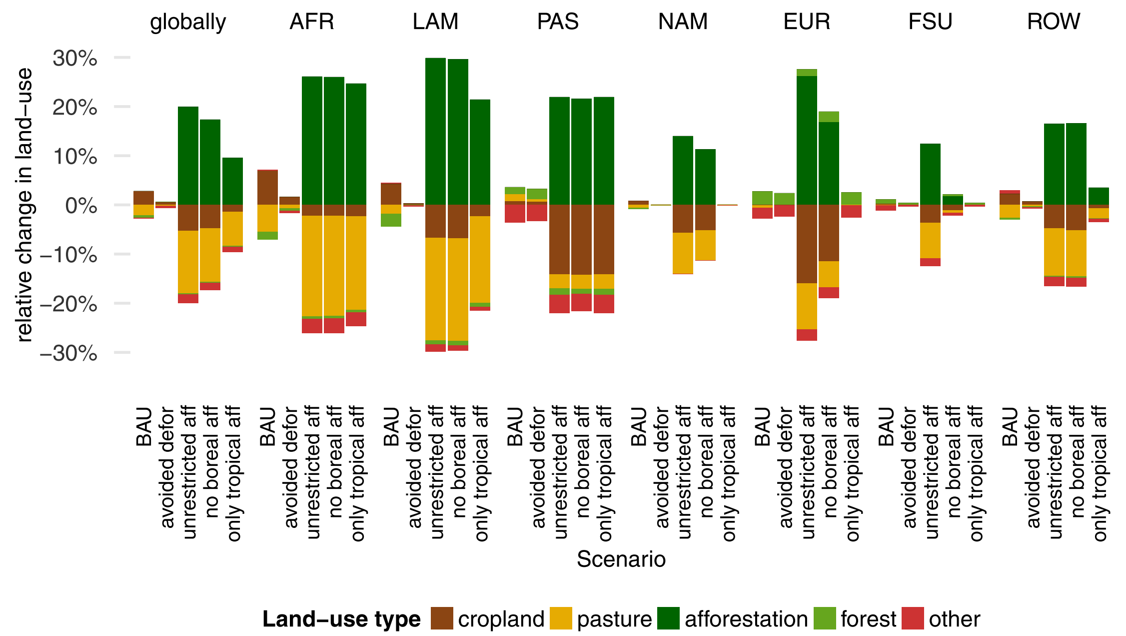

Figure 1. Change in land-use between 2010 and 2100 relative to total areas of the world or the regions (%). Positive values represent a net expansion of the land-use class, negative values a reduction. The land-use type 'other' refers to other natural vegetation not classified as forest. AFR: Sub-Saharan Africa, LAM: Latin America, PAS: Pacific Asia, NAM: North America, EUR: Europe, FSU: Former Soviet Union, ROW: Rest of the World (four remaining model regions aggregated).

pricing policy on land-use emissions is implemented. These rates are, especially in the tropical regions, substantially higher than those observed in the recent past (Fischer *et al* 2014). Until the end of the century average annual technological change rates range between 0.44% in *BAU* and 1.34% in the *unrestricted* afforestation scenario. Large regional differences are observed, with yields being about 5.5 times as high in Africa at the end of the century in the *unrestricted* case compared to 2010, but less than double within Europe in the same scenario (see figure S8 for regional yield development).

Carbon sequestration

Afforestation leads to considerable carbon sequestration. While in the *BAU* case more than 90 Gt of CO_2 are released as a result of land-use change, up to 860 Gt CO_2 are sequestered in the case of *unrestricted* afforestation between 2010 and 2100. The pricing of CO_2 emissions from land-use change in the *avoided deforestation* scenario results in no net release of carbon from the land-use system.

Restricting afforestation to non-boreal and tropical regions reduces the area and therefore the amount of carbon sequestered (figure 2(a)). For the *no boreal* scenario carbon removal is 8%, and the afforested area about 13% lower globally compared to the *unrestricted* scenario. In the *only tropical* afforestation scenario, terrestrial carbon uptake is about 40% lower than in the *unrestricted* scenario, while afforestation area is reduced by about 50%. The stronger reduction of afforestation area relative to CDR is as a result of higher carbon accumulation rates in temperate and tropical forests compared to boreal regions.

