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# Global variation in the cost of increasing ecosystem carbon

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**Slowing the reduction, or increasing the accumulation, of organic carbon stored in biomass and soils has been suggested as a potentially rapid and cost-effective method to reduce the rate of atmospheric carbon increase[1]. The costs of mitigating climate change by increasing ecosystem carbon relative to the baseline or business-as-usual scenario has been quantified in numerous studies, but results have been contradictory, as both methodological issues and substance differences cause variability[2]. Here we show, based on 77 standardized face-to-face interviews of local experts with the best possible knowledge of local land-use economics and sociopolitical context in ten landscapes around the globe, that the estimated cost of increasing ecosystem carbon varied vastly and was perceived to be 16–27 times cheaper in two Indonesian landscapes dominated by peatlands compared with the average of the eight other landscapes. Hence, if reducing emissions from deforestation and forest degradation (REDD+) and other land-use mitigation efforts are to be distributed evenly across forested countries, for example, for the sake of international equity, their overall effectiveness would be dramatically lower than for a cost-minimizing distribution.**

Changes in agriculture, forestry and other land uses are considered central in the mitigation pathways envisioned by the Intergovernmental Panel on Climate Change (IPCC)[3]. Because deforestation 'business as usual' tends to benefit forestland holders and often even forested countries[4], a system of compensated deforestation reduction between poor forested and rich countries has been developed[5]. Hundreds of projects aimed at REDD+ and other forest carbon initiatives with similar objectives have been launched[6]. Their combined impact on the global carbon cycle has so far remained modest[3], but this may change thanks to the signing of the Paris Agreement in early 2016[7].

Information on the costs of mitigating climate change is valuable to avoid spending in landscapes with high cost-effectiveness ratios. Cost curves for forest-based mitigation have been estimated, from the local to global scale, using household-level field surveys[8], contracts allocated by inversed auctions[9], census-based municipal-level data[10] and global simulation models based on national census data[11]. For example, a recent pantropical household survey across 17 different sites finds the time-discounted value of costs per Mg of carbon to vary by more than two orders of magnitude from US$7 to US$944 (ref. [12]). Local-level data are generally methodologically complicated to upscale, whereas census-based approaches often overestimate mitigation costs because agricultural productivity in remote deforestation frontiers often falls markedly short of census-based averages that focus more on modern production systems. Likewise, significant risks of poor governance in environmentally fragile frontier regions remain widely unaccounted.

Hence, the economic literature gives clues, but certainly no consensus, on mitigation costs. Even when only large-scale top-down models are compared, a one-time payment of US$50 for a reduction of one Mg of atmospheric $CO_2$ directed towards land use (comparable with US$183.33 for a sequestered Mg of carbon) is estimated to trigger an annual global atmospheric carbon reduction from as little as 0.14 Pg to as much as 1.39 Pg or equivalent climate impact by 2030[13]. Still more uncertainty is unavoidable when local[14] and global studies[15] are compared. Therefore, the IPCC report lists the cost of mitigation based on land use as a knowledge gap[13].

A well-selected group of local experts may add new knowledge of local land-use economics by being able to combine biogeochemical with sociopolitical information, such as an understanding of institutional opportunities and barriers or resistance caused by perceptions of inequity, in ways that would be very challenging for non-local scholars. Interviews of local experts from around the world, using comparative methods, enables acquiring bottom-up mitigation cost estimates that are open to all mitigation efforts, and accounts for uncertainty caused by variation in expert opinions and carbon data. Below we explore this promising pathway to narrowing an important knowledge gap.

Our objective was to interview the best-available land-use experts of ten landscapes (Supplementary Data) in five countries and continents (Fig. 1) to elicit their opinions on the cost of increasing the ecosystem carbon locally. We conducted eight interviews in each landscape (but only seven in MexicoEast and only six in MexicoWest). We followed a rigid interview structure, beginning with a discussion of the assumptions. We then inquired how land use might change if an annual payment of US$1 were made for every extra Mg of carbon stocked in the landscape. Finally, we asked the same question with a hypothetical payment of US$10. In both cases we asked interviewees to assume the current conditions except good governance that ensured an efficient local distribution of carbon funding. We coded the interview responses on land-use changes relative to the baseline scenario using a new tool called CarboScen[16]. We made the carbon implications available during the interviews so that the interviewees could modify their responses based on the graphic outputs of the tool.

The ten landscapes had widely differing carbon densities in 2015 (Table 1 and Fig. 2). These ranged from 63 Mg ha$^{-1}$ in TanzaniaWest,

