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Supporting Information for

Unexpectedly large impact of forest management and grazing on global vegetation biomass

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Contextualizing the difference of potential and actual carbon stocks with global carbon balance accounts

The difference between potential and actual biomass stocks of approximately 375-525 PgC (inner quartiles of all 42 calculations) estimated in this study (Fig 1B) does not represent an account of the net biomass balance between two points of time, which would also be influenced by changes in environmental conditions etc. It rather can be interpreted as a rough proxy of the C emissions from land use, with important limitations (see below). The potential-actual difference is larger than most previous estimates of carbon emissions resulting from land-use change (Extended Data Table 2), even when accounting for changes of carbon pools in soils and wood products.

Hence the question arises whether the potential-actual difference is consistent with the current understanding of the global carbon cycle and atmospheric CO_2 records over the Holocene, e.g. those derived from ice-core records[1,2] and direct atmospheric CO_2 observations for recent decades[3].

Soil Carbon and Biomass Products

Soil carbon and biomass products were not included in the account. Including soil carbon fluxes would probably increase the difference between potential and actual terrestrial carbon stocks because the conversion of pristine ecosystems is associated with soil carbon losses[4]. However, the amount of carbon lost from soils is highly uncertain and probably considerably smaller than C losses from biomass changes[5]. The inclusion of biomass products would reduce net flows. Examples from Europe indicate that this effect is also comparatively small, amounting to approximately 10% of the biomass stock changes in the last decades[6]. Globally, the role of wood products is estimated to be much smaller[7].

Isolating Land-Use Impacts on Biomass Stocks

Starting point of our study is the assessment of the global potential biomass carbon stocks. In this study, potential biomass stock was defined as the carbon stock of the current potential natural vegetation, i.e. the vegetation that would prevail in the absence of human activities under current climate[8] (Extended Data Figure 2).

The potential vegetation (β in Extended Data Figure 2A) differs from the prehistoric vegetation (α in Extended Data Figure 2A) before the onset of civilization, i.e. in the absence of land-use change, because of environmental changes that have occurred since then. The difference (β-α) between the prehistoric and the (hypothetical) potential biomass stocks results from the effect of environmental changes (temperature, precipitation, increasing atmospheric CO_2 concentration, changing nutrient cycles and/or fire suppression, etc.) on biomass stocks alone.

Calculating the difference between prehistoric (a) and actual (γ in Extended Data Figure 2A) biomass stock assesses the cumulative C emissions from biomass to the atmosphere. This difference is – in line with widely-applied definitions of land-use change emissions[9,10] – determined by two factors: the effect of land use on carbon stocks (β-γ), and changes in storage potentials due to changes in environmental conditions (β-α).

Thus, calculating the difference between the current potential (β) and actual biomass stock (γ), as assessed in this study combines these two components: cumulative C emissions from biomass (α-γ), land-use and environmental-change induced) and the effect of environmental changes on biomass stocks (β-α) on the areas affected by land-use (change). The potential-actual difference hence isolates the effect of land use on biomass stocks ((α-γ)+(β-α)=β-γ). Corollary, the larger the environmental-change induced storage potential changes (β-α), the bigger the divergence between accounts of cumulative emissions (γ-α) and of the difference between potential and actual biomass stocks (β-γ). Thus, interpreting the potential-actual difference as land use change (LUC) emissions would implicitly assume that environmental-change induced change in biomass did not occur.

Industrial and Preindustrial Era Emissions From Land Use

Post-1800 LUC emissions of 100 to 260 with an average of 180 PgC, as estimated by IPCC[11] are consistent with present-day atmospheric CO_2 concentrations[3]. Higher emissions, especially in the last 250 years, would still be consistent with the atmospheric CO_2 records if the storage potential of natural ecosystems increased more strongly than currently thought within that period[12]. Neglecting that latter possibility, as well as the increases in carbon storage potential that have probably occurred since prehistoric times, the IPCC numbers for the emissions since 1800 imply that 115 to 425 PgC of the estimated 375-525 PgC land use change emissions must be assumed to have occurred in the pre-industrial era.

