2nd generation biofuels from short rotation plantations are less efficient in climate-change mitigation than reforestation within reasonable timeframes

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Abstract:

Second generation biofuels (2G biofuels) produced from lignocellulosic biomass are often considered as integral part of a future sustainable transport system. Provided that substantial areas of agricultural land can be diverted from food and feed production without impairing food security, energy plantations managed in short rotation appear as a promising option for supplying large amounts of biomass feedstock. However, instead of using agricultural land for energy plantations, it could also be reforested, thereby acting as a long-term carbon (C) sink that also results in climate benefits. This paper provides a systematic comparison of the long-term C benefits from 2G biofuels produced from plantation biomass with the C sink strength of natural succession on arable land (i.e. renaturation).

C benefits of the two options are calculated on a per-km^2 basis. The dynamics of C accumulation in natural vegetation as well as plantations (i.e. biomass yields) strongly depend on site-specific natural conditions. We apply a global perspective and assume that the considered area is distributed among ecological zones and climate zones exactly like actual global cropland areas. To this end, global raster data (5 arc minutes resolution) on cropland distribution, ecosystem and climate zones are merged, and representative C accumulation curves for renaturation in 11 world regions and on global scale are derived. Due to uncertainties with regard to biomass yields of energy plantations, harvest losses and future conversion efficiencies of 2G biofuel processes, a Monte Carlo simulation is carried out with these parameters being varied in ranges derived from literature data.

Results show that natural succession is highly likely to be superior (i.e. to result in higher C benefits) for timeframes up to 50 years. Hence, it takes more than 50 years of continuous land use as short rotation plantation and substitution of fossil fuels with 2G biofuels until this alternative results in higher cumulated C benefits than renaturation. This finding is robust to uncertainties related to yields and technological progress in 2G biofuel production. We conclude that allowing agricultural land to revert to its natural state must seriously be considered as low-cost climate mitigation strategy and alternative to biofuel production.

Keywords: second-generation biofuels, natural succession, reforestation, renaturation, climate mitigation, natural climate solutions, carbon sequestration, carbon stock change

1 Motivation and objective

Second generation biofuels (2G biofuels) produced from lignocellulosic biomass are often considered as integral part of a future sustainable transport system. Provided that substantial areas of agricultural land can be diverted from food and feed production without impairing food security, energy plantations managed in short rotation (plantations of willow, eucalyptus and other fast-growing tree species) appear as a promising option for supplying large amounts of biomass feedstock. In contrast to raising wood removals from forests, growing biomass specifically for energy does not interfere with forest carbon (C) stocks and can therefore be perceived to be truly C-neutral within short timeframes (i.e. the timespan between C accumulation in biomass and C release resulting from combustion). However, instead of using agricultural land for energy plantations, it could also be reforested (or allowed to regrow natural vegetation), thereby acting as a long-term C sink that also results in climate benefits.

A schematic illustration of the research topic is shown in Fig. 1: In the "bioenergy case" ("BE"), cropland is converted to energy plantations (short rotation coppice, "SRC"), which are harvested periodically to supply wood chips and the recovered biomass converted to 2G biofuels. Disregarding auxiliary energy consumption for biomass transport, processing etc., the total C emissions of this route correspond to the amount of C sequestered from the atmosphere during biomass growth. Hence, the bioenergy strategy lies in replacing a petroleum-based, net carbon-emitting transport system with one characterized by a closed carbon cycle. Reforestation (modelled as natural succession; "nSucc") follows a different strategy: To establish a net carbon sink that offsets the net emissions from fossil fuel combustion. The purpose of this work is to provide a systematic comparison of the C benefits of these two land-based C mitigation options.

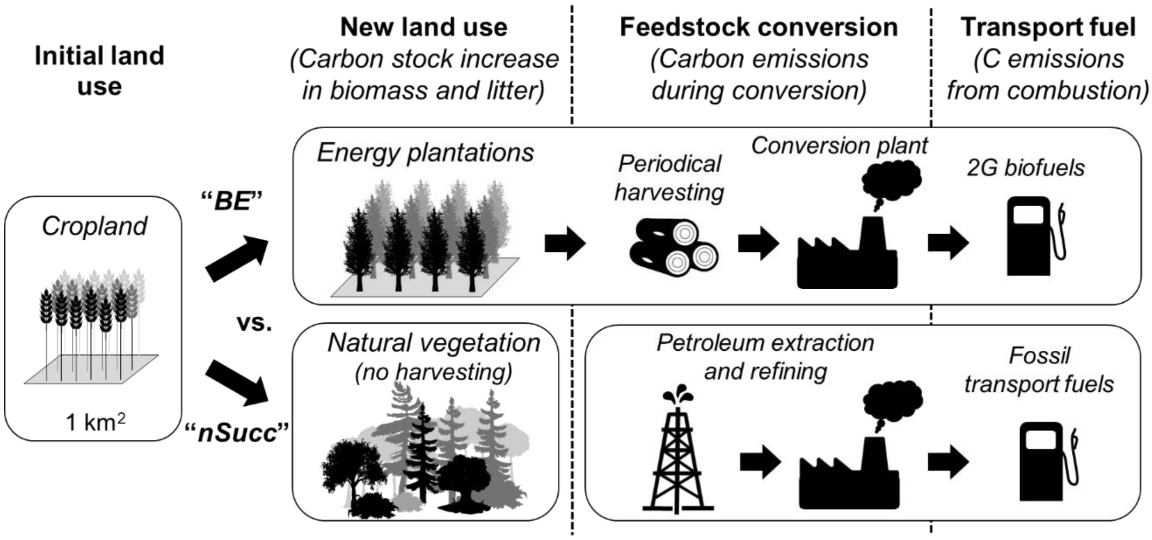

Figure 1. Schematic illustration of the research topic: Energy plantations are harvested periodically for biofuel production; alternatively, the same area is allowed to revert to its natural state and petroleum is used for transport fuel production

2 Objectives and scope

The core objective of this work is to quantify the C benefits of the two options (natural succession and 2G biofuels from energy plantations) and identify the superior option as well as the relevance of different influencing parameters. Particular focus is given to uncertainties regarding parameters such as timeframes, SRC yields and 2G biofuel conversion efficiencies. We apply a global perspective but also investigate differences between 11 world regions.