Food price effects

The increasing food demand from a growing population with an increased per capita demand for meat products does not lead to very significant changes in food prices. In the *BAU* scenario, without any pricing of emissions from the land-use system, food prices are projected to stay rather constant, or to decrease slightly to about 10% lower than in 2010 (figure 2(b)), caused by a decline in demand towards the end of the century (figure S2). The exponentially increasing CO_2 price on land-use-changes emission in the *avoided deforestation* scenario prevents the conversion of pasture and forest to cropland. Increasing land scarcity and the necessary investment costs for research and development increase prices at maximum by about 40% on global average in this case.

Afforestation leads to competition for land between carbon sequestration and agricultural production and results in substantial food price increases. Under *unrestricted* afforestation food prices increase by about 80% up to 2050 and are on average more than four times higher in 2100 than in 2010. Excluding boreal regions from afforestation reduces this effect only by about 9% in 2100. However, when afforestation is limited to the zone of highest cooling effectiveness—the tropics—the food price impact is significantly reduced. In the *only tropical* afforestation scenario, food prices peak in 2075 having increased by about 100%, followed by a decline in prices due to decreasing demand for food at times of high agricultural yields

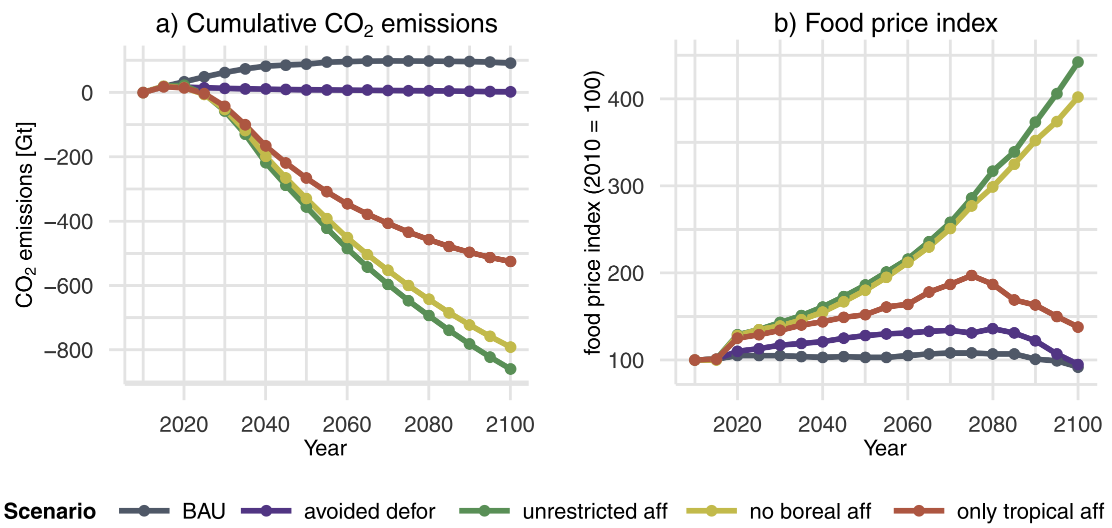

Figure 2. Cumulative emissions and food prices. (a) Cumulative CO_2 emissions from land-use change and afforestation from 2010 until 2100. (b) Laspeyres food price index for crop and livestock commodities (2010 = 100).