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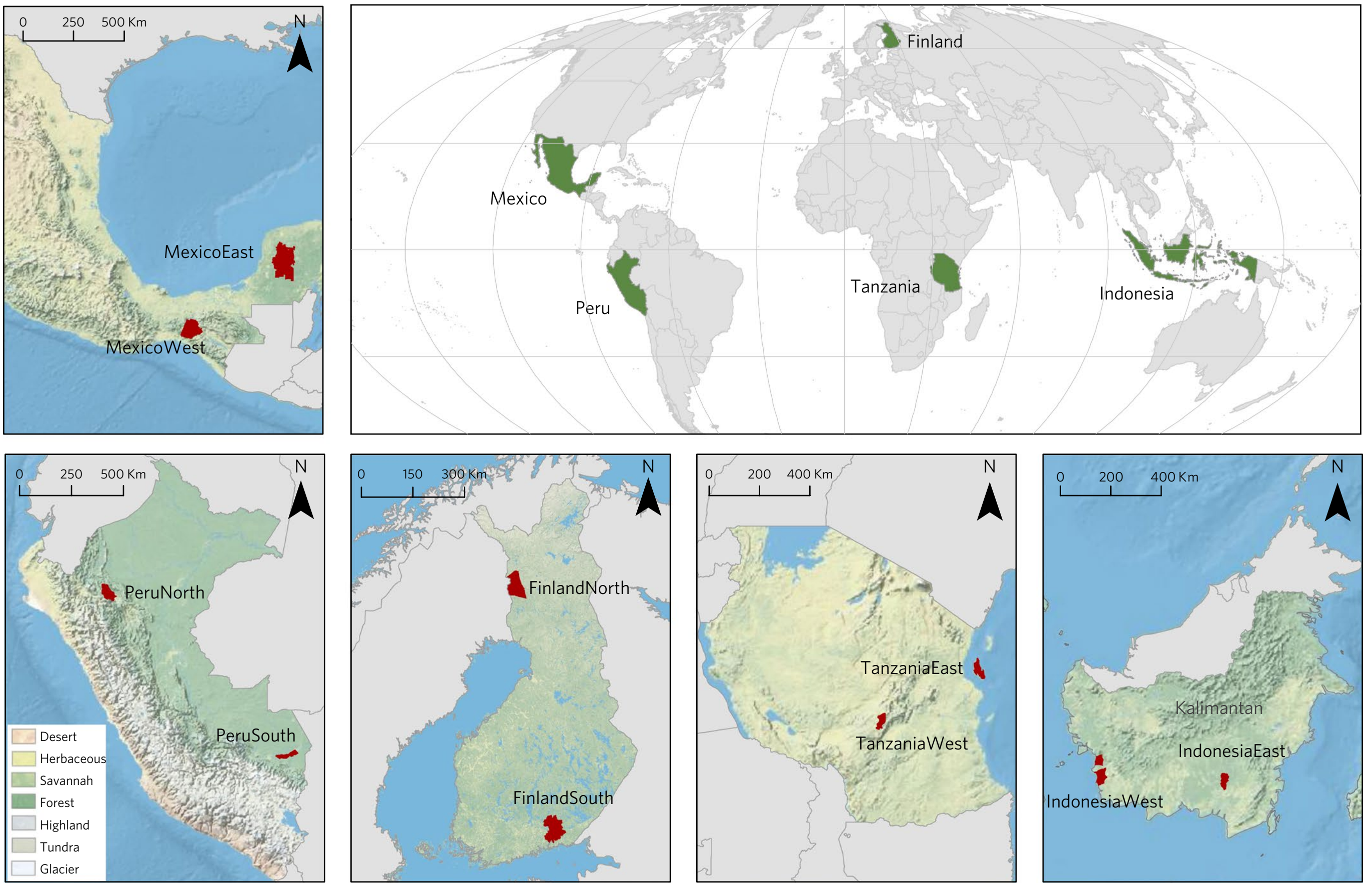


**Fig. 1 | Location of the landscapes.** The large panel shows the five countries in green and the small panels the landscapes in red.

**Table 1 | Initial ecosystem carbon densities and potential additions (Mg ha$^{-1}$)**

| | Carbon density 2015 | | Additional carbon density, US$1, all interviewees[a] | | Additional carbon density, US$10, all interviewees[a] | | Additional carbon density, maximal based on weighted-mean carbon densities[a] |
|---|---|---|---|---|---|---|---|
| | Weighted mean | Confidence interval based on variation in carbon-density data | Mean | Confidence interval based on variation in expert opinions | Mean | Confidence interval based on variation in expert opinions | |
| FinlandNorth | 129.5 | NA | 4.3 | 2.1–6.6 | 14.5 | 10.3–19.4 | 28.1 |
| FinlandSouth | 108.5 | NA | 3.5 | 2.1–5.3 | 8.9 | 6.9–11.1 | 35.0 |
| IndonesiaEast | 4607.6 | NA | 105.6 | 43.6–169.7 | 150.3 | 60.9–240.8 | 492.0 |
| IndonesiaWest | 1933.7 | NA | 36.6 | 7.6–72.2 | 111.0 | 67.7–154.5 | 392.2 |
| MexicoEast | 150.8 | 136.5–159.8 | 2.0 | 0.4–4.5 | 7.3 | 2.8–12.2 | 44.7 |
| MexicoWest | 94.5 | 82.7–117.1 | 0.2 | 0.0–0.5 | 2.7 | 1.2–4.4 | 18.2 |
| PeruNorth | 160.2 | 133.8–337.3 | 3.3 | 1.6–5.2 | 8.7 | 6.5–11.1 | 30.4 |
| PeruSouth | 165.7 | 157.8–175.0 | 4.1 | 2.3–6.2 | 10.4 | 8.5–12.2 | 32.9 |
| TanzaniaEast | 79.6 | 77.2–85.2 | 1.1 | 0.4–1.9 | 2.8 | 1.7–3.8 | 31.0 |
| TanzaniaWest | 63.5 | 45.6–109.3 | 4.2 | 2.0–6.8 | 9.7 | 5.9–13.7 | 45.4 |

[a]We computed additions for 2015–2214 by discounting weights with 3%, so that that the closer the addition is in the future, the more it impacts the value.

with large areas of grassland, to 4,608 Mg ha$^{-1}$ in IndonesiaEast. The two Indonesian landscapes are mainly peat soils. These were included in the analyses because peat layers are vulnerable to human-caused oxidation, unlike organic carbon at similar depths in mineral soils. The initial carbon density varied modestly in the other eight landscapes, depending mainly on the quality and quantity of the remaining forest. We developed baseline scenarios based on plausible land-use changes from 2015 to 2045 and that assumed no payments for additional carbon. Of the eight landscapes, only FinlandNorth showed a substantial increase in carbon density in

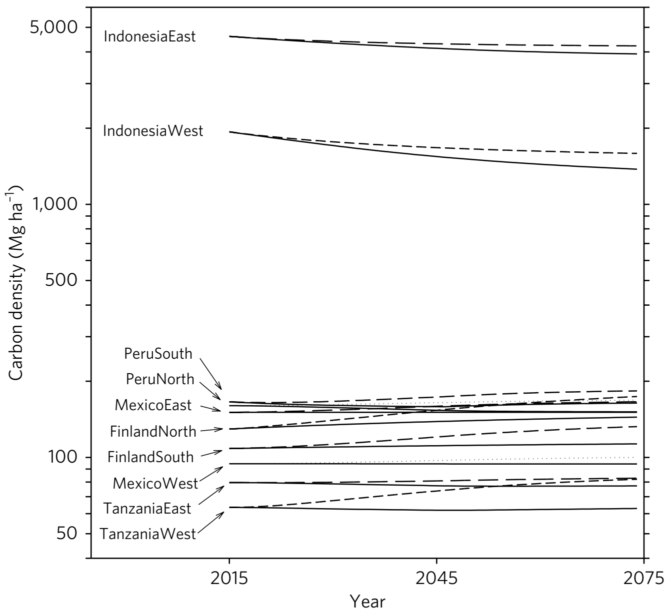


**Fig. 2 | Carbon densities in the studied landscapes during the first 60 years of the simulation.** Solid lines mark the baseline scenarios and dashed lines the scenario with the assumed US$10 annual payment for every additional Mg of ecosystem carbon.