The following figure illustrates the fundamentals of the research topic: Fig. 2a) exemplarily shows the development of C stocks if one hectare of cropland is given over to reforestation. If we assume that this land-use change occurs after a final crop harvest, the initial C stock in year zero is essentially made up of soil organic carbon (SOC). Biomass growth (above- and belowground) in subsequent years follows a characteristic pattern that is characterized by relatively slow growth during the first years, followed by rapid and later on decreasing C accumulation. According to (IPCC, 2006a), soil and litter carbon stocks can be assumed to have reached a new equilibrium state after 20 years. The cumulative C benefits of nSucc correspond to the total difference in C stocks between the initial and the final year of the considered timeframe.

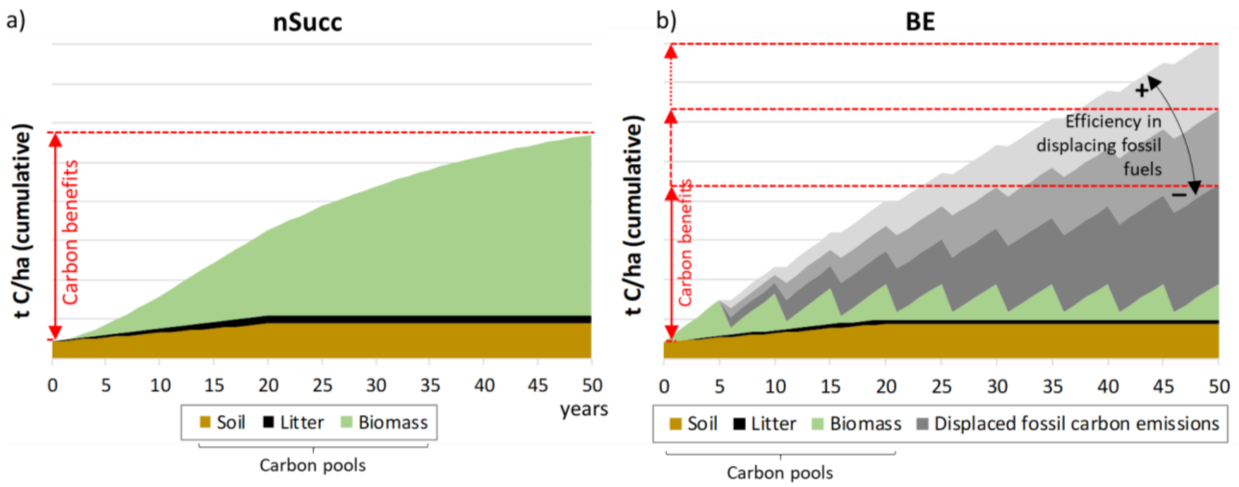

Figure 2. Schematic illustration of carbon stock changes and carbon benefits in the two alternative options natural succession ("nSucc") and plantation-based bioenergy ("BE"). Carbon benefits from displaced fossil fuels in the BE case strongly depend on the considered bioenergy pathway and the fossil-based counterpart. This is schematically illustrated with areas in different grey shades. Source: Own schematic illustration based on default data according to IPCC (2006a) and Winrock International (2014)

In contrast, the development of C stocks in energy plantations (Fig. 2b) is characterized by rapid initial growth, followed by a depletion of the aboveground biomass C stock after the rotation period. The harvested biomass is used to substitute fossil fuels. This substitution means that fossil C emissions are avoided, contributing to the C benefits of this option. The amount of displaced C emissions depends on the efficiency of the considered bioenergy pathway and the fossil-based counterpart. If biomass displaces a high-carbon fossil fuel (e.g. coal), using a high-efficiency bioenergy technology, more fossil C is displaced per unit of biogenic C than in case of rather inefficient bioenergy plants and displacement of low-carbon fossil fuels (e.g. natural gas). In Fig. 2b, this is schematically shown with grey areas of different brightness. In this option, the bulk of C benefits results from fossil fuel displacement rather than C stock changes in the BE-case.

The figure also illustrates that due to non-linear characteristics of nSucc growth curves, it depends on the considered timeframe whether nSucc or BE results in higher cumulative benefits. Moreover, as nSucc growth curves as well as SRC yields are highly diverse for different world regions and ecosystems, it is necessary to pay due regard to regionally specific parameterization of the model.

In this paper, the only considered bioenergy option is 2G biofuel production from short rotation plantations. We generally assume that 2G biofuels directly displace the respective fossil transport fuels. The fact that 2G biofuels used in combustion engines could to some extent also compete with propulsion systems that are not based on internal combustion of liquid fuels (especially electric drives) is disregarded. With regard to feedstock types, we only consider fast-growing trees, while energy grasses like miscanthus or switchgrass are disregarded.

3 Methodology and data

Carbon benefits of the two options are calculated on a per-area unit basis (kt C/km^2). Calculations are performed for 11 world regions as well as on global scale. We assume that the considered area is distributed among ecological zones and climate zones exactly like total cropland areas.