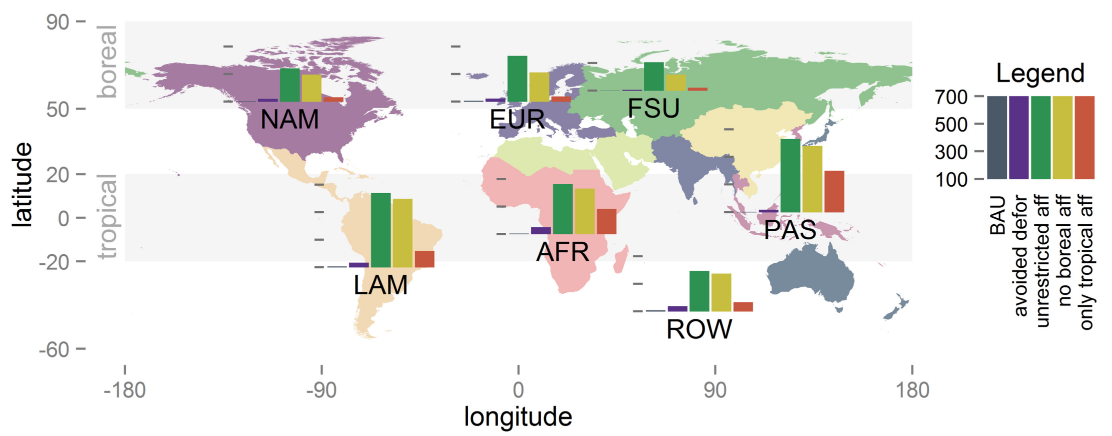

Figure 3. Regional food price indices at maximum over the course of the century (2010 = 100) for 6 out 10 modelled regions AFR: Sub-Saharan Africa, LAM: Latin America, PAS: Pacific Asia, NAM: North America, EUR: Europe, FSU: Former Soviet Union, ROW: Rest of the World (four remaining model regions aggregated).

and a slowdown of forest expansion. Especially in the *unrestricted* and *no boreal* scenarios, the additional land-use competition through afforestation influences prices much more strongly than the mere effect of emission pricing in the *avoided deforestation* scenario. Food prices are also sensitive to the CO_2 price. Lower CO_2 prices lead to lower carbon sequestration, but also reduce food prices (figure S9).

Food prices in different regions are affected differently by the modelled afforestation scenarios (figure 3). *Unrestricted* afforestation leads to the highest prices of all scenarios over the century within all regions, with the highest values occurring in Pacific Asia (PAS: 630) and Latin America (LAM: 640). In the Former Soviet Union (FSU) the increase is lowest, with prices three times higher in 2100.

Excluding the boreal zone from afforestation leads to lower food commodity prices than *unrestricted* afforestation, especially in regions that are partly in the boreal zone. In Europe (EUR) and FSU estimated food prices in 2100 are then about 30% lower. FSU turns into a net exporter of crops, EUR into a net exporter of livestock products towards the end of the century (figures S6 and S7), which also influences food prices in other regions. In Africa (AFR) and LAM, prices are 7% lower in the *no boreal* than in the *unrestricted* scenario in 2100, even though afforested area differs by less than 1% (see also figure 1).

Limiting afforestation to the tropical zone results in a food price index much closer to the BAU scenario, and much lower than for *unrestricted* and *no boreal* afforestation, but in tropical regions the price increases are still substantial. In Pacific Asia the food price index is highest in 2100 with a value of 400, while in Latin America the maximum index level of 219 is reached in 2070. The influence on temperate and boreal regions is much lower. In EUR, NAM and FSU the price indices are at maximum increased by 35% to

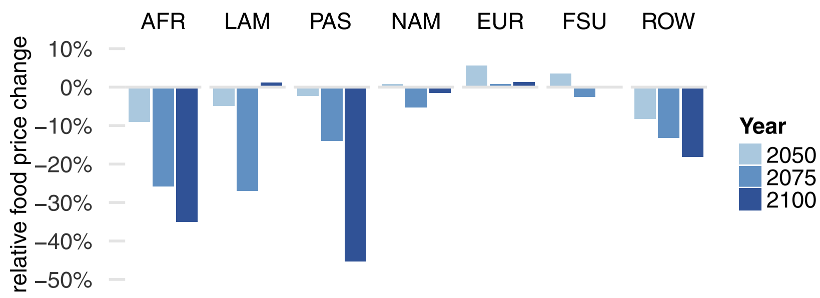

Figure 4. Influence of liberalised trade on regional food prices in 2050, 2075 and 2100. Comparison between the *only tropical aff* and the *only tropical aff tradelib* scenario. 2075 is the year in which food prices were highest globally.

40% compared to the BAU case. In this scenario, food price increases are in all regions lower than the assumed increase in GDP (figure S5).