30 years, from 130 to 139 Mg ha$^{-1}$. In contrast, the carbon densities in the two Indonesian landscapes were assumed to collapse under the baseline scenario from 4,608 to 4,133 Mg ha$^{-1}$ and from 1,934 to 1,546 Mg ha$^{-1}$, whereas changes in the baseline scenarios of the other seven landscapes were modest, as shown in Fig. 2. The base map on the top left and the base maps on the bottom row are reproduced with permission from the US National Park Service.

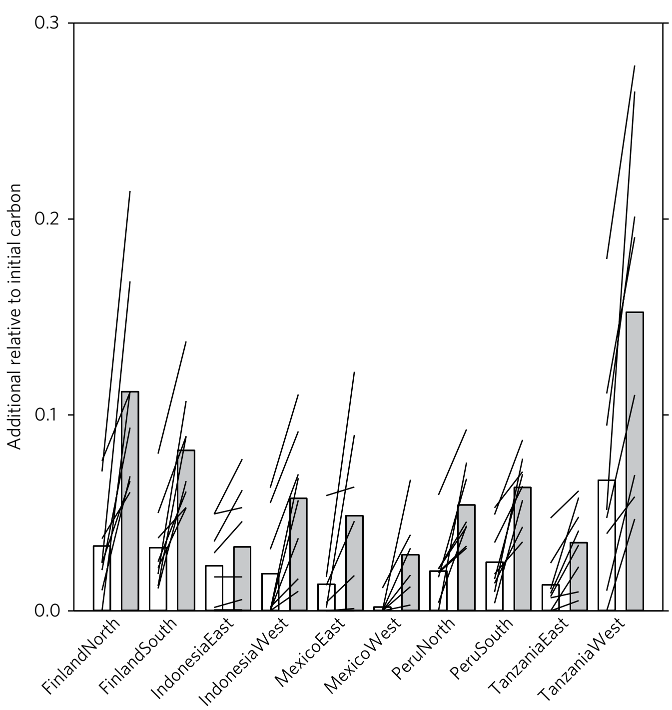


**Fig. 3 | Potential carbon additions as a result of payments relative to the initial by discounting weights with 3%.** The white bars (left) represent the mean expert opinion with an imagined payment of US$1 and the grey bars (right) the mean with a payment of US$10. The lines show responses from individual interviewees from which the means were computed.

Carbon additions from our hypothetical performance-based payments varied significantly relative to the reference scenario, even when the means of all the interviewed experts for a given landscape were compared. For comparison, instead of equally weighting carbon additions for a fixed period of time and not taking carbon implications thereafter into account, we used the mean carbon-density addition discounted by 3%, so that the near future was weighted more than the distant. Based on a hypothetical payment of US$1, this mean varied 578-fold, ranging from 0.2 Mg ha$^{-1}$ in MexicoWest, where all but one of the interviewees did not believe any change would occur, to 105.6 Mg ha$^{-1}$ in IndonesiaEast (Table 1). With a payment of US$10, the range narrowed to 56-fold (Table 1 and Fig. 3). According to the experts, a payment of US$10 led only to a 1.4–3.6-fold carbon increase compared with a US$1 payment, except in MexicoWest where this increase was 14.8-fold (Fig. 3). The less than tenfold carbon change with a tenfold payment suggests marginally declining returns, so that a cost-effective programme would be based on small payments but over large areas. However, a larger area is likely to increase the monitoring cost per added unit of carbon, and thus partially even out the difference. The differences between landscapes diminish when potential additions are compared with the initial carbon densities (Fig. 2) or the nominal potential, that is, the technical maximum (Table 1, right-most column).

We computed the net carbon changes only, and did not attempt to separate quantitatively changes that strengthened positive action, such as reforestation, and weakened negative action, such as deforestation, because their definitions are dependent on spatial and temporal scales. Instead, we qualitatively describe here the envisioned changes. In both Finnish landscapes, the interviewed experts anticipated that most of the carbon increase would result from an increasing carbon density on forestry land, with a small amount from afforestation, and an increased carbon density on cropland. In the Indonesian landscapes, most actions triggered by hypothetical carbon payments occurred on peatlands. Afforestation and rising water-table levels resulted in anticipated changes that conserved some of the peat from oxidization because of aerobic decomposition[17] or from fire[18]. Expert responses in MexicoEast were similar to those in Finland, that is, with increasing carbon density in already forested areas and a small amount of afforestation. In MexicoWest, the experts envisioned, in addition to increasing carbon density of forested areas, a significant afforestation of the area classified as 'Pasture and savannah'. In PeruNorth, the assumed payments triggered carbon increase through 'Coffee' conversion to 'Eco-coffee', that is, coffee production under shade trees[19]. Experts in PeruSouth anticipated a significant increase in the carbon density of forested land, but, additionally, noteworthy afforestation was predicted on agricultural land. In TanzaniaEast, the experts were unusually unanimous in believing that a modest increase in ecosystem carbon could result from forest tree plantations to replace coral rag scrub. In TanzaniaWest, the potential carbon increase was assumed to result from coniferous tree plantations on various open lands.

The scatter of the lines in Fig. 3 reveals the variability in the expert views. Variation was smallest in Finland, probably because of clear land ownership and the common objective to profit from wood production, in addition to the relative ease of envisioning how carbon funding is channelled to forest owners. In contrast, experts in the other landscapes showed a large variation in their views, most of which we are unable to explain with the basic information that we report in Supplementary Table 2 or other knowledge that we learned in the interviews. The only exceptions were the two experts (IndonesiaEastD and MexicoEastG) who did not perceive any influence of the finance assumed to come from a global fund. Their views appeared to originate from thinking that their countries and their peasants should remain independent from funds that come from high-income countries.