Such early carbon releases do not directly imply large changes in atmospheric CO_2. The airborne fraction of early land use emissions has been estimated to be much smaller (around 20%) in the preindustrial era than in recent decades (around 45%[13]) due to efficient ocean and land uptake in response to a small and generally slowly increasing forcing[14–16]. Reconstructions of atmospheric CO_2 and its ^{13}C isotopic composition suggest a net terrestrial balance of ~40 to 125 PgC emissions between 7 ka BP and 0.25 ka BP[17]. Although these emissions may stem from human land use changes, the observed changes in the isotopic composition of the atmospheric CO_2 can likewise be explained by natural factors[18]. The large uncertainty of pre-industrial fluxes and the knowledge gaps related to processes affecting pre-industrial terrestrial carbon inventories leave a range of possible land use (change) histories to be consistent with this balance[15]. Peat accumulation, for instance, is reported to have sequestered ~270 PgC[19–21], with some estimates even larger[22], implying that preindustrial land use change emissions of ~310 to 395 PgC are consistent with present day understanding of the global carbon cycle[23] (Extended Data Table 3).

Our inferred result of the 115-425 PgC (see above) is consistent with this account for pre-industrial LUC emissions. Depending on the magnitude of LUC emissions in the industrial period, 62% (lower boundary of 100 PgC LUC emissions) to 95% (upper boundary with 260 PgC LUC emissions) of the 42 potential-to-actual biomass stock permutations (see Method section) are consistent with the atmospheric CO_2 records, even if no environmentally induced change in storage potentials occurred.

The Strength of the Terrestrial Biosphere Sink

Although first principles of ecophysiology (e.g. Liebig's 'Law of the Minimum') suggest that an increase in storage potential is likely under increasing temperature, atmospheric CO_2 concentrations and N-deposition[12], quantifying this increase remains an area of active research[12]. A comparison of the carbon in potential vegetation calculated in our study and results from a modelling study[17] suggests that the change in storage potential could amount to approximately 100 PgC. However, the applicability of current models is limited due to their simplistic assumption on turnover times[24,25], which are decisive for reliably calculating the build-up of carbon stocks associated with increased productivity[26,27]. Only reduced uncertainties related to the increasing storage potentials in the past would allow to robustly accounting for such flows.

Our finding of a large (375 – 525 PgC) impact of land use on biomass stocks is thus consistent with the current understanding of the global carbon balance. The contextualization of the potential-actual difference with accounts of the global carbon balance suggests that either land use had a considerably impact on biomass stocks before the industrial era (Extended Data Table 3), or the terrestrial biosphere sink is larger than previously thought, or both.

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Supporting Information Table 1. Potential biomass stock density values used for the IPCC- based (FRA and Pan-adjusted) maps. Sources: IPCC best practice guide 2003[28], Table 3A.1.2, Pan et al., 2011[29] for the boreal zone, and Saugier et al. 2001[30] to close data gaps.

		Nearctic	Neo-tropic	Afro-tropic	Paleo-arctic [kgC m^{-2}]	Indo-Malay	Oceania	Austral-asia
Moist (evergreen)	Tropical and Subtropical Moist Broadleaf Forests	19.4	18.6	19.2	13.8	21.7	21.7	21.7
Deciduous	Tropical and Subtropical Moist Broadleaf Forests	16.2	13.6	16.1	13.8	18.0	18.0	18.0
Montane	Tropical and Subtropical Moist Broadleaf Forests	17.0	14.5	11.8	13.8	22.4	-	22.4
Dry	Tropical and Subtropical Dry Broadleaf Forests	13.5	13.5	16.1	13.8	10.2	10.2	8.3
	Tropical and Subtropical Coniferous Forests	13.5	13.5	16.1	13.8	10.2	10.2	8.3
	Temperate Broadleaf and Mixed Forests	13.4	13.4	7.7	13.8	13.8	13.8	13.8
	Temperate Coniferous Forests	13.3	13.3	13.3	13.3	13.3	13.3	13.3
	Temperate continental / mixed	11.5	11.5	7.8	11.5	11.5	11.5	11.5
	Temperate Oceanic	12.4	12.4	10.6	12.4	12.4	12.4	12.4
	Boreal Forests/Taiga	40.6	12.4	10.6	12.4	12.4	22.1	12.4
Woodlands	Tropical and subtropical grasslands, savannas, and shrublands	6.3	6.3	6.3	5.7	5.7	5.7	5.7
Forest-savanna mosaic	Tropical and subtropical grasslands, savannas, and shrublands	13.5	13.5	7.8	8.1	8.1	8.1	8.1
Savanna	Tropical and subtropical grasslands, savannas, and shrublands	9.2	9.2	6.2	5.9	5.9	5.9	5.9
Bushland and thickets	Tropical and subtropical grasslands, savannas, and shrublands	5.0	5.0	4.6	3.8	3.8	3.8	3.8
Grassland	Tropical and subtropical grasslands, savannas, and shrublands	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	Temperate Grasslands, Savannas, and Shrublands	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Savanna	Flooded Grasslands and Savannas	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Grassland	Flooded Grasslands and Savannas	0.4	5.0	4.6	2.0	3.8	3.8	3.8
Grassland type	Montane Grasslands and Shrublands	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Bushland/thickets	Montane Grasslands and Shrublands	0.4	0.4	0.4	0.4	0.4	0.4	0.4
	Forest tundra	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	Tundra	3.3	3.3	3.3	3.0	3.0	3.0	3.0
Chapparal-macchia type	Mediterranean Forests, Woodlands, and Scrub	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Forest type	Mediterranean Forests, Woodlands, and Scrub	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	Deserts and Xeric Shrublands	4.0	4.0	4.0	4.0	4.0	4.0	4.0
	Mangroves	0.4	0.4	0.4	0.4	0.4	0.4	0.4