The effect of global trade under tropical afforestation

More liberalised trade helps to buffer food price increases driven by tropical afforestation. We compared the food prices of the *only tropical* scenario to a scenario where the deviation from historical trade patterns was twice as fast (figure 4). In this *only tropical aff tradelib* scenario the overall, interregional trade volume increases faster (see also figures S6 and S7). Latin America turns from an exporter of food commodities into a net importer towards the end of the century. Africa further increases its imports of livestock products, which are mostly supplied by North America. In 2075, the year in which prices are highest globally, food prices are reduced by more than 25% in Latin America and Africa (figure 4). In Pacific Asia, where food prices are highest in 2100, the price index changes from 400 to 219. Subsequent price increases in Europe are negligible. While trade liberalisation has a strong influence on prices, it does not decrease afforested area (1275 Mha) or the sequestered amount of carbon (552 Gt).

Discussion

Afforestation impacts food prices

Our results show that large-scale afforestation can lead to significant carbon sequestration in the land-use sector, but can also lead to strongly rising food prices. In our study, these food price increases were the consequence of a large-scale transformation of the land-use sector, where food has to be produced on a much smaller overall agricultural area. In the scenario of *unrestricted* afforestation, cropland area is reduced by almost half to a global value of about 800 Mha in 2100, and pasture shrinks by more than 50% to about 1465 Mha, values that were last observed at around the year 1900 (Klein Goldewijk *et al* 2011). This decline in agricultural areas is enabled by significant investments into yield-increasing technological change and comes along with a pronounced increase in food prices. Avoided deforestation alone does not drastically spike food prices, which is in line with an earlier study by Schneider *et al* (2011). The finding that afforestation drives up food prices is also the result of a previous study by Calvin *et al* (2014), in which afforestation was also incentivized by a price on emissions from land-use, and resulted in increasing wheat prices. In contrast to this study, we report a combined food price index for meat and food-crop products for different afforestation scenarios. We also compare food prices under afforestation to a scenario where emissions from land use are priced, which leads to *avoided deforestation*. This comparison shows that most of the price increase can in fact be attributed to afforestation, while the emissions pricing alone is of lesser importance.

Limiting afforestation to the tropics—where it is most effective in decreasing global temperatures –substantially reduces the impact on food prices. Earlier studies with earth system models showed that afforestation in the tropics, through the combined effect of carbon sequestration and albedo change, leads to a net cooling, while planting trees in the boreal zone might even increase global temperatures (Bala *et al* 2007, Bathiany *et al* 2010, Arora and Montenegro 2011). While this simplified, latitudinal dependence seems to hold true in general, exceptions are possible under specific site conditions. Since historical boreal and tropical deforestation took place on the most productive lands with above-average carbon stocks and below-average snow cover, a reforestation of some boreal areas might also decrease global temperatures (Pongratz *et al* 2011). And an afforestation of tropical and subtropical desert areas could result in net warming because of the prevalence of the albedo effect (Keller *et al* 2014). Desert areas with high albedo, however, were not considered for afforestation in our study. Rather, afforestation was restricted to agricultural areas in certain latitudinal zones, excluding boreal and temperate zones where afforestation might not show a global cooling effect. Integrating the albedo-induced radiative forcing effect of afforestation directly in the model, as has been done by Jones *et al* (2015), should be considered for future model applications.

While limiting afforestation to the tropics reduced food prices globally, food price indices remained higher in tropical regions. These increased price levels in the tropics could be buffered by a more liberalised trade policy, with an ensuing shift of agricultural production to non-tropical regions. However, this interregional reallocation would also increase the import dependency of some tropical regions and might hamper the development of the agricultural sector within these regions.