The local experts are well placed to combine information on local social and political conditions with land-use economics, and it is very likely that they could realistically envision the changes triggered by the hypothetical payments. We avoided similar backgrounds and selected a group that was probably more diverse than if chosen randomly from local experts. Therefore the variation in their responses (Table 1 and Fig. 3) is likely to overestimate uncertainty relative to a random selection. However, the means derived from their responses could still be biased if several of the experts were influenced by the same biased information. For example, we did not ask the interviewees to think out loud, but most of them justified their responses in detail, and it appears that most did not sufficiently consider the potential price increases of agricultural products caused by carbon payments, and therefore underestimated the cost of increasing carbon. Nevertheless, we believe that such potential biases are similar in all the landscapes, and, therefore, even if the magnitude is off and comparison with other mitigation options could be biased, comparisons among the landscapes should not be influenced drastically. Hence, our data set offers an unprecedented opportunity to shed new light on the global variation in the cost of increasing ecosystem carbon, and could be compared with studies that use completely different methods.

Comparisons with previously published costs to mitigate climate change with land-use change are complicated by different units (Methods). The IPCC reported[13] values based on carbon added from a one-time payment of US\$50 per Mg of $CO_2$ or equivalent correspond to our annual payment of US\$1 with an interest rate of 0.55% or our annual payment of US\$10 with an interest rate of 5.5%. The IPCC reported that a range for the land-use-based annual mitigation of 0.14–1.39 Pg of carbon translates into 0.011–0.107 Mg of carbon annually on every land hectare of the earth. Converting further to the mean carbon addition by weighting the near future more (discounting with 3%) used in this study led to 0.34–3.51 Mg per hectare when this mitigation rate was assumed to remain constant for the whole 200-year period. Assuming the 5.5% interest rate, the upper end of the range is not far from the values of MexicoWest and TanzaniaEast, but much lower than the average of all ten landscapes (32.6 Mg $ha^{-1}$) (Table 1). Adding carbon into our landscapes given good governance was based on our study and a 5.5% interest rate, and was between one and two orders of magnitude more cost-effective than the extremes of the range reported by IPCC[13].

The reasons behind the substantial differences among the landscapes cannot be quantified, but the justifications of the interviewees revealed three main factors that determined the perceived cost to increase ecosystem carbon: (1) the large variation in the potential to increase carbon relative to the baseline future scenario, (2) the economics of the alternative land uses and opportunity costs of substituting them with higher carbon-density land use[20] and (3) how the interviewees perceived the assumptions on good governance and efficient distribution of carbon funding. Payments given the current governance conditions, which vary among landscapes[21], would probably have yielded quite different results. FinlandNorth, where the implementation of carbon-addition projects would be straightforward, might be less risky, and hence perhaps eventually a more cost-effective landscape in which to allocate carbon funding compared with Indonesia, where various levels of government advance conflicting agendas[22], and where recent attempts backed by substantial foreign funding have not been able to influence carbon density[23].

The future role of land use in mitigating climate change is likely to depend largely on agricultural subsidies that have globally been several hundred times higher than REDD+ funding[24,25] and have perversely incentivized land owners to keep ecosystems open, especially in wealthy countries. It seems possible that policies promoting an increase in ecosystem carbon in rangelands, wastelands and other land uses spared from intensive crop production[26] could greatly mitigate climate change without significantly reducing global food production. Yet, as shown, the effectiveness of an ecosystem carbon subsidy would depend a lot on the policy's ability to target globally the sites with the largest potential to make a difference.

## Methods

Methods, including statements of data availability and any associated accession codes and references, are available at https://doi.org/10.1038/s41558-017-0015-7.

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## Author contributions
M.Ka. raised the funding, M.L. and M.Ka. developed the research idea, M.L., H.G., M.Ku., J.K., N.K. and M.Ka. worked on the land-use and carbon data, M.L. and M.Ka. performed the interviews, M.L. analysed the data and wrote the first draft of the main manuscript, M.L., M.Ku. and J.K. wrote the first draft of the Supplementary Methods and M.L., S.W., A.M.L., M.Ku., N.K. and J.K. edited the draft to produce the final version.

## Competing interests
The authors declare no competing financial interests.

## Additional information
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## Methods

**Workshops and landscapes.** Most of our research was associated with participatory workshops[27,28] on land use that M.Ka., M.L., A.M.L. and others organized as part of a collaboration between the University of Helsinki, CIFOR (Center for International Forestry Research) and local organizations. Typically, 20–30 participants who ranged from the national to local level and represented the government, private sector, non-governmental organizations (NGOs) and research organizations participated in these two-day workshops, which developed alternative landscape scenarios using large printed land-use maps. The locations of these landscapes were not chosen randomly, but were located in areas where CIFOR had worked previously on land use and governance, and had established contacts in local communities. In general, the landscapes were selected previously because of their varied land uses and rapid land-use changes, and therefore they tended to be more complex and dynamic than average. The two landscapes in each country were generally chosen to represent regions with different drivers of deforestation and degradation.

To link our interviews with the landscapes of the workshops was advantageous, as we obtained valuable land-use and carbon data from key workshop participants and understood more of the local land-use history and drivers of change thanks to participation in the workshops. This process enabled us to select the experts to be invited for interview. Of our ten landscapes, the eight tropical ones were the same as those used in the workshops, and in five of these areas our interviews were conducted during the days after the workshops.

We added the two Finnish landscapes to test the methods and to expand the data set to include a biome and continent not incorporated in the project that organized the participatory workshops. We chose the locations of the Finnish interviews to include one landscape that represented the typical land use of southern Finland, whereas the other represented northern Finland.

Landscape borders are available in Supplementary Data Landscape Borders.