For plausibility reasons, it is further assumed that in both cases (nSucc and BE), land-use change on the considered area is a gradual process that lasts 10 years. After these 10 years, total C stocks in energy plantations remain constant (because biomass removal from a patch that was ready for harvest is compensated by biomass growth on immature patches) and plantations yield identical amounts of biomass in each year.[1]

3.1 Data on carbon stock changes and SRC yields

Following IPCC Guidelines (IPCC, 2006a), C stocks are differentiated into “above- and belowground biomass”, “dead organic matter” comprising “litter” and “deadwood”, and “soil”. C stock increases (C benefits) are calculated according to the “stock-difference method”, i.e. based on the difference in carbon stocks at two points of time. Similar to Albanito et al. (2016), we here use default values provided for Tier 1 approaches in IPCC (2006a) whenever possible. C stock changes in soil are disregarded because they are assumed to be equal for natural forest and forest plantations/perennial crops under Tier 1. Regarding biomass and litter, default values are only available for “natural forest” (i.e. natural vegetation in all ecological zones with the exception of deserts and steppe), but not for energy plantations. Parameters for energy plantations are therefore derived from yield estimates, assumed losses and litter decay rates. Deadwood is generally disregarded in Tier 1 approaches and thus also not taken into account here.

1 This implies that the schematic illustration shown in Fig. 2, where all aboveground biomass is harvested after 5 years (resulting in a “sawtooth pattern” of biomass C stocks) does not reflect the circumstances in the actual model.

Carbon stocks in natural vegetation

The dynamics of C accumulation in natural vegetation strongly depend on site-specific natural conditions. In order to derive representative C accumulation curves for renaturation in 11 world regions and on global scale, global raster data (5 arcmin resolution) on cropland distribution (Erb et al., 2007), ecosystem zones (FAO, 2012) and climate zones (JRC, 2018) are merged and IPCC Tier 1 standard values applied to calculate C stock changes for each relevant raster cell. Fig. 2 shows the regional differences in annual aboveground biomass C accumulation (a) and the timespan until a constant C stock is reached in natural vegetation (b) according to IPCC default values.

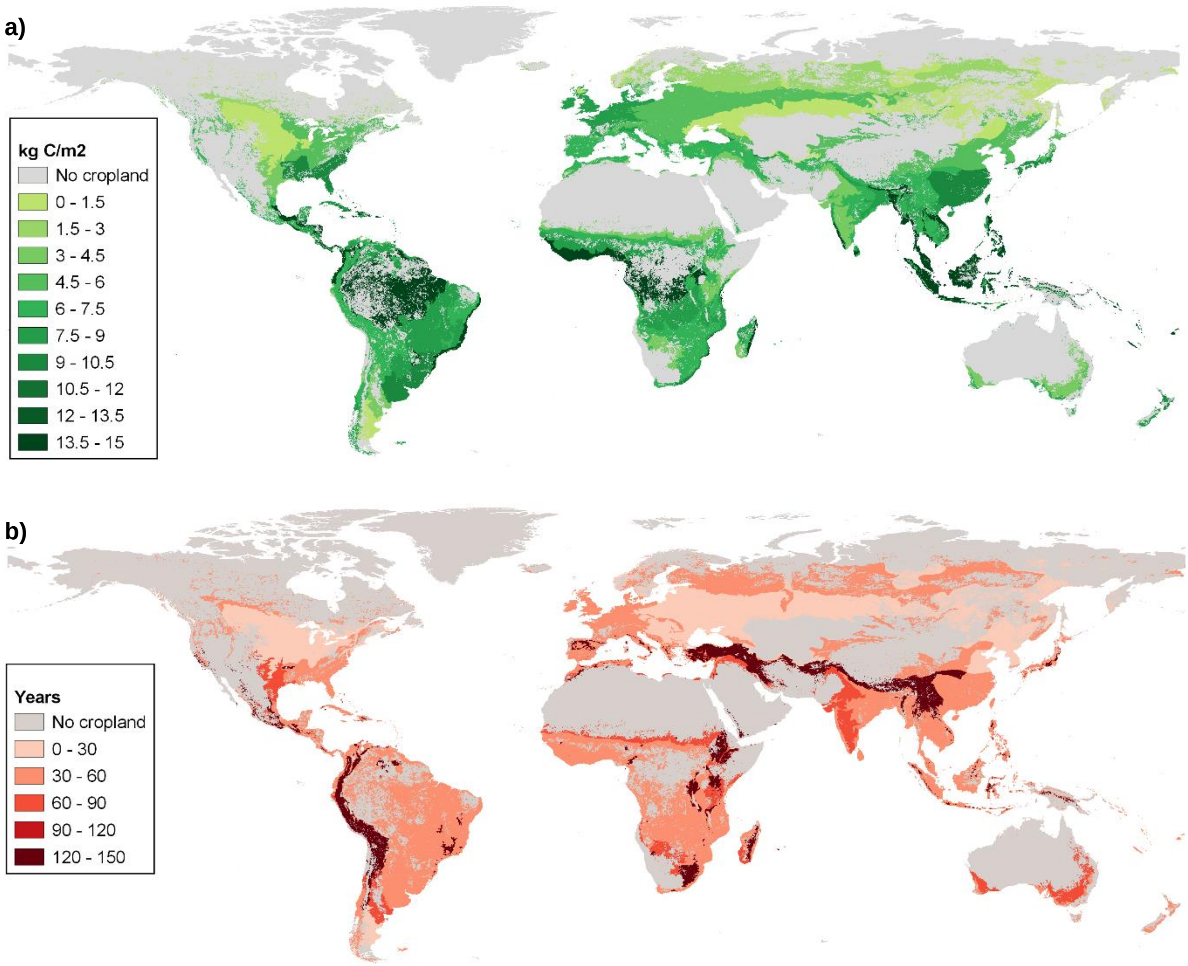

Figure 3. a) Potential aboveground biomass carbon stock in natural vegetation and (b) saturation time of natural vegetation on grid cells with cropland (own calculations and illustration based on(IPCC, 2006a) and data obtained from Erb et al. (2007), FAO (2012) and JRC (2018).

The assumed aboveground biomass accumulation curves in the different ecological zones as well as the resulting curves for 11 world regions are shown in Fig. 4. Belowground biomass C stocks are estimated to be 30 % of aboveground stocks (cf. Table 4.4 in (IPCC, 2006a)[2].

[2] According to Saugier et al. (2001), the root-to-shoot ratios in tropical, temperate and boreal forests are 28 %, 27 % and 36 %, respectively.