Afforestation requires the reversal of deforestation and R&D spending trends

Before afforestation can be considered as a serious means to mitigate climate change, deforestation has to come to an end. In our study this happened as soon as there was a price on CO_2 emissions from deforestation. At the moment, however, no such policy is in place on a global level and much of the carbon stored in tropical forests is released into the atmosphere. Gross carbon emissions from tropical regions were estimated to be around 0.81 GtC yr^{-1} between 2000 and 2005 (Harris *et al* 2012), with yearly emissions of deforestation from the Amazon basin alone accounting for 0.18 GtC between 2000 and 2010 (Song *et al* 2015). The current trend is opposite to what we described in our *only tropical* afforestation scenario. Between 1993 and 2012 tropical forests lost aboveground biomass carbon (−0.21 GtC yr^{-1}), while boreal and temperate forests gained it by about the same amount (+0.18 GtC yr^{-1}) (Liu *et al* 2015). However, Brazil—the country with the greatest absolute forest area reduction—has recently reduced its deforestation curve through conservation policies and stricter law enforcement on the ground (Assunção *et al* 2015, Tollefson 2015, FAO 2015b). China has initiated a large afforestation programme, with plans to increase afforested area by 40 Mha by 2020, a measure which was found not only to sequester carbon but also to decrease local land-surface temperatures (Peng *et al* 2014). And in December 2015, ten African countries launched AFR100, and initiative to restore 100 Mha of degraded and deforested land by 2030—partly as a climate change mitigation measure (WRI 2015). These developments are just few of many that indicate that global afforestation efforts now have better prospects for success.

Continuous yield increases and substantial investment into yield-increasing R&D would be needed to fulfil the food demands of a growing population, especially when agriculture competes with afforestation. The high price on CO_2 emissions, and hence the strong incentive to free up agricultural land for afforestation, initiates continuous yield-increasing technological change in our study, with values well above those observed historically. In contrast to other partial equilibrium land-use models (e.g. GLOBIOM: Kraxner *et al* 2013, GCAM: Calvin *et al* 2014), technological change is endogenously derived within MAgPIE (Dietrich *et al* 2014, Von Lampe *et al* 2014), and yields tend to increase stronger in response to additional pressures on the land-use system (Lotze-Campen *et al* 2014, Nelson *et al* 2014, Delincé *et al* 2015). During recent decades, yields of main staple crops increased linearly at average rates of 1% (wheat, rice, soybean) and 1.5% (maize), while the relative annual rate of increase constantly dropped (Fischer *et al* 2014). Increased investment into R&D would be needed to make afforestation a realistic option, but when research spending increased in recent years this was largely driven by the development in single countries like China and India. Almost every third OECD country actually had a negative trend in public agricultural R&D spending. And in the developing world, especially in Sub-Saharan Africa, where in our afforestation scenarios yields more than tripled between 2010 and 2100, public spending on agricultural R&D amounted to only about 1.6 billion US$ or 5% of global agricultural R&D spending in 2008, and almost half the African countries had a negative trend in their budgets (Beintema *et al* 2012). This trend of low R&D spending would certainly have to turn around in order to achieve the yields projected in our model.

The yield increases triggered by afforestation could also alter agricultural N_2O and CH_4 emissions, a dynamic that was not in the focus of this study. Intensification could both increase or decrease N_2O emissions from soils, depending on whether intensification is reached through higher inputs (e.g. fertilizer) or better agronomic practices (Bodirsky and Müller 2014, Lassaletta *et al* 2014). CH_4 emissions from the livestock sector would likely be decreased by intensification due to a more efficient feed conversion (Herrero *et al* 2013).

Results set in context

The food-price increases presented in this study have to be seen in the context of a general increase in wealth. For this study we assumed the GDP development of the SSP2 scenario (Dellink *et al* 2015), which is steadily increasing for all model regions, and is also the basis for the increased per capita demand for food products. In most regions the rates of GDP increase are higher or in the same range as the price increases due to afforestation, so that share of expenditure for food would stay constant or decrease for a representative agent (see figure S5). Still, increases in wealth would not necessarily be distributed evenly among the population, so that the change in prices reported here could still have drastic impacts on the poorer parts of society. This is especially true for people whose share of expenditure on food is currently quite high, such as the poorest people in some African and Asian countries who currently expend above 70% of their available income on food (FAO 2015a).