**CarboScen.** A programme named CarboScen was developed as a carbon calculation tool to compute the mean carbon density in landscapes with changing land uses, particularly for future land-use scenarios[16]. In a static situation, the mean carbon density could be computed simply by taking the mean carbon-density values weighted by proportions of the land-use classes. However, when land uses change, simply using the carbon density of the new land use is misleading if carbon density changes slowly towards the new value. These changes are typically slow with soil organic carbon[29,30] and when afforestation is involved[31]. Instead of the linear changes commonly used[32], CarboScen assumes that carbon density approaches the new carbon density equilibrium asymptotically following:

$$\rho_c = \rho_s + (\rho_e - \rho_s)(1 - e^{-ft})$$

where $\rho_c$ is the carbon density of the cohort in question, $\rho_s$ is carbon density at the start of the examination period, $\rho_e$ is the equilibrium carbon density of the land-use type in question, $f$ is a parameter for the transition speed and $t$ is time. Land-use changes are coded in CarboScen in a land-use change matrix, and enable the rapid visualization of changes suggested by the interviewed experts. CarboScen also allows bootstrapping of the uncertainty caused by the variability in the carbon-density estimates. For simplicity, CarboScen is for use on ecosystem carbon only, and does not include other climate impacts of land use such as carbon stored in products manufactured from wood that originated from the landscape, the substitution of fossil fuels or products, emissions of methane and other secondary greenhouse gases, the production of volatile organic compounds and albedo.

**Carbon data.** The workshops and interviews in the eight tropical landscapes were based on land-cover maps. We obtained the borders of the land coverage from these maps. We did not prepare maps for the Finnish landscapes as they had administrative limits, but we obtained the land-use areas from national statistical sources.

We based the carbon-density estimations for most landscapes on a large number of sources (Supplementary Data Carbon Density). Normally, potential sources are classified in a binary way so that some are included and others not. Instead, we assigned weights to each carbon-density value based on the trustworthiness and relevance of the data, and then computed weighted arithmetic means. For example, data reported in well-known journals, based on the most-reliable methodology described in detail and from an ecosystem similar to the land-use type of the landscapes used in our study and located close by received high weights.

The parameter values for the speed of carbon-density transition (parameter $f$ above) were set at a plausible level based on meta-analyses[30,31] and data that are now published[32].

M.L. visited and explored all the tropical landscapes for our research, and was already previously familiar with the Finnish landscapes.

**Reference scenarios and technical maximum.** We based the expert interviews on business-as-usual or reference land-use scenarios that were assumed to happen if funding to increase ecosystem carbon was not granted. The objective was not to develop meticulously the most likely scenarios, but rather to create a plausible scenario for the landscapes and simply let the experts assume that this is the future without carbon payments. As the objective of our research was to quantify the impact of the carbon payments, even a large bias in the reference scenario relative to true future development would presumably lead to only a small bias in the opinions of the interviewed experts.

We computed the 'technical maximum' scenarios (Table 1, right-most column) by converting immediately all of the area to the land use with highest carbon density. Naturally, when the landscape had climatically or edaphically differing conditions, the conversion was to the land use with the highest carbon density of that elevation or soil class. We do recommend the meticulous comparison of the technical maxima, as they depend on our definitions, and there is no natural upper limit for adding ecosystem carbon, for example, in the form of biochar or coarse woody debris brought from elsewhere.

**Interviews.** When the interviewees were selected, the objective was to find the best experts primarily on land-use economics and land-use changes, but who also understood the very basics of ecosystem carbon and why it is valuable. In practice, this meant that nearly every interviewee for the eight tropical landscapes had worked in or close to the given landscapes for many years. As Finland has a much more homogeneous land use and policy, the interviewees were also experts of more-distant areas in their country. To avoid pseudoreplications, we did not interview more than one expert from each institution, and we attempted to balance the number of representatives from the government, NGOs, private sector and research.

Our objective was to conduct eight interviews per landscape, but because of difficulties we completed only seven interviews in MexicoEast and six in MexicoWest. We interviewed five national-level experts for both Finnish landscapes and one expert for both Indonesian landscapes, and thus completed 77 interviews with 71 experts. In a few cases the interviewees wished their colleagues to be present also. We allowed this, but stressed that the views should be those of the principal interviewee. The majority of the interviewees had participated in the workshops, which therefore facilitated the process, as they were familiar with identical landscape definitions and CarboScen. As the activities in the workshops were different, we do not believe that participation in them significantly influenced the experts' responses during the interviews.

M.L. was the interviewer and M.Ka. participated in most of the interviews in IndonesiaEast, IndonesiaWest, PeruSouth and TanzaniaEast. The interviews were held in Finnish in Finland, in Spanish in Mexico and Peru, mainly in English in Tanzania, but with the help of a Kiswahili-English translator during some of the interviews, and mainly in Indonesian and partly in English in Indonesia, with the help of an Indonesian–English translator. The risk of significant bias because of inadequate translation was minimal, as all the interviewed Tanzanians understood English as well, and M.Ka. could control the quality of the Indonesian–English translations. To keep a confidential and relaxed atmosphere, we did not record the interviews, which also assured that the interviewee felt that he or she may respond freely to the questions based on his or her personal thinking, and not influenced by the views of others.

If considered potentially useful, the interviewees were given a land-use map of the landscape to refer to during the interview. More importantly, the interviewees could watch either a laptop computer monitor or a projected screen that pictured assumptions of carbon densities, land-use change and additional carbon based on the changes they had suggested. The interviews were based on a set structure (Supplementary Box 2), but in practice M.L. presented the assumptions and questions in an informal discussion. The interviews began with a description of CarboScen, the landscape and the reference scenario. Each interviewee was asked to envision a reference scenario for the future land use given that no carbon funding was available. Next, each interviewee was asked to imagine an annual payment of US$1 for every additional Mg of carbon, and to describe the land-use changes that this payment could cause during the first 30 years.

Assumptions made during the interviews were that the payments would be adjusted for inflation, that they came from a global fund also in charge of carbon quantification and that equivalent payments were given in all landscapes of the world. We additionally assumed that the payments are made to the central government of the country, but that an efficient distribution mechanism exists for the funding along with good governance. After making sure that the interviewee understood these assumptions, they were asked to envision a payment of US$1 for every additional Mg of carbon and to describe the land-use changes that would occur as a result. M.L. then coded the changes suggested by each interviewee, and the additional carbon could then be seen on the screen. M.L. next asked whether these changes initially suggested were realistic and whether other possible land-use changes existed. This iterative process continued until the interviewee was satisfied with the land-use scenario. The same process was then repeated, but with an assumed annual payment of US$10 for every additional Mg of carbon. We chose the payments of US$1 and US$10 as they were round numbers and corresponded roughly to the range of payments made in various projects. We did not use the common consensus-seeking Delphi technique[33], as we did not want to force the interviewees to justify their reasoning and wanted to complete the data set collection with one visit.