IPCC Tier 1 methods suggest that soil C stocks in natural forests and forest plantations as well as perennial crops are identical (see default “stock change factors” in IPCC (2006a)). Hence, C stock changes in soils are disregarded in the present assessment.

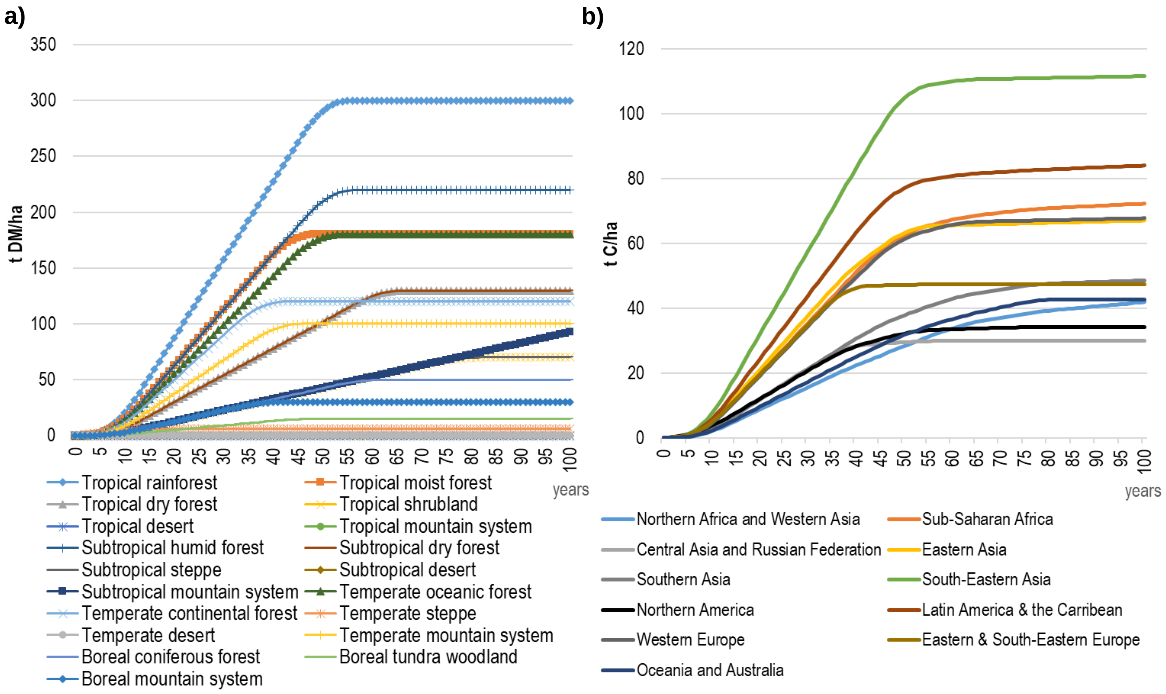

Figure 4. Aboveground biomass growth patterns for ecological zones (left) and world regions (right) assumed in this study. Note that the unit is tons of dry matter per hectare in the left figure while it is tons C per hectare in the right one. Source: own calculations based on default data from (IPCC, 2006a) and GIS data provided in Erb et al. (2007), FAO (2012) and JRC (2018).

Carbon stocks in short rotation plantations

The required parameters for plantations (annual biomass growth, corresponding biomass yields, harvest losses and litter accumulation) are based on a comprehensive literature review. It was found that average potential net primary production values (“NPPpot”) according to Haberl et al. (2007) are suitable proxies for short rotation yields in the different regions when “aboveground losses” (shed leaves, biomass lost to herbivores, harvest losses etc.; see Clark et al. (2001)) around 20 % are assumed. For the region “Northern Africa and Western Asia”, the default SRC yield was adjusted to 5.6 tons of dry matter per hectare (t_{DM}/ha) (based on Albanito et al., 2016). For the Monte Carlo simulations (see below), the default values are varied by +/-20% and losses from 10 to 30 %.

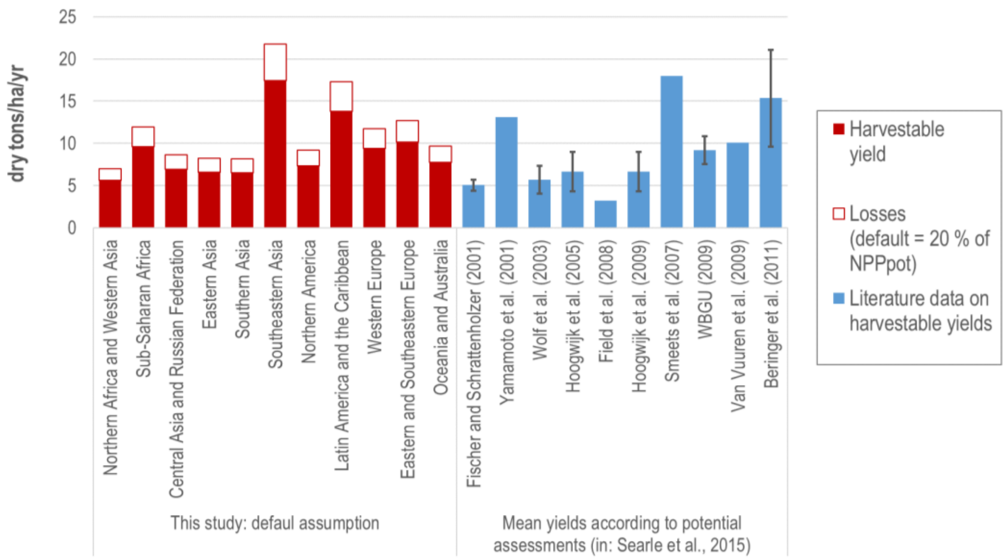

Figure 5. Default SRC yields in 11 world regions assumed in this study as compared to mean global yields assumed in bioenergy potential assessments (Sources: Albanito et al., 2016; Haberl et al., 2007; Searle and Malins, 2015

3.2 Calculation of carbon benefits

We calculate and compare total cumulative C benefits resulting from natural succession (CB_{nSucc}) and plantation-based 2G biofuels (CB_{BE}) for different timeframes TF. In the case of natural succession, they correspond to the difference in total C stocks at the beginning and the end of the considered timeframe:

$$CB_{nSucc} = \Delta C_{nSucc} = \Delta C_{nSucc}^{BM\_above} + \Delta C_{nSucc}^{BM\_below} + \Delta C_{nSucc}^{Litter} \quad (1)$$

As stated above, C stock changes of deadwood are generally disregarded under IPCC Tier 1, and since no difference is assumed and soil C stock changes can also be neglected because they are identical for nSucc and BE.