A number of factors influence the formation of food prices, and our study focuses on the more long-term drivers. In the coming decades, a growing global population is expected to increase the demand for food, in particular for livestock products (Alexandratos and Bruinsma 2012, Bodirsky *et al* 2015). This, together with a likely elevated demand for bioenergy, will increase the total demand for agricultural products. These long-term trends are overlain by a number of more short-term factors affecting prices, such as weather variability, financial speculation or restrictive export policies in response to increasing prices (Mueller *et al* 2011). Lagi *et al* (2015), for instance, were able to replicate the FAO food price index between 2004 and 2012 with a dynamic model, where the underlying upward trend was due to an increasing demand for ethanol production, while the short-term peaks were caused by speculation. Our model is designed to capture the medium-term to long-term drivers of food price formation, and reveals the relative difference between afforestation scenarios and a world without forest-based climate mitigation. It does not consider specific policies and drivers on local or short time scale.

Food demand was provided exogenously to the model as a function of per capita income and population. Since price hikes in the afforestation scenarios were quite high with respect to the BAU case, it could be expected that the consumption of agricultural products declines, in spite of relatively low demand-to-price elasticises of food products, especially in high income countries (Hertel 2011, Muhammad *et al* 2011). Also for this reason, MAgPIE represented the upper range of food price estimates when climate change effects were assessed in a model inter-comparison (Nelson *et al* 2014). However, we also assumed that currently developing regions become relatively wealthy towards the end of the century when food prices are projected to be at the highest level, which would result in lower shares of income expenditure on food and low demand elasticities.

Afforestation at the scale as described in this study would imply macro-economic effects that should be subject to further research, for instance within a general equilibrium framework. The MAgPIE model is a partial equilibrium model of the agricultural sector, impacts of afforestation on other sectors of the economy such as labour, capital and carbon markets were therefore not part of this study. We would expect that increasing food prices also increase the income of net food sellers, and reduce the incomes of net buyers as non-food expenditures are reduced, which could in consequence change the demand for food (Dorward 2012). Afforestation might also create new jobs in the short term for the planting of trees, but these jobs would vanish once the forests are established. Rent-seeking behaviour and opportunities to invest in land under a policy rewarding carbon removal could substantially shift production input factors from other sectors. Furthermore, our analysis of trade was focused on the agricultural sector. For the *only tropical* afforestation scenario we assessed how trade liberalisation would influence regional food prices. We have, for instance, not considered how the consequential change in trade flows (e.g. increased imports of livestock products to Africa) would have to be compensated by trade flows in other sectors to avoid trade deficits, or how trade liberalisation would affect economies in general. Finally, the creation of an international market for carbon credits could create a substantial flow of money from CO_2-emitting countries to those actively sequestering carbon through afforestation. These revenues could be used to finance, among other things, the import of food.

Conclusions

In order to mitigate climate change, land-based carbon dioxide removal will likely have to play an important role. Afforestation has been identified as a comparatively low-cost option to sequester carbon, but side-effects of afforestation at large-scale were so far not much in the focus. Afforestation will, if it competes with food production for the same areas, lead to an increase in food prices. Moreover, as previous research has shown, afforestation in high latitudes will likely only have a small cooling effect on the global average temperature, or could even increase it, because of the counteracting albedo warming effect.

Our study confirms that afforestation offers a high potential for carbon dioxide removal, and more than 860 Gt of CO_2 are sequestered in our unrestricted afforestation scenario up to the end of the century. However, we also find that this afforestation leads to a more than fourfold increase in food prices by 2100. When afforestation is restricted to the tropics—and thus the albedo warming effect avoided—still substantial carbon sequestration can be achieved. This, at the same time, lowers global food prices substantially which nevertheless remain increased in tropical regions compared to a world without large-scale forest expansion. Our study suggests that a liberalisation of agricultural trade could further dampen the remaining price increases in tropical regions.

By sequestering carbon though afforestation, tropical regions would offer a valuable service for the benefit of the whole world. An international carbon market for carbon credits could be the source of monetary flows to those tropical countries undertaking afforestation and could compensate for some of the disadvantages coming along with it. Thoughtfully designed policies would have to avoid that established forests are cut down again and release the carbon stored. The raised money should also be used for investments into agricultural R&D, to achieve necessary rates of yield increase. And lastly, policies should be designed in a way which assures that not only landowner profit, but revenues are also distributed to those people affected most by the food price increases.

We conclude from our study that afforestation should not be seen as the silver bullet of climate change mitigation, but set in the right context and done at the right location it can well be a complement to other mitigation options.

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