best-available estimates on potential, landscape-averaged biomass-stock densities for zonal vegetation, mainly from IPCC values[51], with the exception of boreal forests. For boreal forests, owing to large uncertainties[42,52,53], the maximum values of biome-wide actual biomass stocks per unit area between 1990 and 2007[16] 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 map based on ref. 16.

Potential biomass stock maps 3 and 4. Maps 3 and 4 were based on classic ecological data: cell-based minima and maxima; see Extended Data Fig. 4c, d. Two further maps were calculated by using biomass stock density values[3,38,54] for natural, zonal vegetation, from synthesis efforts of site-specific data, for example, from the International Biological Programme[55]. Similar to maps 1 and 2, these values were allocated to the three biome maps[37–39], and the cell-based minima (map 3) and maxima (map 4) of all three maps were calculated.

Potential biomass stock map 5. A remote-sensing-based map; see Extended Data Fig. 4e. A fifth map was derived from the remote-sensing maps 3 and 4 on actual biomass stocks. For all 1,303 ecozones that result from the intersection of the three biomes maps[37–39] mentioned above (see Extended Data Fig. 5e), the 95 percentile biomass stock values of all 30 arc second grid cells (1×1 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 on the assumption that in each ecozone, areas of natural vegetation units remain that are representative for the potential biomass-stock densities of the respective ecozone 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 that the 95 percentile is on average 51% lower than the maximum values found in each ecozone. Using maximum 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 (owing to, for example, 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.

Potential biomass stock map 6. An independent sixth map was taken from the literature[56]; see Extended Data Fig. 4f.

Calculation of the land-use-induced difference in potential–actual biomass stocks. 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 where necessary, so that the actual biomass stocks would not surpass the potential biomass stocks. Increases in 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[57,58] on longer time scales. On unused land (for example, 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. For two of the actual biomass stock maps, we could isolate and quantify the impact of individual land-use types, that is, the maps based on consistent, detailed land-use information (actual biomass stock maps 1 and 2). From these maps, land-cover conversion impacts were calculated as the sum of potential–actual biomass-stock differences due to cropland, artificial grassland (that is, 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 (Extended Data Fig. 2). Forest management was considered to dominate land-management effects in forests, and land-management practices on other used lands were considered 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-cover conversion, whereas 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 and so on, but still remains within key forest parameters (for example, >10% tree cover, stem height >5 m), it is eventually an arbitrary decision whether this 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 wood extraction for fuel in natural grasslands. Given these practical and theoretical 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 Figs 1c and 2b, we calculated the contributions of land management and conversions separately for the maps based on the data from FRA and ref. 16. The minima of the contribution of each land-use type were used for the attribution. The difference in the sum of all minima to 100% was labelled as 'ambiguous', as it is attributed to land management in the map based on FRA[15] and land-cover conversion in the map based on ref. 16, or vice-versa (see Extended Data Table 1).

Calculation of the detection limits on the basis of 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 in approaches rather than measurement errors within a single approach and that the seven estimates of the actual biomass stocks are equally likely and, therefore, 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 were 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[9,10,59]. 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.

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

Data availability. The data sources for actual and potential biomass-stock estimates are listed above. Source Data for Figs 1b, c, 2a, b, 3a, b and Extended Data Fig. 1 are provided with the online version of the paper. Final results, data and maps are 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.

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