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Supporting Information Table 2. Potential biomass stock density values from seminal literature on undisturbed* vegetation: Ajtay et al., 1979 [31], Olson et al., 1983 [32], and Saugier et al., 2001 [30] used for the "classic data" maps.

		Olson [kgC m^{-2}]	Ajtay [kgC m^{-2}]	Roy, Saugier, Mooney [kgC m^{-2}]
Moist (evergreen)	Tropical and Subtropical Moist Broadleaf Forests	19.4	18.9	19.4
Deciduous	Tropical and Subtropical Moist Broadleaf Forests	19.4	11.3	19.4
Montane	Tropical and Subtropical Moist Broadleaf Forests	19.4	11.3	19.4
Dry	Tropical and Subtropical Dry Broadleaf Forests	19.4	11.3	19.4
	Tropical and Subtropical Coniferous Forests	19.4	13.8	19.4
	Temperate Broadleaf and Mixed Forests	13.4	12.6	13.4
	Temperate Coniferous Forests	13.4	13.5	13.4
	Temperate continental / mixed	13.4	13.1	13.4
	Temperate Oceanic	47.3	47.9	47.3
	Boreal Forests/Taiga	4.2	7.7	4.2
Woodlands	Tropical and subtropical grasslands, savannas, and shrublands	11.2	6.8	11.2
Forest-savanna mosaic	Tropical and subtropical grasslands, savannas, and shrublands	11.2	6.8	11.2
Savanna	Tropical and subtropical grasslands, savannas, and shrublands	2.9	3.4	2.9
Bushland and thickets	Tropical and subtropical grasslands, savannas, and shrublands	2.9	2.3	2.9
Grassland	Tropical and subtropical grasslands, savannas, and shrublands	0.4	1.0	0.4
	Temperate Grasslands, Savannas, and Shrublands	0.4	0.9	0.4
Savanna	Flooded Grasslands and Savannas	2.9	3.4	2.9
Grassland	Flooded Grasslands and Savannas	0.4	0.9	0.4
Grassland type	Montane Grasslands and Shrublands	0.4	0.6	0.4
bushland/thickets/woodlands	Montane Grasslands and Shrublands	2.9	2.3	2.9
	Forest tundra	2.2	4.0	2.2
	Tundra	0.3	0.3	0.3
Chapparal-macchia type	Mediterranean Forests, Woodlands, and Scrub	6.0	3.2	6.0
forest type	Mediterranean Forests, Woodlands, and Scrub	11.2	6.8	11.2
	Deserts and Xeric Shrublands	0.4	0.5	0.4
	Mangroves	19.4	13.5	19.4

* Please note that in some sources no reference is given if values refer to undisturbed or used ecosystems. Comparisons with site data (e.g. [33] reveal that the values refer to old-grown vegetation and are thus interpreted as being applicable for potential biomass stocks.

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Suporting Information Table 3. Biomass stock values for permanent crops

Source	Crops	Total Biomass* kgC m^{-2}
Kroodsma & Field, 2006 [34]	mean of 7	3.15
Kroodsma & Field, 2006 [34]	mean of 6, without vineyards	3.49
Erb, 2004 [35]	Horticulture	2.52
Huffman et al., 2015 [36]	Orchards	2.87
Huffman et al., 2015 [36]	Vineyards	2.49
Zanotelli et al., 2013 [37]	Apple orchard	1.16
Values used in this study	Trees	3.0
Values used in this study	Shrubs	1.5

* assuming 20% belowground biomass for estimates of AGB only

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