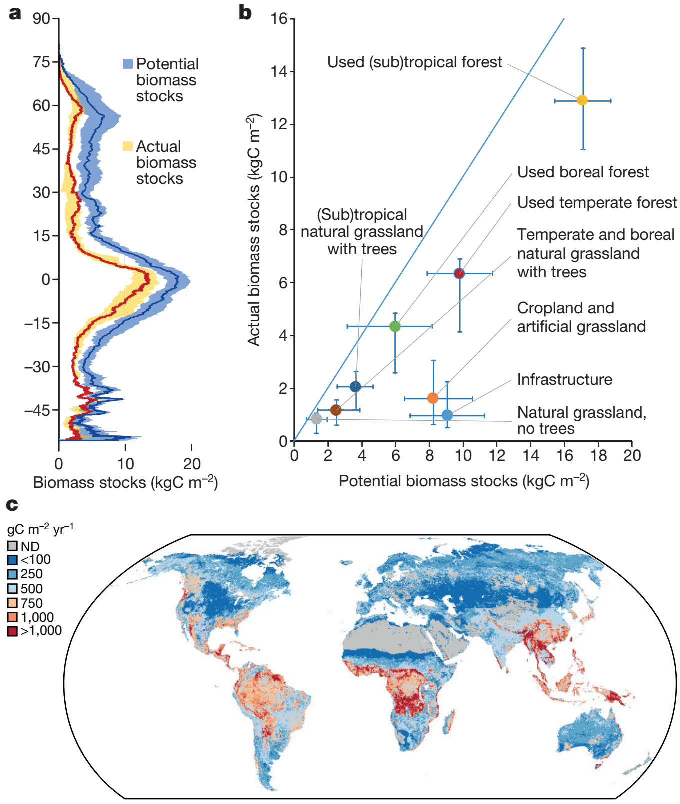

Figure 3 | Uncertainty of biomass stock estimates. a, Latitudinal profile of all seven actual (yellow) and all six potential (blue) biomass stock estimates, the lines indicate the respective median, shaded areas the range. **b**, Ranges of potential and actual biomass stocks per land-use type, intersected 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 therefore deviate slightly 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, for example, in monitoring or stocktaking efforts such as foreseen in the Paris Agreement.

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 findings[20]; these larger pre-industrial emissions are consistent with recent estimates of the global carbon budget considering strong but uncertain processes of natural sinks, such as the build-up of peat (see Supplementary Information).

Alternatively—or in addition—they indicate an underestimation of the strength of the current terrestrial carbon sink, as suggested by model-based studies[12,13]. 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, which are 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. Firstly, it does not include soil carbon and product pools. Including soil carbon would probably increase the difference, whereas including products would decrease it. There are large uncertainties for these two components, but their effects are generally estimated to be small in comparison to biomass changes[12,21]. Secondly, 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, therefore, 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 Fig. 2 and Supplementary Information). Therefore, cumulative emissions are probably smaller than the overall impact of land use on biomass stocks, depending on the uncertain[13,20] 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 boundary of the carbon-sequestration potential of terrestrial vegetation. Long-term changes in growth conditions, for example, due to large-scale alterations in 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 uncertain[13,22,23]. 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 per year (PgC yr^{-1}), but that is not feasible, because it would mean taking all agricultural land out of production. More plausible potentials are much lower (Extended Data Table 4); for example, restoring used forests to 90% of their potential biomass would absorb fossil-fuel emissions for 7–12 years. However, such strategies would entail severe reductions in annual wood harvest volumes, because optimizing forest harvest reduces forest biomass compared to potential biomass stocks[24]. By contrast, widely supported plans to substantially raise the contribution of biomass to raw material and energy supply, for example, in the context of the so-called bioeconomy[25], imply a need for increased harvests[24]. From the perspective of greenhouse gas emissions, 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). Although 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 (Fig. 3b, c), a region that contains more than half of the current global biomass stocks (Fig. 1c).

The spatial uncertainty patterns are relevant for designing and monitoring climate-change mitigation efforts such as carbon-stock restoration. Whereas 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 study[5,16]. 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 improved estimates of actual biomass stocks will soon become available (for example, the Biomass mission of the European Space Agency[26], the Global Ecosystem Dynamics Investigation mission of the National Aeronautics and Space Administration[27] as well as integration efforts (http://globbiomass.org/)). The current planning, however, suggests that this capacity will not be fully operational before the inception of the stocktaking processes, and until then, restoration planning and monitoring will have to rely on existing global datasets and their present-day uncertainties.

In boreal and temperate forests, restoration efforts would be detectable even with the present-day uncertainties (Fig. 3c). But three-quarters of the global restoration potential can be found in tropical regions (Fig. 1c and Extended Data Table 4), where biomass stocks would need to increase by over 750 gC m^{-2} yr^{-1} for 10 consecutive years to be detectable against variation between global data. A large threat to biomass-stock conservation comes from the use of dry tropical forests and savannahs, in particular in Africa, where these biomes have been identified as having a high potential for increasing global agricultural production, to improve global food security or bioenergy supply[28]. Given current detection limits for tropical biomes, both the intensification of land use in dry tropical forests and savannahs and the restoration efforts in tropical forests are questionable because of the