**Analysis.** The analysis was straightforward, as we obtained the carbon implications of the alternative land-use scenarios from CarboScen, and compared them with those from reference land-use scenarios. Instead of comparing differences at a certain point of time or average differences until a certain point of time, as commonly done, we computed the average differences but weighted the proximate future more than the distant future. We discounted the weights with 3% (ref. [34]), so that the first year influenced the average 3% more than the second, and roughly as much as the 23rd and 24th years combined. We did not include carbon implications beyond 200 years in the future.

We used bootstrapping[35] to quantify uncertainty in the discounted averages. The confidence intervals reported in Table 1, based on variation in the expert opinions, are based on the percentile method, and are computed with the R software environment[36] and 10,000 bootstraps, and the variation in carbon-density data are computed in CarboScen[16] with 1,000 bootstraps. We could not compute the uncertainty from carbon density data for the Finnish and Indonesian landscapes, as carbon modelling was largely based on single-data sources. Carbon estimation for some of the important land uses was also based only on a single value in some of the other landscapes, which causes an underestimation of the uncertainty.

**How to compare with costs reported in other studies?.** The cost of climate change mitigation is typically linked to perhaps the most natural unit when cutting emissions from fossil fuel usage: the annual reduction in $CO_2$ emissions. This is a natural unit also for land-use-based estimations if the harm caused by mitigation is the loss of timber revenue from an unsustainable clear-cut. However, more typically the envisioned loss is from a stream of revenue, for example, from the annual harvest of agricultural crops. Then, future revenues would need to be discounted to the present-day value to compare with the carbon payment of the lost opportunities. Using the carbon-rental approach[37] is more straightforward in these cases. In this approach future revenues from lost opportunities can be compared directly with the carbon payments. An additional benefit of this approach is that it cannot lead to payments back to the donor (except in some theoretical cases), which would be difficult to implement in the least-developed countries.

These two approaches are comparable assuming a fixed interest rate and very long simulation period. The annual payment for additional carbon can be perceived as the interest for capital received from one-time payments. Therefore, for example, with an interest rate of 10%, the annual interest from a one-time payment of US$10 is US$1, equivalent to an annual carbon payment of US$1. As $CO_2$ contains oxygen in addition to carbon, its mass is multiplied by 3/11 to obtain the mass of carbon only. To convert global values into land-area-based values, the global potential can be divided, for example, by the total land area of 13 billion hectares, or a smaller region if the focus is, for example, on the tropics only. Finally, our reported numbers (Table 1) are weighted-mean additions. Therefore, for conversion, the period for which the constant ecosystem carbon addition is made needs to be defined, and the weighted-mean addition after discounting weights with 3% must be computed as explained above.

**Ethics statement.** The methodology used in this paper does not require institutional ethical approval according to the guidelines set out by the University of Helsinki. Informed consent was obtained from all the interviewees.

**Data availability.** The CarboScen files on the simulations are available from M.L. on request. All other the data are available as Supplementary Data or as Supplementary Tables in the Supplementary Information.

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SUPPLEMENTARY INFORMATION
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# Global variation in the cost of increasing ecosystem carbon

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## Supplementary Methods

### Carbon density weights

Supplementary Box 1. Protocol to assist setting weights for the carbon density values. This was used in most of the studied landscapes and influenced the set carbon density values.

- *Select the data sources that increase knowledge on carbon density in either biomass (above-ground biomass, below-ground biomass and necromass) or soil (litter and soil down to 0.3 m depth or down to mineral soil on peatlands).*
- *Compute the desired carbon densities (for either biomass or soil) if that is not directly given. For example by adding a value on carbon density of litter to the original partial soil carbon value if litter was not included.*
- *Assign a weight based on the relevance and trustworthiness of the carbon density value. The weight value should consider the following points:*
    - *The weight should be determined based on the trustworthiness of the data and the similarity between the studied ecosystem and the ecosystem from which the data was collected. It is important to consider that:*
        - *If the research organizations, researchers and media of publishing are well know; trustworthiness levels increases.*
        - *If the particular methodology has not been described in detail or the used methodology was deficient; trustworthiness levels decreases.*
        - *If the original value needs corrections, such as adding litter carbon density; trustworthiness levels decreases.*
        - *If the carbon density value is an outlier, and far from other values; the risk of severe errors such as confusion between the concepts of carbon and biomass needs to be considered and potentially the weight lowered.*
        - *The similarity of the studied ecosystem is influenced by geographic distances and/or differences in the classification of land use types.*
    - *The assigned weights range from 1 to 100. The exact values are not relevant; however, weight values should be set according to the relevance between other weights in the same land use class and carbon pool (biomass or soil).*
        - *For example, if a carbon density value from publication A should influence the best estimate as much as values from publications B and C together, the sum of weights for the values from B and C should equal to the weight from publication A (e.g. A: 80; B: 35; C: 45).*
        - *In another example, institutions A and B are equally trustworthy and have spent equally resources to collect and analyze carbon data. However, A publishes only one value which matches the studied ecosystem. On the other hand B publishes ten values for ten subgroups; which together form the studied ecosystem. In this case the weight for the carbon density value of A should equal the sum of weights for the ten values from B (e.g. A: 95, B: 6, 8, 2, 20, 9, 3, 8, 3, 14, 22)*

## Interviews

Supplementary Box 2. Structure of the interviews to help ML remember to provide the interviewees with the assumptions and other necessary information.

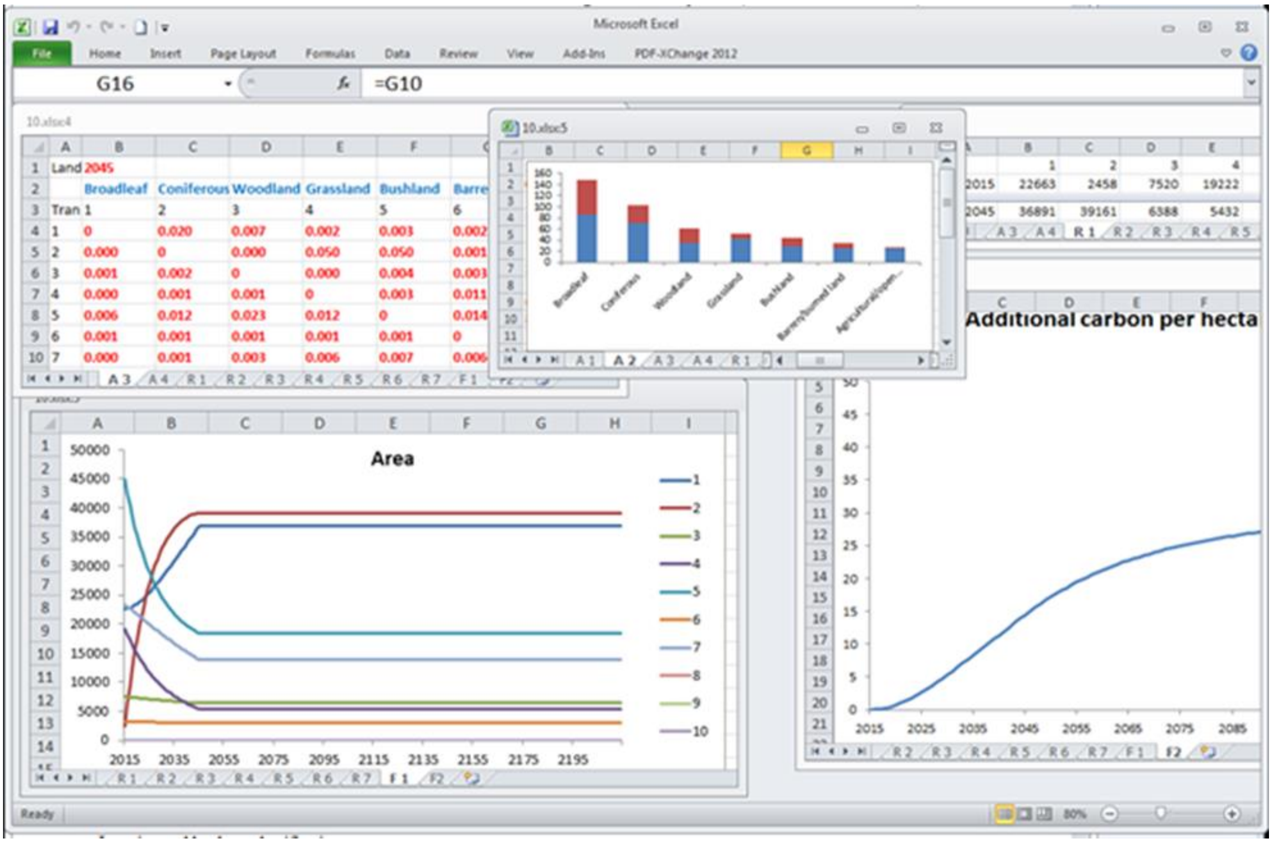
- *Welcome and thank you for agreeing to participate*
- *Description of the project*
- *Objective of this exercise is to try to understand perceptions of experts on land use of the landscape in question*
- *Names of people or institutes not mentioned except in the Acknowledgements for those who reply and accept this*
- *Do not explain what you wish to happen or what your organization is expecting to happen but simply what you think that is going to happen*
- *CarboScen*
    - *Relatively simple carbon bookkeeping model*
    - *Based on land-use classes and changes between them*
    - *Carbon density equilibrium values given for each land use class*
    - *Carbon density approaches these equilibrium values with a set speed*
- *Landscape*
    - *Location and land use classification*
- *Reference scenario*
    - *Land use classes*
    - *Carbon densities for these classes*
    - *Speeds of change*
    - *Potential causes of the changes*
- *Even if this unrealistic in your opinion lets imagine now that this is what is going to happen without any carbon financing*
- *Now imagine that a global payment of US$1 (2014 value) per ton of carbon per year is given for extra ecosystem carbon stored in the landscape*
    - *Payment is adjusted for inflation and will be given for an infinite time period*
    - *It is from a global fund and distributed globally with identical principles based on measurements funded by the same fund*
    - *Central government decides on the mechanisms of distribution and finances it*
    - *Assumed efficient distribution and good governance related to the payments*
- *How would land use change?*
    - *This is rough estimation but even approximate estimations are better than nothing*
    - *30-year-period of land use change assumed but carbon stocks change even after that*
    - *Carbon and financial implications are shown and probable land use change iterated with several rounds*
- *Now imagine that a global payment of US$10 per ton of carbon per year is given for extra carbon biospheric stored in the landscape*
    - *same assumptions as above*
    - *Carbon and financial implications are shown and probably land use change iterated with several rounds*
- *Thank you for your time*

Supplementary Table 1. Climate of the studied landscapes based on FAO New_locClim[39].

| | ***Coordinates used in climate estimation*** | ***Elevation used in climate estimation (m above sea level)*** | ***Mean annual temperature (°C)*** | ***Range in monthly mean temperatures (°C)*** | ***Annual precipitation (mm)*** | ***Range in monthly precipitations (mm)*** |
|---|---|---|---|---|---|---|
| ***FinlandNorth*** | *24.0°E; 67.4°N* | *200* | *-1.3* | *-15.4–13.9* | *330* | *23–67* |
| ***FinlandSouth*** | *26.7°E; 60.9°N* | *70* | *3.9* | *-8.9–16.9* | *608* | *29–81* |
| ***IndonesiaEast*** | *114.5°E; 2.2°S* | *20* | *26.4* | *26.1–27.0* | *2362* | *92–309* |
| ***IndonesiaWest*** | *110.2°E; 1.9°S* | *30* | *26.0* | *25.3–26.6* | *3264* | *132–464* |
| ***MexicoEast*** | *89.5°W; 20.1°N* | *100* | *26.7* | *22.9–29.6* | *1058* | *26–182* |
| ***MexicoWest*** | *93.5°W; 16.9°N* | *900* | *23.4* | *20.5–25.6* | *815* | *4–184* |
| ***PeruNorth*** | *77.4°W; 5.8°S* | *1800* | *17.7* | *16.8–18.4* | *936* | *31–145* |
| ***PeruSouth*** | *69.5°W; 12.7°S* | *230* | *25.5* | *23.9–26.8* | *2092* | *52–319* |
| ***TanzaniaEast*** | *39.3°E; 6.1°S* | *20* | *27.1* | *25.3–28.8* | *1908* | *67–381* |
| ***TanzaniaWest*** | *35.9°E; 8.0°S* | *1700* | *18.6* | *16.3–20.7* | *735* | *0–165* |

Supplementary Table 2. Interviewee backgrounds and interview durations. For example, FinlandNorthA60 refers to the first interview (A) in landscape FinlandNorth, and indicates that the core interview lasted 60 minutes. Five experts were first interviewed for FinlandNorth and then FinlandSouth. These were FinlandNorthC55-FinlandSouthA14, FinlandNorthD33-FinlandSouthE10, FinlandNorthE46-FinlandSouthF26, FinlandNorthF47-FinlandSouthG26, and FinlandNorthG40-FinlandSouthH23, and one expert for the Indonesian landscapes IndonesiaEastH14-IndonesiaWestH08. Experts were considered subnational roughly at the following spatial focuses: FinlandNorth Lapland; FinlandSouth Kymenlaakso; IndonesiaEast Central Kalimantan; IndonesiaWest West Kalimantan; MexicoEast Yucatán; MexicoWest Chiapas; PeruNorth San Martin; PeruSouth Madre de Dios; TanzaniaEast Zanzibar; TanzaniaWest Iringa. Experts of significantly larger and smaller areas were considered national and local, respectively. Representatives of NGOs established to support the private sector, and cooperatives were grouped under the private sector.

| | ***Government*** | ***NGO*** | ***Private sector*** | ***Research*** |
|---|---|---|---|---|
| ***National*** | *FinlandNorthE46*<br>*FinlandNorthF47*<br>*FinlandSouthF26*<br>*FinlandSouthG26*<br>*PeruNorthC84*<br>*PeruSouthG59* | *FinlandNorthA60*<br>*IndonesiaEastH14*<br>*IndonesiaWestF29*<br>*IndonesiaWestH8*<br>*MexicoEastB25*<br>*MexicoWestC111* | *FinlandNorthD33*<br>*FinlandNorthG40*<br>*FinlandSouthE10*<br>*FinlandSouthH23*<br>*TanzaniaWestH40* | *FinlandNorthB40*<br>*FinlandNorthC55*<br>*FinlandSouthA14*<br>*IndonesiaEastA48*<br>*MexicoEastF86*<br>*TanzaniaWestA56*<br>*TanzaniaWestA25* |
| ***Subnational*** | *FinlandSouthB63*<br>*IndonesiaEastC40*<br>*IndonesiaWestC33*<br>*MexicoEastG45*<br>*PeruNorthF52*<br>*PeruNorthG54*<br>*PeruSouthB35*<br>*PeruSouthD54*<br>*PeruSouthE55*<br>*TanzaniaEastB34*<br>*TanzaniaEastC68*<br>*TanzaniaEastE49*<br>*TanzaniaWestC44* | *FinlandSouthC62*<br>*IndonesiaEastB63*<br>*IndonesiaEastD45*<br>*IndonesiaWestD36*<br>*MexicoWestD70*<br>*MexicoWestF31*<br>*PeruNorthA71*<br>*PeruSouthA31*<br>*PeruSouthC59*<br>*PeruSouthF79*<br>*TanzaniaEastF33*<br>*TanzaniaWestD39* | *FinlandNorthH90* | *MexicoWestE31*<br>*TanzaniaEastA35* |
| ***Local*** | *IndonesiaEastE26*<br>*IndonesiaEastF40*<br>*IndonesiaWestB30*<br>*IndonesiaWestE29*<br>*MexicoEastA48*<br>*MexicoWestA30*<br>*PeruNorthB72*<br>*PeruNorthD57*<br>*TanzaniaEastD57*<br>*TanzaniaEastH50*<br>*TanzaniaWestE55*<br>*TanzaniaWestF42*<br>*TanzaniaWestG44* | *IndonesiaWest21*<br>*MexicoEastE32*<br>*MexicoWestB38*<br>*PeruNorthE60*<br>*PeruSouthH60*<br>*TanzaniaEastG66* | *FinlandSouthD62*<br>*IndonesiaEastG26*<br>*IndonesiaWestA55*<br>*MexicoEastC31*<br>*MexicoEastD27*<br>*PeruNorthH45* | |




Supplementary Figure 1. An example of the laptop or projected screen visible for both interviewer and interviewee at the end of interview TanzaniaWestH40 and the imagined payment of US$10. The top-left window shows the land use change matrix, the bottom-left window shows changes in area for the seven simulated land use classes, the top-middle window shows the assumed carbon densities for the seven land use classes, the top-right area is equivalent to the bottom-left window but including numbers, and the bottom-right window shows the additional carbon density thanks to the payment. The interviewees based their reasoning mainly on the three graphical windows, the bottom ones of which changed when the interviewer modified the top-left window.

**FinlandNorth**

We chose the municipality of Kolari to represent northern Finland. Kolari is located in western Lapland neighbouring Sweden, and has an area of 2618 $km^2$ when water is included[40]. We excluded water bodies and settlements from our landscapes and the simulations began with 2463 $km^2$ of forestry land and 11 $km^2$ of cropland[41]. A large part of the “forestry land” is treeless due to waterlogging of undrained peatlands, along with a smaller area above the alpine tree line located roughly at 440 m above sea level[42]. The elevation ranges from 100 to 719 m above sea level, and most of the area is lower than 200 m above sea level[43].

The population density for the whole municipality was 1.5 $km^{-2}$ in 2013, well below the national average[44]. After a decline in mining operations, tourism has become the main industry[43], but it has a relatively low impact on land use in the entire landscape. