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

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Abstract

Carbon stocks in vegetation play a key role in the climate system1–4, but their magnitude and patterns, their uncertainties, and the impact of land use on them remain poorly quantified. Based on a consistent integration of state-of-the art datasets, we show that vegetation currently stores ~450 PgC. In the hypothetical absence of land use, potential vegetation would store ~916 PgC, under current climate. This difference singles out the massive effect land use has on biomass stocks. Deforestation and other land-cover changes are responsible for 53-58% of the difference between current and potential biomass stocks. Land management effects, i.e. land-use induced biomass stock changes within the same land cover, contribute 42-47% but are underappreciated in the current literature. Avoiding deforestation hence is necessary but not sufficient for climate-change mitigation. Our results imply that trade-offs exist between conserving carbon stocks on managed land and raising the contribution of biomass to raw material and energy supply for

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climate change mitigation. Efforts to raise biomass stocks are currently only verifiable in temperate forests, where potentials are limited. In contrast, large uncertainties hamper verification in the tropical forest where the largest potentials are located, pointing to challenges for the upcoming stocktaking exercises under the Paris agreement.

The amount of carbon stored in terrestrial vegetation is a key component of the global carbon cycle4. Changes in carbon stored in vegetation biomass have a large impact on the atmospheric CO_2 concentrations either through sequestering or releasing carbon2. The urgency to conserve and, where appropriate, enhance the carbon reservoirs of terrestrial vegetation has long been recognized and is reflected in, for example, the inclusion of the land sector in UNFCCC reporting, the program for Reducing Emissions from Deforestation and Forest Degradation (REDD+), and the acknowledgement of biomass stocks as an essential climate variable5. Hence, monitoring changes in biomass stocks is key for securing progress towards the commitment of halting global warming below 1.5 degrees Celsius.

Although aboveground biomass stocks are straightforward to measure at the site level, their assessment at landscape to global scales is time-consuming, costly and requires extrapolations5. Remote Sensing is well-established for wall-to-wall mapping of biomass stocks, but the methodological differences between different remote sensing products6–8 and the scale mismatch to ground data9–11 hamper their comparability. Consequently, and in spite of efforts to improve observational databases3, biomass stocks and their spatial distribution remain uncertain at the global scale (Extended Data Figure 1). Many global change studies focus on changes in vegetation biomass without quantifying absolute amounts of biomass stocks2,12, which is indispensable for tracing the role of vegetation in the carbon cycle over time but does not allow calculating e.g. restoration potentials. Furthermore, large knowledge gaps remain concerning the impact of various land use activities on biomass stocks1,2,13.

Informed design, implementation, monitoring and verification of land-based climate change mitigation strategies requires comprehensive and systematic stocktaking of the carbon stored in vegetation14. Beyond accounts of carbon-stock changes, stocktaking also needs to consider (a) the potential and actual biomass stocks of the terrestrial vegetation, (b) the full impact of land use on biomass stocks, i.e. both land cover conversion and land management, and (c) the uncertainty of biomass stock estimates. Here, we compile such information, complementary to current approaches that quantify actual biomass stocks6–8,15,16 (Extended Data Figure 2).

We present seven global maps of the actual biomass stocks (Extended Data Figure 3), here defined as the terrestrial living aboveground and belowground vegetation biomass measured in grams of carbon, based on remote sensing6–8 and inventory-derived information15,16. Ecological literature on biomass stocks of natural zonal vegetation (Supporting information Tables 1-2) was combined with state-of-the-art biome maps (Method section), accounting for areas without vegetation, to obtain six reconstructions of potential biomass stocks, defined as biomass stocks that would exist without human disturbance under current environmental conditions (Methods section, Extended Data Figure 4). Because actual and

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potential biomass stocks both refer to the same environmental conditions, their difference isolates the effect of land use on biomass stocks (Methods section).

Variation within both sets of maps was interpreted as a measure of uncertainty, assuming that the uncertainty is the result of differences between approaches rather than measurement errors within a single approach. From the variation between the seven actual biomass estimates, a detection limit map for stock changes was calculated (Methods section). Permuting potential and actual maps resulted in 42 pairs enabling to quantify the effects of land use on biomass stocks17,18. Note that landscape level spatial variability in biomass stocks, e.g. due to age class structure, variation in soil fertility and soil water availability, are accounted for differently for the potential and actual biomass stock estimates (Method Section). This could introduce a bias of unknown sign and size when interpreting the fine-scale spatial patterns of the biomass-stock reduction maps.

Two of the actual biomass stock maps (“FRA15-based” and “Pan16-based”) were established on the basis of a present day land-use dataset (Methods section) and therefore allowed systematically separating the effects of (a) land-cover conversion, i.e. change in the biomass stocks due to conversion of pristine ecosystems into artificial grassland, cropland or infrastructure, and (b) land management, i.e. management-induced changes that occur within unaltered land-cover types such as forests, savannas and other natural grasslands (Extended Data Figure 2).

At the global scale, the biomass stocks of the currently prevailing vegetation amount to a mean of 450 PgC (range of the seven estimates: 380 to 536 PgC, coefficient of variation 11%). In contrast, biomass stocks of potential vegetation amount to a mean of 920 PgC (range of the six estimates: 771 to 1,107 PgC, coefficient of variation 12%). Our analysis thus suggests that land use halves the amount of carbon potentially stored in terrestrial biomass (Fig. 1). Irrespective of the climate zone, the potential-actual difference of biomass largely follows the pattern of global agriculture, with hotspots in South and East Asia, and Europe, as well as the Eastern part of North and South America (Fig. 1A). Considerable differences between potential and actual biomass stocks also occur in regions dominated by forest and natural grassland use (Extended Data Figure 5a and b). Given that biomass stocks are a function of net primary production and turnover time, a 50% reduction of the turnover time18 and a 10% land-use induced decrease in NPP19 explains the reduced biomass stocks.

The 42 pairs of potential-to-actual biomass stock differences show a median of 49%, with the inner quantiles ranging from 43 to 55%, which implies an average impact on biomass stocks of 447 PgC (inner quartiles 375 to 525 PgC; Fig. 1B).

The FRA- and Pan-based approaches allow separating the effects of land-cover conversion and land management (Fig. 1C). Due to land-cover conversion (Method section), actual biomass stocks reach only 10% of potential biomass stocks per unit area (Fig. 2A), affecting only a relatively small area of 28 Mkm^2. In contrast, on an area of 56 Mkm^2 of managed but not converted ecosystems, the actual biomass stocks reach 60 to 69% of the potential biomass stock per unit area. In consequence, land-cover conversion (53-58%) and land management (42-47%) contribute almost equally to the overall difference between potential and actual and biomass stocks. Forest management contributes two thirds and grazing one third to the management-induced difference in biomass stocks (Fig. 1C and 2B; Extended Data Table 1).

The massive impact of land management on vegetation biomass suggests that estimates of historical land-use change emissions are incomplete if only deforestation is considered (Extended Data Table 2). Contextualizing our results with accounts of the global terrestrial carbon balance suggests that pre-industrial land use impacts on biomass stocks were considerable (115-425 PgC of the total difference of 375-525 PgC; Extended Data Table 3), corroborating model-based findings20; such larger preindustrial emissions are consistent with recent estimates of the global carbon budget considering strong but uncertain processes of natural sinks such as peat build-up (see Supporting Information).

Alternatively -- or in addition -- they point to an underestimation of the strength of the current terrestrial carbon sink, as suggested by model-based studies12,13. In order to reduce the large uncertainty range of current estimates, future research will need to scrutinize the role of land management, in particular in non-forest ecosystems, often ignored in global carbon studies. It is important to note that the difference between potential and actual biomass stocks represents only a rough proxy for cumulative emissions from land use. First, it does not include soil carbon and product pools. Including soil carbon would probably increase the difference, including products would decrease it. Large uncertainties prevail for the two components, but their effects are generally estimated to be small in comparison to biomass changes12,21. Second, the difference between actual and potential carbon stocks is not identical to stock changes between two points in time. Both actual and potential biomass stocks refer to the same environmental conditions, thus their difference integrates two effects: cumulative land-use emissions and land-use induced reductions in carbon sequestration that would result from environmental changes (Extended Data Figure 2, Supporting Information). Therefore, cumulative emissions are probably smaller than the overall impact of land use on biomass stocks, depending on the uncertain13,20 strength of the environmental effect.