For plantation-based 2G biofuels, C benefits result from C stock changes and displacement of fossil fuels:

$$CB_{BE} = \Delta C_{BE}^{BM\_above} + \Delta C_{BE}^{BM\_below} + \Delta C_{BE}^{Litter} + CB_{fuel\_disp} \quad (2)$$

C benefits from fossil fuel displacement (CB_{fuel_disp}) are calculated as follows: Since 2G biofuels are direct substitutes for fossil fuels, it is assumed that a certain quantity of 2G biofuels, measured in energy units, displaces the same quantity of the corresponding fossil fuel. Hence, 1 Joule of Fischer-Tropsch diesel or lignocellulosic ethanol is assumed to displace 1 Joule of fossil diesel or fossil petrol, respectively. To calculate the total avoided fossil fuel emissions resulting from this displacement, we calculate the “carbon displacement factors” of 2G biofuels (see Marland and Schlamadinger, 1997). A displacement factor (DF) is defined as the ratio of fossil C emissions avoided per unit of biomass C used for 2G biofuel production. It is calculated as

$$DF = \frac{\eta_{2G}}{\eta_{ref}} \cdot \frac{CE_{fossil}}{CE_{BM}}, \quad (3)$$

where η_{2G} represents the feedstock-to-fuel conversion efficiency of 2G biofuel production and η_{ref} the efficiency of petroleum refining. $CE_{fossil/BM}$ are fuel combustion emissions (per energy unit) of petroleum derivatives and biomass, respectively. Hence, the displacement factor captures a) energy losses during the respective conversion from primary resource to final energy carrier, and b) differences in emission factors between biomass and petroleum. Upstream emissions in fuel supply chains (e.g. resulting from petroleum exploration, biomass harvesting and transport etc.), denoted as $UE_{BM/fossil}$ can be considered by applying the following extended equation:

$$DF = \frac{\eta_{2G}}{\eta_{ref}} \cdot \frac{CE_{fossil}+UE_{fossil}}{CE_{BM}} - \frac{UE_{BM}}{CE_{BM}}, \quad (4)$$

To calculate the C benefits resulting from fossil fuel displacement per area unit and year, we simply multiply the average amount of biomass C harvested on this area with the DF of the considered 2G biofuel technology:

$$CB_{fuel\_disp} = DF \cdot \overline{y_{wr}} \cdot n_{wr} \quad (5)$$

CB_{fuel_disp} represents the carbon benefits from fossil fuel displacement, $\overline{y_{wr}}$ is the average biomass yield of energy plantations in the considered world region "wr", and n_{wr} the number of harvests in the considered timeframe and world region.[3]

Biomass-to-fuel conversion efficiencies around 43 % (Ail and Dasappa, 2016; Daioglou et al., 2016; Hamelinck and Faaij, 2006), a typical petroleum refining efficiency of 94 %[4] and default combustion emission factors according to (IPCC, 2006b) give a displacement factor of 0.30. Disregarding upstream emissions, this is assumed as default value.

3.3 Monte Carlo simulation

Due to considerable uncertainties with regard to plantation-based 2G biofuels, a Monte Carlo simulation with 10.000 runs is carried out. The ranges are derived from literature data and uniform probability distributions are assumed:

- Energy plantation yields: +/-20 % of default yields shown in Fig. 5.
- Aboveground biomass losses in energy plantations: 10 to 30 % of NPPpot.
- 2G biofuel conversion efficiency: Biomass-to-fuel efficiencies ranging from 30 to 55 %, resulting in displacement factors between 0.21 and 0.39.

For the sake of simplicity, we assume that these parameters remain constant throughout the considered timeframes.

[3] $n_{harvests,wr}$ depends on the considered timeframe and the length of the rotation period (assumed to range from 2 to 5 years; derived from literature). The latter is relevant because it determines the timespan from the establishment of a plantation (i.e. the beginning of the considered timeframe) and the first harvest.

[4] Based on 6 % refinery own consumption and losses according to Eurostat (2018).

4 Results

Figure 6 shows the cumulated C benefits from natural succession in comparison to those from plantation-based 2G biofuels for 5 different timeframes: 30, 40, 50, 70 and 100 years. The results for 2G biofuels are shown as box plots resulting from 10.000 Monte Carlo simulations.

For timeframes ranging from 30 to 50 years, natural succession results in higher cumulated C benefits than the vast majority of Monte Carlo simulations for 2G biofuels. The savings from natural succession are about 30 % higher than the median values for plantation-based 2G biofuels for the 30- and 40-year timeframe, and 23 % higher for the 50-year timeframe.

For longer timeframes, saturation effects in biomass accumulation in natural forests become increasingly relevant. For 70 years, the savings from nSucc are already slightly lower than the median value for BE, and for 100 years the vast majority of Monte Carlo simulations for 2G biofuel production exhibits higher savings than nSucc.