The large importance of land management for terrestrial biomass stocks has far reaching consequences for climate-change mitigation. The difference between actual and potential biomass stocks can be interpreted as the upper bound of the carbon sequestration potential of terrestrial vegetation. Long-term changes of growth conditions, e.g. due to large-scale alterations of hydrological conditions or severe soil degradation, could lower this potential. Conversely, climate change could increase the future potential biomass stocks of ecosystems, but this effect is highly uncertain13,22,23. Managing vegetation carbon so that it reaches its current potential would store the equivalent of 50 years of carbon emissions at the current rate of 9 PgC yr^{-1}, but that is not be feasible because it would mean taking all agricultural land out of production. More plausible potentials are much lower (Extended Data Table 4); e.g. restoring used forests to 90% of their potential biomass would absorb fossil fuel emissions for 7 to 12 years. However, such strategies would entail severe reductions in annual wood harvest volumes, because optimizing forest harvest reduces forest biomass compared to potential biomass stocks24. In contrast, widely supported plans to substantially raise the contribution of biomass to raw material and energy supply, e.g. in the context of the so-called bioeconomy25, imply a need for increased harvests24. From a greenhouse gas perspective, the challenge for land managers is to maintain or increase biomass productivity while at the same time maintaining or even enhancing biomass stocks.

Although the uncertainty ranges of actual and potential biomass stocks are typically around 35% of the median estimate, the estimates rarely overlap across the latitudinal north-south gradient (Fig. 3A). While the potential biomass stock shows a similar uncertainty level across most relevant biomes, uncertainty patterns are noteworthy for the actual biomass stock. Actual biomass stock estimates are particularly uncertain in the tropics, a region that contains about half of today's global biomass stocks (Figure 1C).

The spatial uncertainty patterns are relevant for designing and monitoring of climate-change mitigation efforts such as carbon stock restoration. While industrialized countries have access to much finer and more robust data than those used here, most developing countries have to rely on global data such as those used in this study5,16. The uncertainty range could be narrowed if a single robust, validated method would be applied continuously in the stocktaking efforts. Indeed, technical facilities for deriving robust estimates of actual biomass stocks will soon become available (e.g. ESA's biomass mission26, NASA's GEDI mission27 as well as integration efforts (http://globbiomass.org/). The current planning, however, suggests that this capacity will not be fully operational before 2023, and until then, restoration planning and monitoring will have to rely on existing global data sets and their present-day uncertainties.

In boreal and temperate forests restoration efforts would be detectable even against the present-day uncertainties. But three quarters of the global restoration potentials are situated in tropical regions (Fig. 1C, Extended Data Table 4), where biomass stocks would need to increase by over 750 gC m^{-2} yr^{-1} for 10 consecutive years in order to be detectable against variation between global data. A large threat to biomass stock conservation comes from the use of dry tropical forests and savannas, in particular in Africa where these biomes have been identified as having high potential for increasing global agricultural production, to improve global food security or bioenergy supply28. Given current detection limits for tropical biomes, both intensified land use in dry tropical forests and savannas as well as restoration efforts in tropical forests are questionable due to the possibility of undetectable carbon debts from land-use intensification29 or unverifiable gains from carbon restoration measures.

Our analysis suggests that land use impacts were significant already in the preindustrial period and reveals that effects of forest management and grazing on vegetation biomass are comparable in magnitude to the effects of deforestation. Hence, a focus on biomass stocks helps recognizing option spaces for land-based GHG mitigation beyond the mere conservation of forest area. Our findings also suggest that important trade-offs in climate-change mitigation are to be tackled. The scientific and political focus on forest protection and productivity increases needs to be complemented by analyses of the interactions between land use and the carbon state of ecosystems.

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Methods

We established six datasets for potential biomass stocks and seven datasets for actual biomass stocks,. All maps were constructed at the spatial resolution of five arc minutes. Datasets were chosen based on their coverage (i.e. only maps covering large parts of the globe were included) and their plausibility. Given that most datasets did not cover all land-use types, all regions of the globe, or all relevant biomass stocks, some completion exercises were performed to generate consistently comparable datasets. These relied on different types of evidence such as land-use information, information from census statistics, remotely-sensed information, and modifications of assumptions on biomass stock density of different land-use categories and ecozones. In the following, the construction of the individual maps is described.

Actual biomass stock maps 1 and 2

(FRA-based and Pan based, extended Data Figure 3A and B) allowed to isolate the effect of individual land-uses. They were based on a consistent land-use dataset, derived and modified from previous work30. The dataset was adjusted to newly available statistical data on the national extent of forests15 and cropland31. Information on cropland types 32 was used to identify permanent crops, other trees within cropland 33 are not included in the cropland layer, complying with FAO definitions31. Unused land was identified on basis of previous assessments (e.g. delineating unproductive land with a productivity threshold of 20gC/ $m^{-2}yr^{-1}$)19,30, information on permanent snow from a land cover product34, a thematic footprint map 35 and a map on intact forests36. All land not classified as infrastructure, cropland or forestry was defined as grazing land. Grazing land was split into three layers: (1) Artificial grasslands, i.e. grasslands on potentially forested areas, (2) natural grasslands with trees, including savannahs and other wooded land, and (3) natural grasslands without tress (e.g. temperate steppes), based on land cover information on the extent of land under agricultural management34, biome maps37–39 and MODIS data40 on fractional tree cover, applying a tree cover of 5% at the resolution of 500m to discern grazing land with and without trees, in fractional cover representation. The final land-use dataset discerns the following classes: *Unused land*: 1. Non-productive and snow, 2. Wilderness, no trees, 3. Unused forests. *Used land*: 4. Infrastructure, 5. Cropland, 6. Used forests, 7. Artificial grassland, 8. Natural grassland, no trees, 9. Natural grassland with trees.

To each land-use unit, typical biomass stock density values from the literature or census statistics were assigned. For forests, the FRA-based map uses national-level data from the global Forest Resource Assessment15. In contrast, the Pan-based map16 uses data from for forest inventories and site data. The Pan-based estimate is higher particularly in the tropical forests, but slightly lower in boreal forest biomass stocks, resulting in overall higher total forest biomass stocks (361 PgC in contrast to 298 PgC, for forests only). National forest biomass stock data were downscaled to the grid using information on tree height from a global database41, following the finding that tree height is among the critical factors determining biomass stocks and can thus serve as proxy to spatially allocate biomass stock densities at large scales18,42. Minimum biomass stock density for forests was set to 3 kgC m^{-2} to discern forests from scrub vegetation and other wooded land. For grassland-tree mosaics, no census data on biomass stocks is available. For some countries, data on wood stocking (in m^3) of other wooded land is available 15, showing a range between 0.4% to 21% (inner 50% quartiles) of forest biomass stocks per unit area, with "outliers" >90%. World region aggregates of biomass stock densities on other wooded land range between 15% and 28% of the values for forests, with a world average of 23%. In order to consider non-woody components, which are of larger importance for other wooded land compared to forests, as well to produce a conservative estimate, we assumed biomass stock per unit area on other wooded land to be 50% of the corresponding values for forests at the national level. For herbaceous vegetation units (artificial grassland on potential forest sites, cropland and natural grassland without trees), we assumed biomass stocks to equal the annual amount of net primary production18. For permanent cropland, we added 3 kgC m^{-2} for tree-bearing systems and 1.5 kgC m^{-2} for shrub bearing systems to account for woody above- and belowground compartments, in line with estimates in the literature (Supporting information Table 3). In the absence of data, and due to the small extent of this land-use type, biomass stocks on infrastructure areas were calculated as one sixth of potential biomass stocks. This assumes one third of infrastructure to be covered by 50% vegetation with trees and 50% artificial grassland (the latter were assigned no additional biomass, as the potential biomass stocks already provide a progressive estimate). Effects of land degradation on natural grassland (with and without trees) were modelled based losses in net primary productivity derived from43.

Actual biomass stock maps 3 and 4

(Saatchi-based and Baccini-based, Extended Data Figure 3C, D). Two remote-sensing based maps were created by combining independent remote-sensing products for tree vegetation (including foliage) and expanding them to account for below-ground and herbaceous compartments where necessary. At the global scale, five distinct regions can be discerned with regards to the availability of global remote-sensing based products. For the northern boreal and temperate forests one product is available8,44. A large part of the tropical zone is covered by two datasets 6,7. These two datasets show pronounced differences, among each other as well as in comparison with in-situ data 9,10. A smaller fraction of the tropical zone, including a large part of Australia, South America and South Africa is covered by only one of the remote-sensing datasets 6, while a region in China is covered by two datasets6,8. For some regions (the southernmost part of Australia, parts of Oceania), no remote-sensing data are available. In these regions, map 1 was used in the compilation of map 3 and 4. Map 3 was constructed by a) complementing forest biomass stock data for the temperate and boreal zones8 with data on net primary productivity18 in order to account for herbaceous vegetation, applying a forest-non-forest mask derived from the GLC2000 land cover map34. The resulting map for the northern forests was b) combined with the biomass stock map for the tropical zone6. The latter was also extended with data on net primary productivity 18 to account for the herbaceous fractions. For map 4, we replaced values for woody vegetation form map 3) with data from Baccini et al.7, where available.

Actual biomass stock maps 5 and 6

(cell-based minima and maxima of the remote-sensing maps, Extended Data Figure 3E, F). While maps 3 and 4 serve as a best guess available from remote-sensing products these two

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maps were based on a statistical approach, calculating the cell-based minima and maxima of various remote-sensing input data, allowing for an assessment of the absolute upper and lower boundaries, breaking up auto-correlated nature of remote-sensing derived maps. Maps 3 and 4 were used as input. Furthermore, a modulation was calculated for the area covered only by the map of Thurner et al. 8. This map uses a forest mask derived from GLC2000 34. In order to reflect the uncertainty of this land cover map, we used an alternative forest mask to calculate new values at the grid level. We projected the grid-based biomass stock density values from Thurner et al. 8 to the MODIS fractional tree cover dataset 40. Additionally, alternative maps for net primary productivity were used to complement these biomass stock map for woody vegetation, derived by a vegetation model45, a numerical model 46, and from remote-sensing data47. Map 5 was calculated as the cell-based minima, map 6 as the cell-based maxima of these input layers.

Actual biomass stock map 7

(Ruesch and Gibbs, Extended Data Figure 3G). A seventh map was taken from the literature48.

No robust empirical information is available that would allow to resolve the discrepancies between the two datasets based on consistent, spatially explicit land-use information (maps 1 and 2). The difference between these two estimates amounts to 79 PgC. Both assessments are inventory-based, but Pan et al.16 use long-term measurements of network plots for the tropical regions to compensate for data gaps, while FRA reports national data which are often based on remote sensing. The contribution of global remote sensing data (“bench-mark maps”) to resolve this discrepancy is still limited. The two available high-resolution datasets covering the tropics6,7 show pronounced differences, between each other and in comparison with in-situ data 9,10. The Pan-based estimate is situated between these two estimates, while the FRA is situated below the minimum. However, a study based on alternative site data49 corrected both maps downwards, close to the grid-based minimum of both accounts, better matching the FRA-based assessment.

Potential biomass stock maps

Potential vegetation refers to a hypothetical state of vegetation which would prevail without human activities but under current climate conditions50. We compiled five maps following an ecozone approach, allocating typical carbon densities of zonal vegetation to state-of-the art ecozone maps for current climate conditions37–39, with current coastlines and current permanent ice cover. The carbon density values refer to landscape-level averages and take effects of age distribution, natural disturbance into account. We used high-resolution data51 to exclude small water bodies and small-scale bare areas, with the exception of ecosystems where carbon stock values take bare areas already into account, e.g. steppes and thorn savannas. Small-scale variability caused by e.g. the spatial variability of edaphic conditions or water availability (azonal vegetation) was neglected. No information is available that allows to determine if this omission, or sampling biases in the input data, introduces an upward or downward bias in the maps. Input data could be biased towards high values if sampling favoured undisturbed, old-grown stands, or towards lower values, if the data were derived from human-disturbed vegetation in the absence of natural vegetation remnants for certain ecosystem types. The comparison with other estimates shows that our data are well in line with the literature (Extended Data Figure 1) and suggest such biases to play a minor role. Furthermore, approximations of upper and lower estimates for potential vegetation were calculated to determine realistic ranges of global biomass stocks.

Potential biomass stock maps 1 and 2

(IPCC-based, FRA adjusted; IPCC-based, Pan adjusted, Extended Data Figure 4A, B). Two maps were constructed to consistently match the actual biomass stock maps 1 and 2. They build upon best-available estimates on potential, landscape average biomass stock densities for zonal vegetation, mainly from IPCC values52, with the exception of boreal forests. Here, due to large uncertainties42,53,54, the maximum values of biome-wide actual biomass stocks per unit area between 1990 and 200716 were used to derive a conservative estimate. Map 1 was subsequently adjusted at the grid-level so that potential biomass stock values below actual biomass stock levels matched the actual biomass stocks in the FRA-based map. For map 2, this adjustment was done with the Pan-based map.

Potential biomass stock maps 3 and 4

("classic data", cell-based minima and maxima, Extended Data Figure 4C, D). Two further maps were calculated by using biomass stock density values 3,38,55 for natural, zonal vegetation, from synthesis efforts of site-specific data e.g. from the International Biological Programme e.g. 56. Similar to maps 1 and 2, these values were allocated to the three biome maps37–39, and the cell-based minima (map 3) and maxima (map 4) of all three maps were calculated.

Potential biomass stock map 5

(remote-sensing based, Extended Data Figure 4E). A fifth map was derived from the remote-sensing maps 3 and 4 on actual biomass stocks. For all 1303 ecozones that result from the intersection of the three biomes maps37–39 mentioned above (see Extended Data Figure 5E), the 95 percentile biomass stock values of all 30 arc second grid cells (1 x 1 km at the equator) within one ecozone, excluding agricultural lands, derived from the GLC2000 34, was calculated. For ecozones covered by more than one remote sensing map, we used the arithmetic mean. This approximation builds upon the assumption that that in each ecozone, areas of natural vegetation units remain which are representative for the respective ecozone's potential biomass stock densities and that the values take natural disturbance into account (owing to the grain size of the input maps and selection procedure). This is confirmed by a cross-check that revealed the 95 percentile to be on average 51% lower than the maxima values found in each ecozone. Using maxima values, the global biomass would be 1.56 times larger than the one estimated here. An upper bias in this map could emerge from the neglect of naturally unfavourable sites within an ecozone (due to e.g. low water availability or soil fertility); a lower bias could emerge if in an ecozone only disturbed vegetation units prevail, or most of the favourable sites are converted.

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Potential biomass stock map 6

(West et al., Extended Data Figure 4F). An independent sixth map was taken from the literature[57].

Calculation of the land-use induced potential-actual biomass stock difference

In order to assess the range of the effect of land use on biomass stocks, 42 potential-actual biomass stock difference maps were calculated by combining the seven actual biomass stock maps with the six potential biomass stock maps. In all cases, we adjusted the maps so that the actual biomass stocks would not surpass the potential biomass stocks where necessary. Increases of actual over potential biomass stocks could be caused, for instance, by fire prevention. However, the magnitude of this effect is highly uncertain at larger spatial scales, because fire prevention often leads to less frequent, but more damaging fires with larger biomass loads that could compensate for carbon gains[58,59] on longer time scales. On unused land (e.g. wilderness), no land-use induced biomass stock reduction was assumed. Unproductive and water areas were excluded from the assessment. Differences in the spatial thematic resolution of potential and actual biomass stock maps warrant a caveat when interpreting the fine-scale results of the biomass stock difference.

Attribution to land management and land-cover conversions

From the seven actual biomass stock maps, only two allow to consistently isolate and quantify the impact of individual land-use types on biomass-stocks and thus for approximating the impacts of land-cover conversion versus land management (Extended Data Figure 2), i.e. the maps based on consistent, detailed land-use information (FRA-based and Pan-based actual biomass stock maps). From these maps, land-cover conversion impacts are calculated as the sum of potential-actual biomass stock differences due to cropland, artificial grassland (i.e. grassland on potential forest sites) and infrastructure. The biomass-stock differences of all other land-use types were accounted for as the impact of land management. Forest management was considered to dominate land-management effects in forests, and land management practices on other used lands were subsumed as grazing. This approach represents a proxy only. A sharp and unambiguous separation between land-cover conversion and land management would require information on past land uses, which currently is not available, as well as arbitrary decisions on thresholds of change. Examples to illustrate these intricacies are: The biomass stock change on a parcel of land that was cleared from pristine forests to cropland in the past and, after cropland abandonment, is used as forest plantation, would be accounted for as land management, while it would – at least to a certain degree – also represent land-cover conversion if historic uses were to be considered. Similarly, if a forest clear-cut area is used for grazing during the re-growth phase, the biomass stock difference would be attributed to land-conversion, while it might also represent land management. If, due to land use, a forest is changed in terms of its species composition, crown closure, stem height etc. but still remains within key forest parameters (e.g. >10% tree cover, stem height >5m), it is eventually an arbitrary decision if such a change is a land-cover conversion or land management. Additionally, the effects of forest management versus grazing cannot fully be disentangled because of practices such as forest grazing and fuelwood extraction in natural grasslands. Given these practical and theoretical

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ambiguities, we argue that the simple allocation scheme adopted here is a useful proxy based on transparent considerations, making best use of the available datasets. For preparation of Fig. 1C and 2B, we calculated the contributions of land management and conversions separately for the FRA- and Pan-based maps. The minima of the contribution of each land-use type were used for the attribution. The difference of the sum of all minima to 100% was labeled as “ambiguous”, as it is attributed to land management in the one and land-cover conversion in the other map (See Extended Data Table 1).

Calculation of the detection limits based on the actual biomass stock maps

The spatially explicit detection limit for stock changes in actual biomass was estimated from the variation between the seven actual biomass estimates. This assumes that the uncertainty is driven by differences between approaches rather than measurement errors within a single approach and that the seven estimates of the actual biomass stocks are equally likely and, hence, the main source of uncertainty. For each grid cell we mimicked a stocktaking at present (t) and after 10 years (t+10) by randomly selecting two biomass stocks from the uncertainty between approaches for that cell. Subsequently, the detected annual change in biomass stock was calculated. A distribution of 1,000 detected annual changes was obtained through resampling. Given that the annual changes were calculated by sampling the same distribution at *t* and *t+10*, there was no underlying changes in biomass stock. The inner 95% of the detected stock changes within each grid cell were assumed to be insignificant. The 5% stock changes that were found to be significant despite the biomass stock being constant between t and t+10, were used as an estimate for the detection limit in that grid cell. Given present day uncertainties, a real stock change should thus exceed the detection limit to be correctly classified as a change. At present, evidence is missing to consider one approach as being more precise and accurate than the other approaches[9,10,60]. Nevertheless, if future advances would enable selecting a single best approach, the uncertainty and detection limit would decrease and in turn enhance the capacity for verification of changes in biomass stocks.

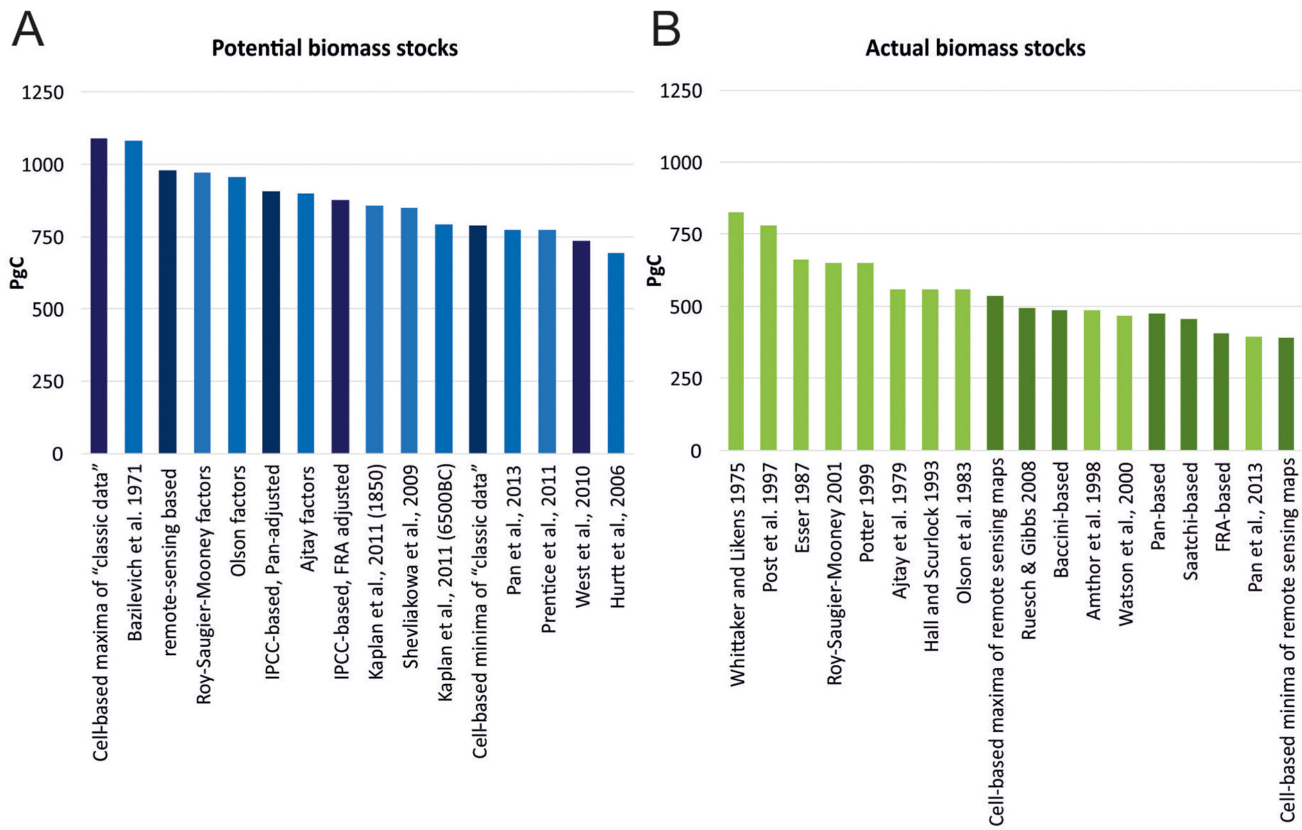
Data availability

The data sources for actual and potential biomass stock estimates are listed above. Source data for Fig1B and C, Fig2 A and B, Fig3A and B, and Extended Data Figure 1 are provided with the paper. Final results, data and maps will be made available at http://www.uni-klu.ac.at/socec. Underlying data, for example, data from other sources, which support findings of this study, are available from the corresponding author upon request.

Code availability

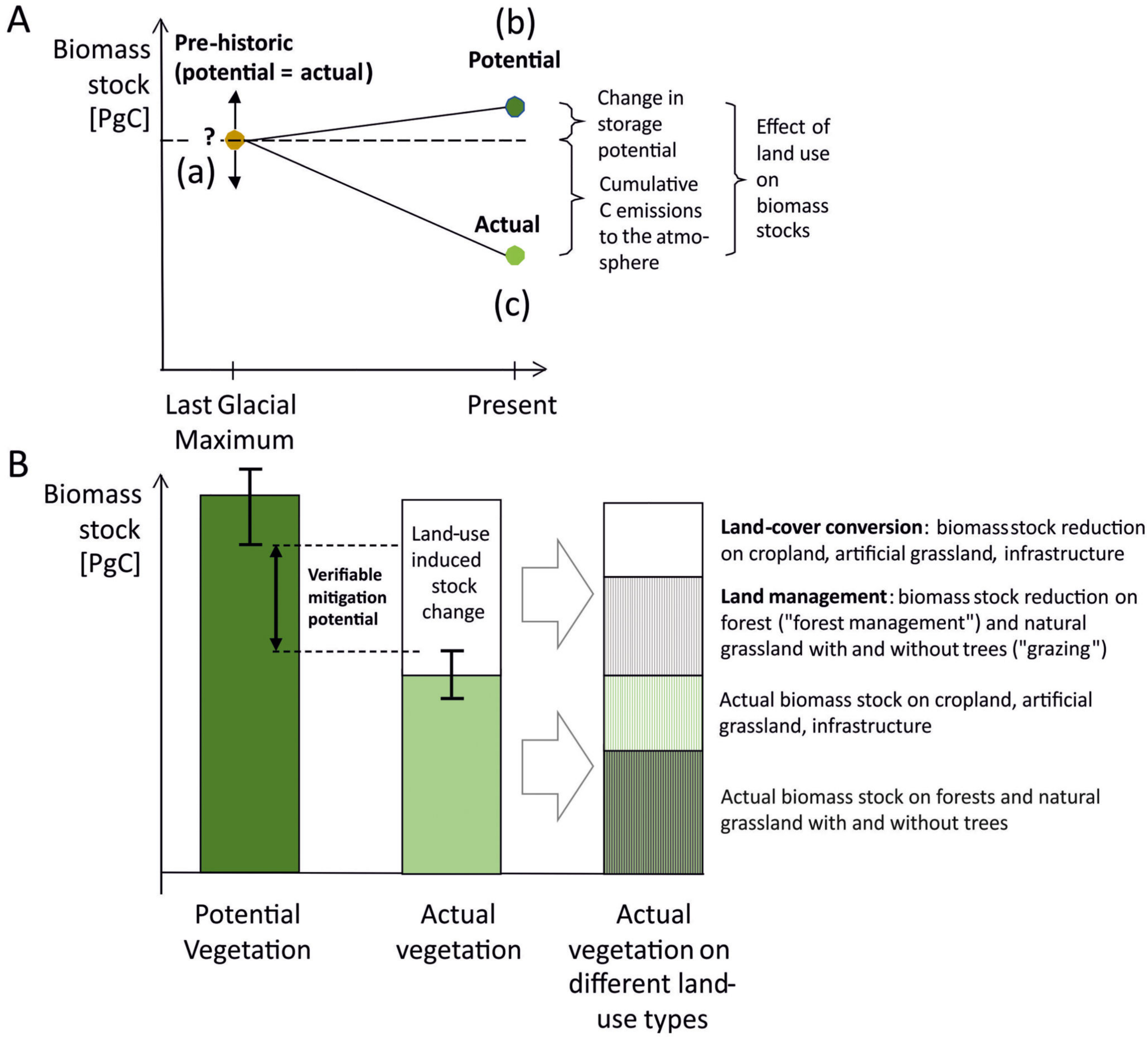
Esri ArcGis and Matlab codes used in the compilation and analysis of results are available upon request from the corresponding author.

Extended Data



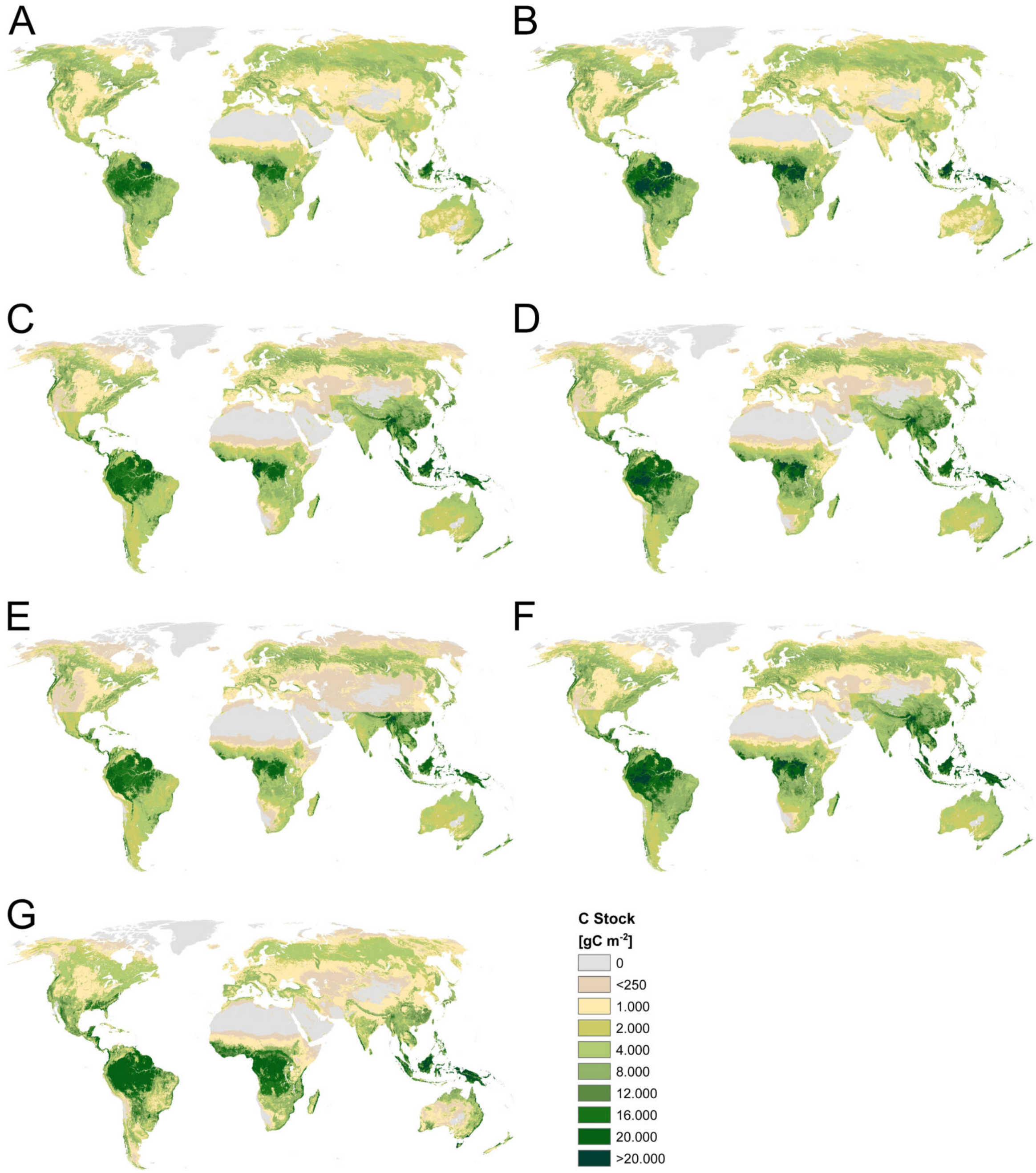
Extended Data Figure 1. Estimates on potential (A) and actual (B) biomass stocks from the literature and this study.

Sources: Bazilevich et al., 197161, Pan et al., 201362, Prentice et al., 201163, West et al., 201057, Hurtt et al., 201164, Whittaker and Likens, 197565, Post et al., 199766, Esser, 198767, Roy-Saugier-Mooney, 20013, Potter, 199968, Ajtay et al., 197955, Hall and Scurlock, 199369, Olson et al., 198370, Ruesch & Gibbs, 200848, Amthor et al., 199871, Watson et al., 200072. The darker shaded columns are those used in this study (for details see text).



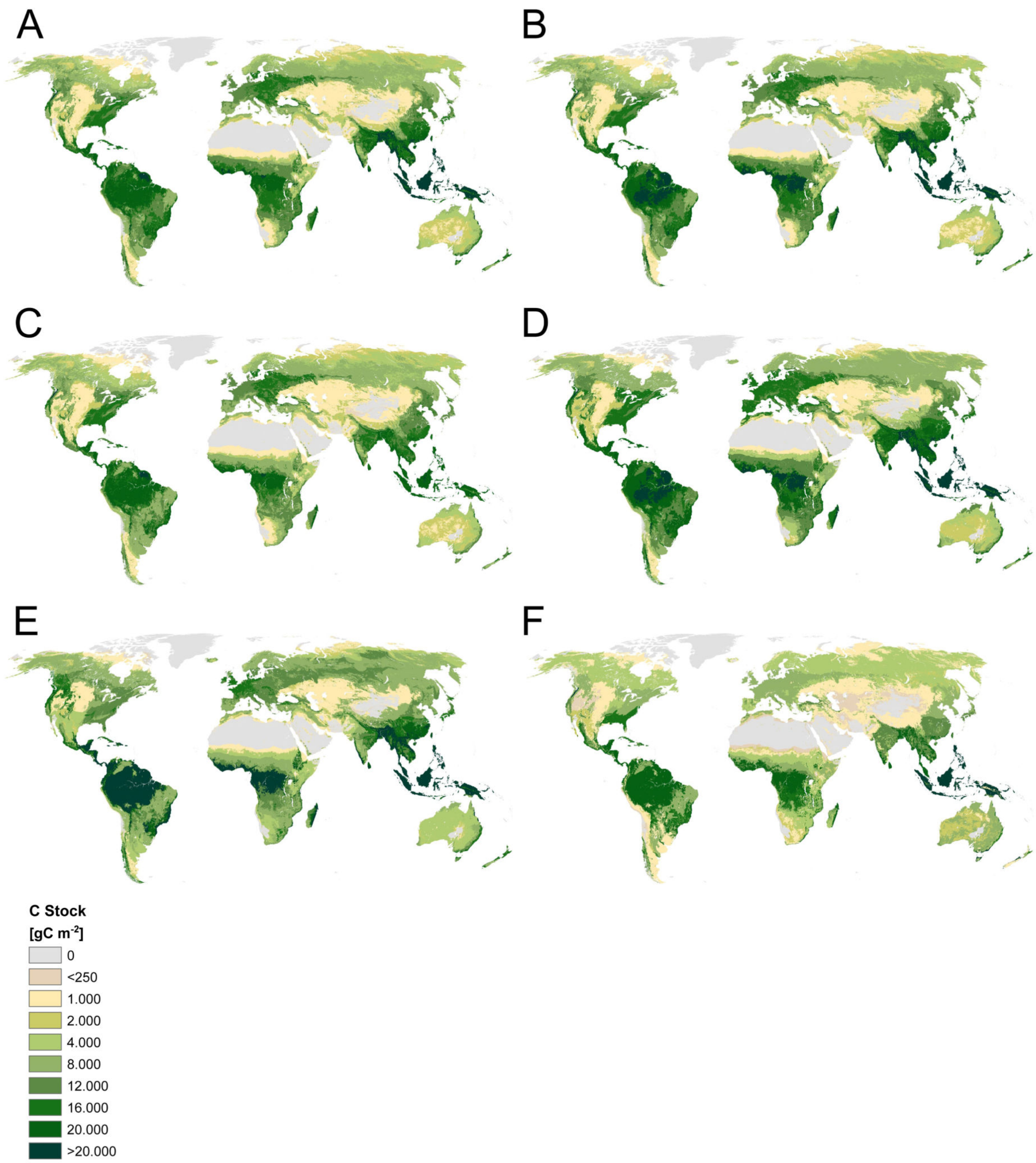
Extended Data Figure 2. Conceptual and methodological design of the study.

A The relation of prehistoric (a), potential (b) and actual (c) biomass stocks. Potential vegetation refers to the vegetation that would prevail in the absence of land use but with current environmental conditions. As both actual and potential vegetation refer to the same environmental conditions, their difference must not be interpreted as a stock change between two points in time. In consequence, the comparison of potential and actual biomass stocks does not refer to the cumulative net balance of all fluxes from and to the biomass compartment (e.g. induced by land use and environmental changes). Rather, it isolates and quantifies the effect of land use on biomass stocks. The effect of land use is comprised of two components, i.e. cumulative land-use emissions and land-use induced reductions in carbon sequestration that would result from environmental changes. For more information and discussion, see Supporting Information. B. Conceptual attribution of the difference between potential and actual biomass stocks to land conversion and land management. Error bars reflect the divergence among datasets for the respective vegetation types and indicate the determination of verification volumes.



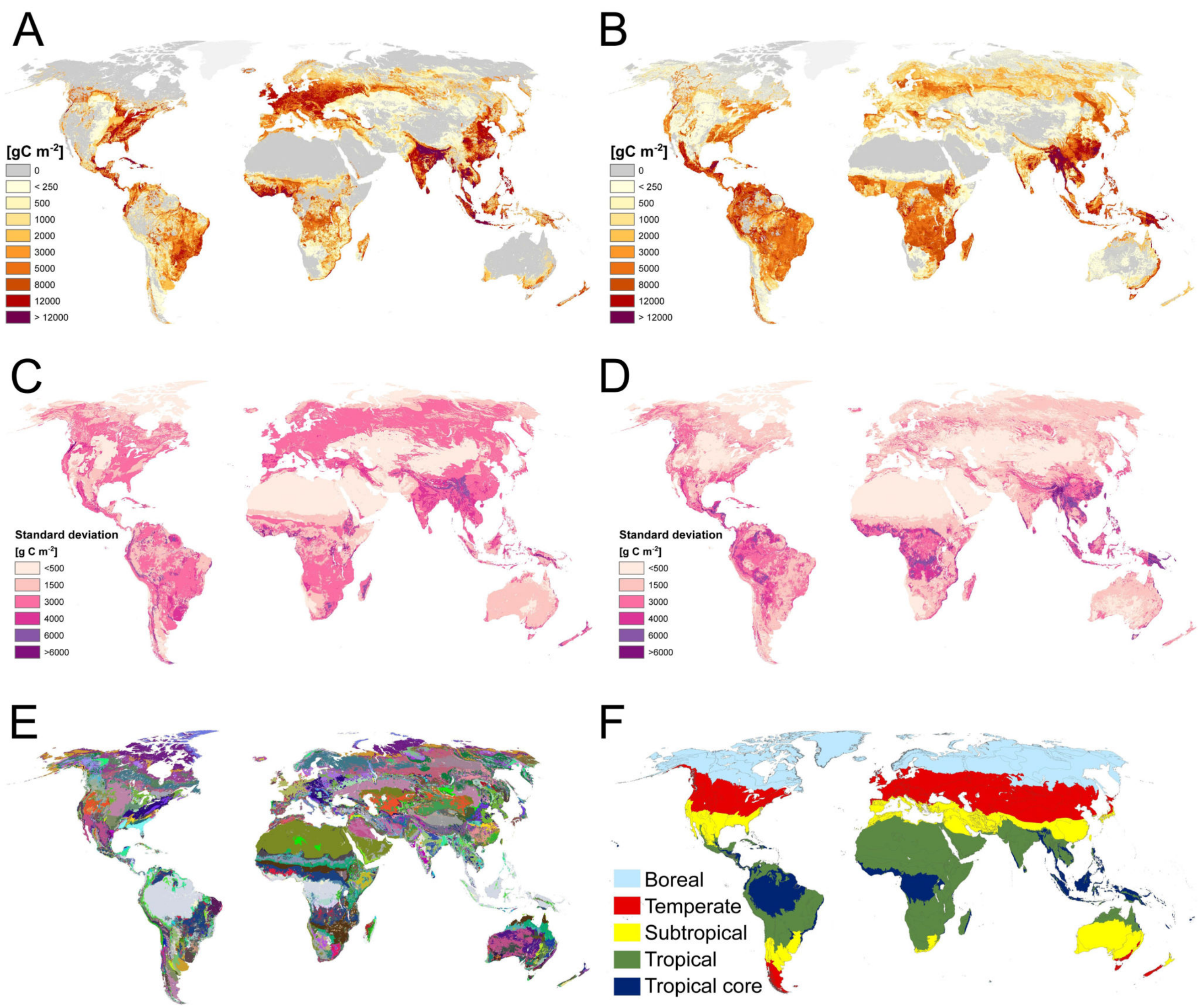
Extended Data Figure 3. Actual biomass stock maps used in the study.

Unproductive areas have been clipped from all maps. A) FRA-based, B) Pan-based, C) Saatchi-based, D) Baccini-based, E) Remote-sensing derived minimum, F) Remote sensing derived maximum, G) Ruesch & Gibbs 200848. For details and sources for maps A-F, see Method section.



Extended Data Figure 4. Potential biomass stock maps used in the study.

Unproductive areas have been clipped from all maps. A) IPCC-based, FRA adjusted, B) IPCC-based, Pan-adjusted, C) Cell-based minima of “classic data”, D) Cell-based maxima of “classic data”, E) Remote sensing derived, F) West et al. 201057. For details and sources for maps A-E, see Method section.



Extended Data Figure 5. Land-use induced difference in potential and actual biomass stocks, uncertainty of input data and vegetation units used in the study.

A) Impact of land-cover conversion, B) impact of land management. A) and B) maps are based on the FRA-based actual biomass stock map and the corresponding, IPCC-based FRA-adjusted potential carbon stock map. C) Standard deviation of potential biomass stocks maps (n=6), D) Standard deviation of actual biomass stock maps (n=7). E) Intersect of all three37–39 biome maps used in the ecozone approaches and for the construction of the RS-based potential biomass stock map. F) FAO Ecozones37 used for the aggregation of results. The “tropical core” consists of humid rainforests. The tropical zones contains moist deciduous forests, dry forests, and tropical shrubs.

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Extended Data Table 1

Biomass stocks per land-use types; ranges indicate the difference between the FRA-based and Pan-based estimate.

	Area	Potential	Actual Biomass Stocks	Difference	Contribution to difference		
	[Mkm^2]	[PgC]	[kgC m^{-2}]	[PgC]	[kgC m-2]	[%]	[%]
Total	**130.4**	**876-906**	**6.7-6.9**	**407-476**	**3.1-3.6**	**48-54%**	**100%**
Infrastructure	***1.4***	***12***	8.6-8.7	***1***	***0.7***	***92-93%***	***2-3%***
Cropland	***15.2***	***139-141***	***9.2-9.3***	***10***	***0.6***	***93%***	***28-31%***
Grassland and grazing land	***54.3***	***374-379***	***6.9-7.0***	***119-121***	***2.2***	***69-70%***	***54-60%***
Forests	***40.7***	***443-460***	***10.9-11.5***	***297-368***	***7.3-9.0***	***22-33%***	***23-31%***
Unused non-forest land	***26.2***	***16-17***	***0.6***	***16-17***	***0.6***	***0%***	***0%***
Land cover change (LCC)							
Cropland	15.2	139-141	9.2-9.3	10	0.6	93%	28-31%
Artificial grasslands	11.3	114-116	10.1-10.3	7	0.6	94%	23-25%
Infrastructure	1.4	12	8.6-8.7	1	0.7	92-93%	2-3%
Land management (LM): forest management							
Used forests							
tropical	22.3	311-327	14.0-14.7	192-251	8.6-11.3	23-38%	18-25%
temperate	5.4	51	9.3-9.4	33-35	6.1-6.4	32-34%	4%
boreal	7.0	40-41	5.7-5.8	30-32	4.2-4.6	21-25%	2%
Subtotal forest management	*34.7*	*401-419*	*11.6-12.1*	*255-318*	*7.3-9.2*	*24-36%*	*23-31%*
Land management (LM): grazing							
Otherwooded land, grasslands-tree mosaics							
tropical	14.6	109-110	7.5	47	3.2	57%	13-15%
temperate	4.0	11	2.8-2.9	5-6	1.2-1.4	50-58%	1-2%
boreal	2.9	10	3.4-3.5	5	1.5-1.7	51-56%	1%
Natural grassland w/o trees	14.2	21	1.5	19	1.3	11-13%	0-1%
Subtotal grazing land	*35.7*	*151-153*	*4.2-4.3*	*75-76*	*2.1*	*5 0-51%*	*16-18%*
No biomass stock change							
Wilderness, productive, w/o trees	9.7	16-17	1.6-1.7	16-17	1.6-1.7	0%	0%
Unused forests	6.0	42-50	7.0-8.3	42-50	7.0-8.3	0%	0%
Unproductive area	16.5	-	-	-	-	0%	0%
Land cover change (LCC)	**27.8**	**265-269**	**9.5-9.7**	**17.1**	**0.6**	**94%**	**53-58%**
Land management (LM)	**56.2**	**553-572**	**7.9-8.1**	**312-374**	**4.7-5.6**	**31-40%**	**42-47%**

Extended Data Table 2

Compilation of published estimates of emissions associated with anthropogenic land-cover change and land management in totals until present (industrial and preindustrial).

Note that most model-based results include fluxes from soils and wood products. *Pre-industrial emissions only

Reference	Land management activities considered	Cumulative emissions
Total cumulative emissions from land use		
DeFries et al., 1999 96	--	182-199
Strassmann et al., 2008 97	--	233
Olofsson and Hickler, 2008 98	--	194-262
Pongratz et al., 2009 83	--	230
Kaplan et al., 2010, Hyde 3.1 based*	--	137-189
Kaplan et al., 2010, KK10 based*	Land-use intensity, shifting cultivation	325-375
Stocker et al., 2014 99	Wood harvest, shifting cultivation	243
This study, FRA- and Pan-based	***Top-down, all activities***	***431-469***
This study, inner quartiles of 42 estimates	***Top-down, all activities***	***375-525***

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Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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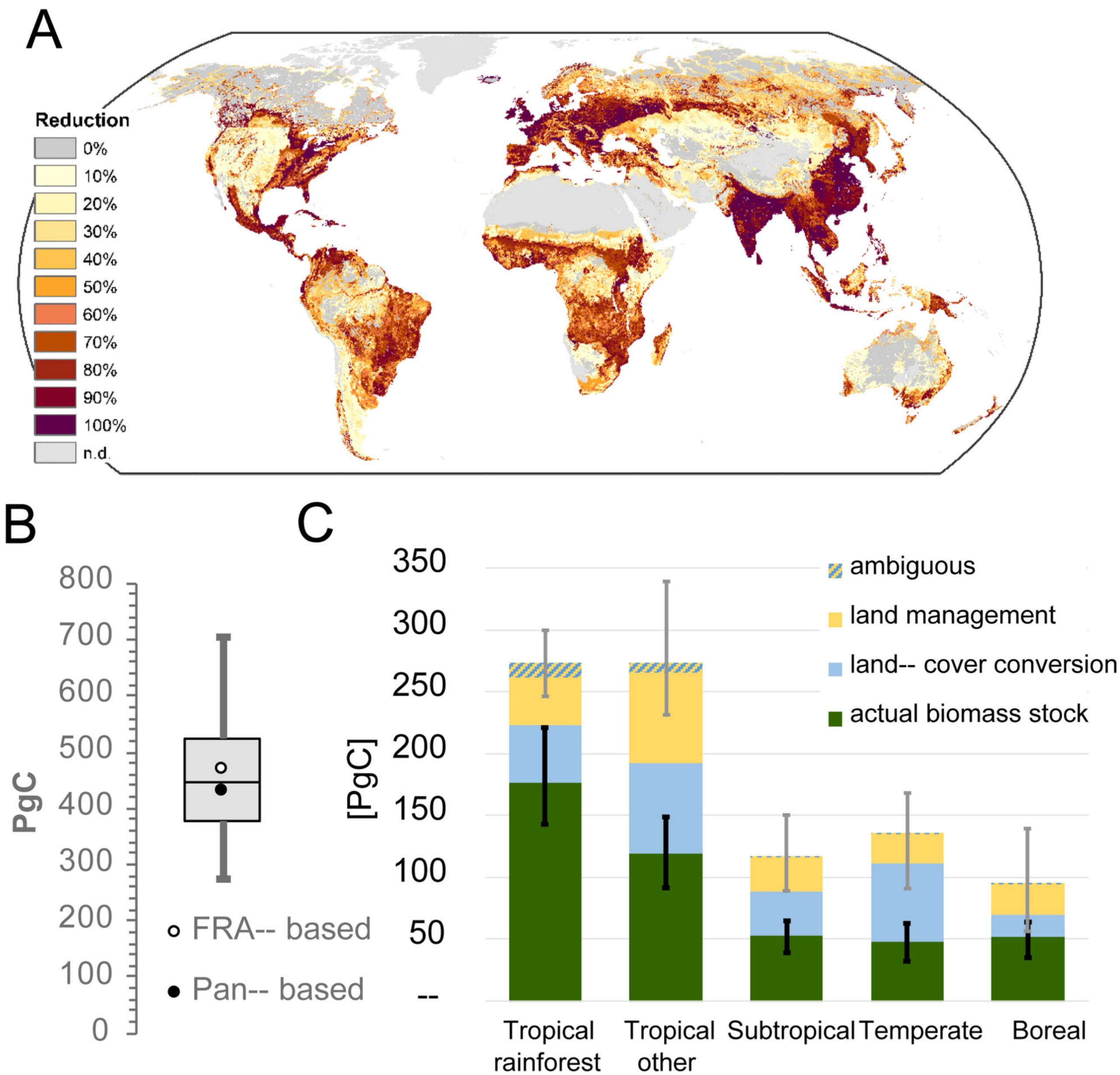

Fig. 1. Differences in biomass stocks of the potential and actual vegetation induced by land use.
A. Spatial pattern of land-use induced biomass stock differences (expressed in percent of potential biomass stocks), mean of all 42 estimates; **B**. Box plot of all 42 estimates. Whiskers indicate the range, the box the inner 50% percentiles, the line the median of all estimates; the two dots represent the results of the two approaches used for the attribution of biomass stock differences to land-cover conversion and land management. **C**. Actual and potential biomass stocks in the world's major biomes (see Extended Data Figure 5f), and role of land-cover conversion and management in explaining their difference. Whiskers indicate the range of the estimates for potential (grey; n=6) and actual (black; n=7) biomass stocks.