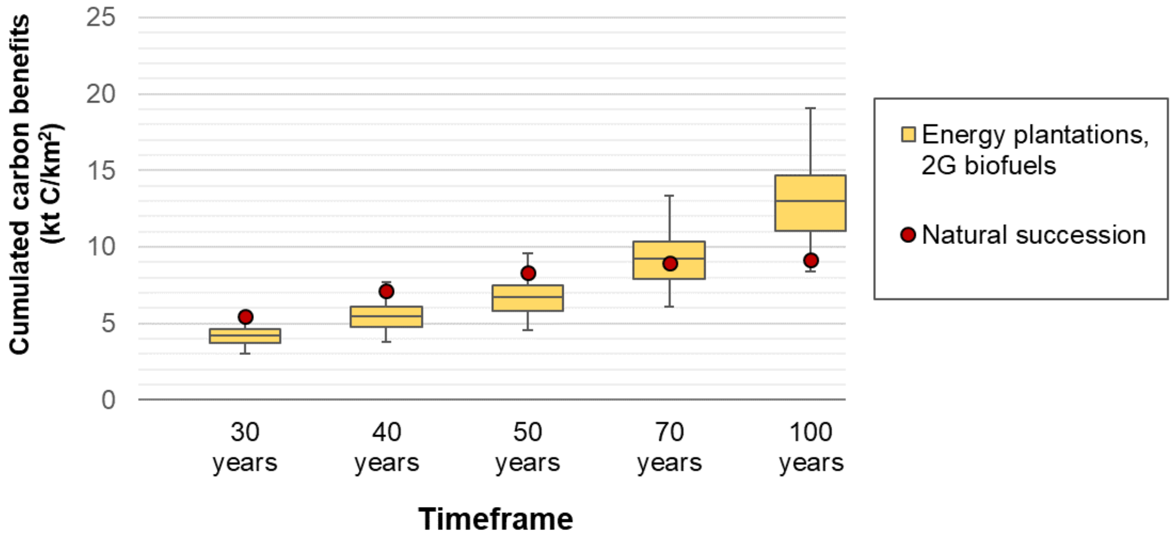

Figure 6. Cumulated carbon benefits per area unit for different timeframes, assuming the same global distribution as total cropland (global weighted average). For 2G biofuels, results are shown as box plots based on 10.000 Monte Carlo calculations, while results for nSucc are based on fixed parameter settings derived from IPCC default values.

As explained above, these results are based on the assumption of a specific global distribution That is, we assume that the distribution of energy plantations/areas for nSucc corresponds to the actual distribution of the global cropland area. Regarding the very different growth curves among ecological zones (Fig. 4), it is interesting to know whether the findings from Fig. 6, and especially the superiority of nSucc for timeframes up to 50 years, remain valid for other area distributions. To investigate this question, the calculations were also performed for 11 world regions individually (Fig. 6). For reasons of simplicity, the C savings from 2G biofuels were only calculated for default parameter values, i.e. without regard to uncertainties.

Fig.7 illustrates that the absolute amounts of C benefits per km^2 resulting from nSucc and BE vary considerably among world regions. Unsurprisingly, the highest values are achieved in tropical regions, namely South-Eastern Asia and Latin America & the Caribbean. For eight out of eleven regions, the performance of nSucc in relation to BE shows a very similar characteristic as the weighted global average: a superiority of nSucc for timeframes up to 50 years (in two regions even up to 70 years). In two regions (namely Southern Asia and Oceania & Australia), nSucc and BE show practically the same per-km² benefits for timeframes up to 50 years. The only truly conspicuous exception regarding the performance of nSucc in comparison to BE is Eastern Asia, where SRC yields are possibly underestimated.[5]

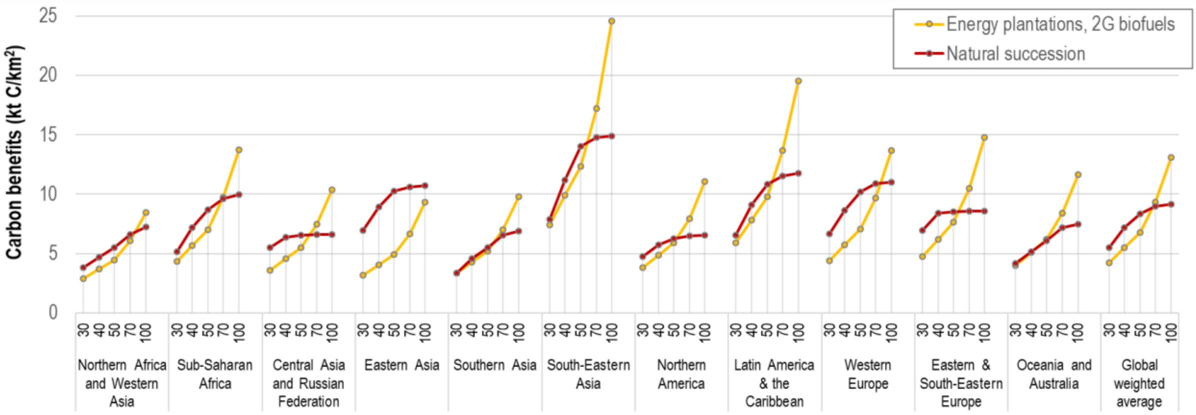

Figure 7. Results for 11 world regions and global weighted average based on default parameter settings.

5 Discussion and conclusions

Recent studies have argued that protection and enhancement of natural carbon sinks should seriously be considered as alternative to bioenergy (see DeCicco and Schlesinger, 2018). Moreover, Griscom et al. (2017) have revealed the vast potentials of "natural climate solutions" (i.e. better stewardship of land) in mitigating climate change. Yet, the C sink strength of natural succession on agricultural land, as compared to biomass plantations providing feedstock for specific bioenergy options, has so far not been investigated in scientific literature.

The results presented in this paper lead to the following main conclusions:

- The climate mitigation effect achieved through C stock changes if agricultural land is allowed to revert to natural vegetation are significant. In terms of C benefits per area unit, natural succession can compete with biomass plantations providing feedstock for advanced biofuel production technologies.
- Accurate quantification of the per-area C benefits from plantation-based 2G biofuels is hindered by uncertain parameters like technical conversion efficiencies and energy plantation yields. Nevertheless, it primarily depends on the considered timeframe whether nSucc or 2G biofuels lead to higher C benefits.
- Natural succession is highly likely to be superior (i.e. to result in higher C benefits) for timeframes up to 50 years. Under very optimistic assumptions regarding technology development and energy plantation yields, the two options lead to very similar C

[5] Literature data for this world region is sparse and was considered too inconclusive for justifying an upwards correction.

benefits for up to 50 years. Only on the very long term (i.e. timeframes beyond 70 years), the 2G biofuel option is clearly preferable.

5.1 Discussion of limitations and suggestions for future research

The aim of this work was to provide best possible estimates on global scale, with consideration of world regional differences, based upon scientifically published and widely recognized data (i.e. IPCC default values), while paying due respect to uncertainties. Nevertheless, we acknowledge that our global approach comes, to a certain extent, at the expense of accuracy. Aspects that should be considered in future research include:

- The growth dynamics for natural forests derived from IPCC Tier 1 default values (Fig. 4) are simplistic. Chapman-Richards growth functions (see Pienaar and Turnbull, 1973)), which are often used to model growth of specific tree species or populations, are characterized by a more gradual decline of C accumulation.
  Suitable data on natural vegetation growth in the different ecological zones is sparse; only for tropical ecosystems, Chapman-Richards-based curves could be obtained from literature (Winrock International, 2014). Apart from more gradual decline of C accumulation, these curves are characterized by higher C stocks than the ones assumed here after about 70 years. Moreover, Keith et al. (2009) and Luyssaert et al. (2008) provide empirical evidence that for several forest types, IPCC default values for biomass C stocks in old forests might be underestimated.
- The fact that deadwood is – following IPCC (2006a) Tier 1 assumptions – entirely disregarded results in a systematic underestimation of C stocks that is quite relevant for nSucc and long timeframes. Previous IPCC default values (IPCC, 2003) suggest that average dead-to-live biomass ratios range from 0.11 to 0.2 for tropical, evergreen and deciduous forests.[6]
  To conclude, there are still considerable uncertainties regarding total C stocks in natural forests, and C stocks in old natural forests are probably underestimated in this study.
- Contrary to Tier 1 assumptions, soil C stock changes might actually differ between natural forest and short rotation plantations.

Further aspects that are not within the scope of this paper and are considered worth investigating include:

- Conversion plants producing not only energy but chemicals or other products for material use alongside with biofuels (so-called “biorefineries”) are often considered more promising than dedicated biofuel plants.
- We here only considered short rotation plantations. In some climate regions, energy grasses (e.g. miscanthus, switchgrass) are likely to yield more biomass per area unit than short rotation plantations (see Albanito et al., 2016, for example). There are also disadvantages to energy grasses that must be considered for direct comparison (e.g. lower energy density, resulting in more energy-intensive transport and logistics).

[6] In IPCC (2006a), no default values on deadwood are provided because literature data are not considered as statistically representative.

Hence, in-depth analysis on the respective value chains (from biomass cultivation to final energy carrier) is necessary.

5.2 Policy implications

Despite the above-described data constraints and limitations, our findings have strong implications for climate policies: Considering that large and early reductions in greenhouse gas emissions are needed until 2050 for holding global warming to well below 2 or even 1.5 degrees" (IPCC, 2018; Knutti et al., 2016; Meinshausen et al., 2009; Rogelj et al., 2015, 2016), it is highly questionable whether C reduction strategies for the transport sector should rely on 2G biofuels; the more so as there are other long term alternatives to fossil transport fuels, that are characterized by higher efficiencies from primary to useful energy and higher energy yields per area (e.g. electric propulsion systems in combination with novel storage technologies or hydrogen fuel cells, based on solar or wind energy, for example).

Undoubtedly, reforestation represents a cost-efficient option for climate mitigation as compared to 2G biofuels and other bioenergy pathways (see Griscom et al., 2017; Kalt and Kranzl, 2011), and has considerable co-benefits like positive effects on biodiversity, air and water filtration, and flood control (Griscom et al., 2017; Millennium Ecosystem Assessment, 2005). However, if reforestation is to be promoted as climate mitigation instrument, consideration must also be given to inherent trade-offs:

- Like all land-based mitigation options, reforestation of agricultural land harbours the risk of driving food prices and aggravating hunger in less developed countries.
- It is of uttermost importance that C stocks in reforestation areas are not depleted at a later time. This can possibly be ensured by declaring them as conservation areas and rigorous enforcement of no-go policies.
- There is also the risk of natural disturbances. Although most wildfires have limited and temporary impacts on C stocks because they mostly effect leaf litter and fine wood debris (Mitchell et al., 2012, 2009), it cannot be ruled out that severe storms or fires of high intensity lead to massive C losses, cancelling out the C accumulation of many years or decades.

Acknowledgements

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Literature

Ail, S.S., Dasappa, S., 2016. Biomass to liquid transportation fuel via Fischer Tropsch synthesis – Technology review and current scenario. Renew. Sustain. Energy Rev. 58, 267–286. https://doi.org/10.1016/j.rser.2015.12.143

Albanito, F., Beringer, T., Corstanje, R., Poulter, B., Stephenson, A., Zawadzka, J., Smith, P., 2016. Carbon implications of converting cropland to bioenergy crops or forest for climate mitigation: a global assessment. GCB Bioenergy 8, 81–95. https://doi.org/10.1111/gcbb.12242

Clark, D.A., Brown, S., Kicklighter, D.W., Chambers, J.Q., Thomlinson, J.R., Ni, J., 2001. Measuring net primary production in forests: Concepts and field methods. Ecol. Appl. 11, 356–370. https://doi.org/10.1890/1051-0761(2001) 011[0356:MNPPIF]2.0.CO;2

Daioglou, V., Stehfest, E., Wicke, B., Faaij, A., van Vuuren, D.P., 2016. Projections of the availability and cost of residues from agriculture and forestry. GCB Bioenergy 8, 456–470. https://doi.org/10.1111/gcbb.12285

DeCicco, J.M., Schlesinger, W.H., 2018. Reconsidering bioenergy given the urgency of climate protection. Proc. Natl. Acad. Sci. 115, 9642–9645. https://doi.org/10.1073/pnas.1814120115

Erb, K.-H., Gaube, V., Krausmann, F., Plutzar, C., Bondeau, A., Haberl, H., 2007. A comprehensive global 5 min resolution land-use data set for the year 2000 consistent with national census data. J. Land Use Sci. 2, 191–224. https://doi.org/10.1080/17474230701622981

Eurostat (2018). Energy balance sheets – 2014 data – 2016 edition. Retrieved from https://ec.europa.eu/eurostat/web/products-statistical-books/-/KS-EN-16-001

FAO, 2012. Global ecological zones for FAO forest reporting: 2010 Update, Forest Resources Assessment Working Paper 179. Food and Agriculture Organisation of the United Nations, Rome.

Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Schlesinger, W.H., Shoch, D., Siikamäki, J.V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R.T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M.R., Herrero, M., Kiesecker, J., Landis, E., Laestadius, L., Leavitt, S.M., Minnemeyer, S., Polasky, S., Potapov, P., Putz, F.E., Sanderman, J., Silvius, M., Wollenberg, E., Fargione, J., 2017. Natural climate solutions. Proc. Natl. Acad. Sci. 114, 11645–11650. https://doi.org/10.1073/pnas.1710465114

Haberl, H., Erb, K.H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W., Fischer-Kowalski, M., 2007. Quantifying and mapping the human appropriation of net primary production in earth’s terrestrial ecosystems. Proc. Natl. Acad. Sci. 104, 12942–12947. https://doi.org/10.1073/pnas.0704243104

Hamelinck, C.N., Faaij, A.P.C., 2006. Outlook for advanced biofuels. Energy Policy 34, 3268–3283.

IPCC, 2003. Good practice guidance for land use, land-use change and forestry. IPCC National Greenhouse Gas Inventories Programme.

IPCC, 2006a. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use (Prepared by the National Greenhouse Gas Inventories Programme). IGES, Japan.

IPCC, 2006b. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 2: Energy (Prepared by the National Greenhouse Gas Inventories Programme). IGES, Japan.

IPCC, 2018. Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. In Press.

JRC, 2018. Renewable Energy Directive. Thematic Data Layers for Commission Decision of [10 June 2010] on guidelines for the calculation of land carbon stocks for the purpose of Annex V to Directive 2009/28/EC. Joint Research Centre of the European Commission.

Kalt, G., Kranzl, L., 2011. Assessing the economic efficiency of bioenergy technologies in climate mitigation and fossil fuel replacement in Austria using a techno-economic approach. Appl. Energy 88, 3665–3684.

Keith, H., Mackey, B.G., Lindenmayer, D.B., 2009. Re-evaluation of forest biomass carbon stocks and lessons from the world’s most carbon-dense forests. Proc. Natl. Acad. Sci. 106, 11635–11640. https://doi.org/10.1073/pnas.0901970106

Knutti, R., Rogelj, J., Sedláček, J., Fischer, E.M., 2016. A scientific critique of the two-degree climate change target. Nat. Geosci. 9, 13–18. https://doi.org/10.1038/ngeo2595

Luyssaert, S., Schulze, E.-D., Börner, A., Knohl, A., Hessenmöller, D., Law, B.E., Ciais, P., Grace, J., 2008. Old-growth forests as global carbon sinks. Nature 455, 213–215. https://doi.org/10.1038/nature07276

Marland, G., Schlamadinger, B., 1997. Forests for carbon sequestration or fossil fuel substitution? A sensitivity analysis. Biomass Bioenergy 13, 389–397.

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S.C.B., Frieler, K., Knutti, R., Frame, D.J., Allen, M.R., 2009. Greenhouse-gas emission targets for limiting global warming to 2 °C. Nature 458, 1158–1162. https://doi.org/10.1038/nature08017

Millennium Ecosystem Assessment, 2005. Ecosystems and human well-being: synthesis. Island Press, Washington, DC.

Mitchell, S.R., Harmon, M.E., O’Connell, K.E.B., 2009. Forest fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems. Ecol. Appl. 19, 643–655. https://doi.org/10.1890/08-0501.1

Mitchell, S.R., Harmon, M.E., O’Connell, K.E.B., 2012. Carbon debt and carbon sequestration parity in forest bioenergy production. GCB Bioenergy 4, 818–827. https://doi.org/10.1111/j.1757-1707.2012.01173.x

Pienaar, L.V., Turnbull, K.J., 1973. The Chapman-Richards Generalization of Von Bertalanffy’s Growth Model for Basal Area Growth and Yield in Even - Aged Stands. For. Sci. 19, 2–22. https://doi.org/10.1093/forestscience/19.1.2

Rogelj, J., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K., Meinshausen, M., 2016. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature 534, 631–639. https://doi.org/10.1038/nature18307

Rogelj, J., Luderer, G., Pietzcker, R.C., Kriegler, E., Schaeffer, M., Krey, V., Riahi, K., 2015. Energy system transformations for limiting end-of-century warming to below 1.5 °C. Nat. Clim. Change 5, 519–527. https://doi.org/10.1038/nclimate2572

Saugier, B., Roy, J., Mooney, H.A., 2001. Terrestrial global productivity. Academic Press, London.

Searle, S., Malins, C., 2015. A reassessment of global bioenergy potential in 2050. GCB Bioenergy 7, 328–336. https://doi.org/10.1111/gcbb.12141

Winrock International, 2014. AFOLU Carbon Calculator. The afforestation/reforestation tool: Underlying data and methods. US Aid.