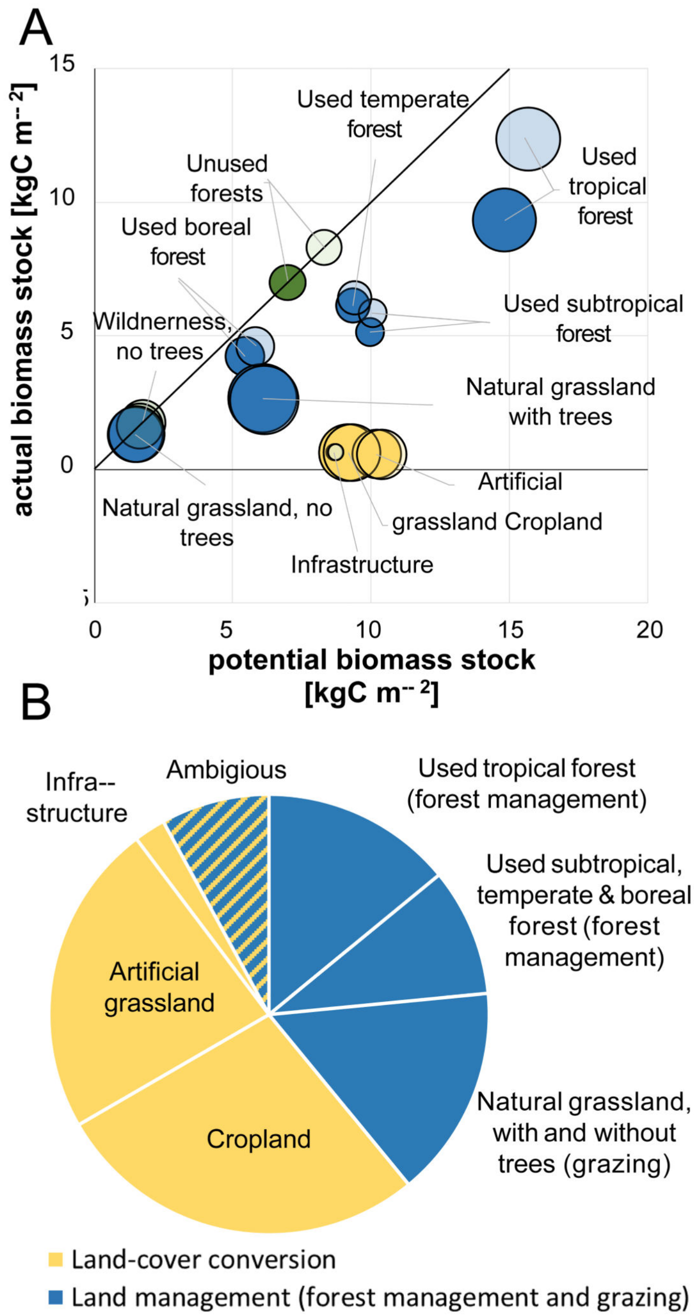

Fig. 2. Contribution of land-use types to the difference between potential and actual biomass stocks.

A. Potential and actual biomass stock per unit area per land-use type for the FRA-based (dark colors) and the Pan-based assessment (light colors). Circle size is proportional to the global extent of the individual land-uses. The diagonal line indicates the 1:1 relationship between actual and potential biomass stocks (no change, green color). **B.** Relative contribution of land-cover conversion and land management to the difference between potential and actual biomass stocks, based on the FRA-based and Pan-based assessments.

"Ambiguous" denotes cases attributed differently in the two assessments (for absolute values refer to Extended Data Table 1).

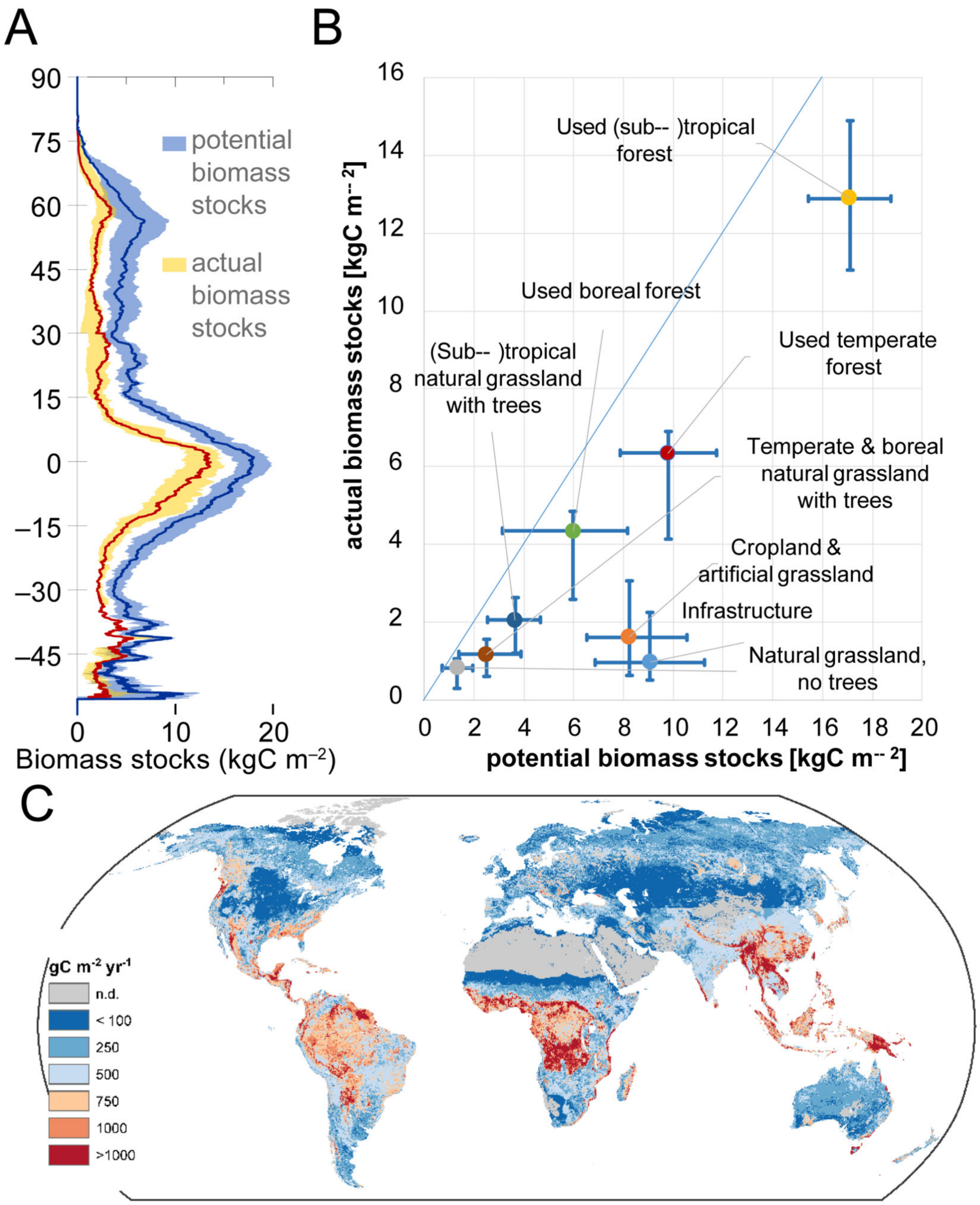

Fig. 3. Uncertainty of biomass stock estimates.

A. Latitudinal profile of all seven actual (yellow) and all six potential (blue) biomass stock estimates, the lines indicate the respective median, shaded areas the envelope (range). **B.** Ranges of potential and actual biomass stocks per land-use type, intersected at the median (n=6 for potential, n=7 for actual biomass stocks). In the absence of consistent land-use information for all layers, biomass stock changes were estimated on grid cells dominated (>85%) by a land-use type and thus slightly deviate from estimates displayed in Fig.2. The diagonal line indicates the 1:1 relationship where actual and potential biomass stocks are equal. **C.** Detection limit of annual changes in actual biomass stocks. Changes in biomass stocks need to exceed the detection limit in order to be detectable, e.g. in monitoring or stocktaking efforts such as foreseen in the Paris Agreement.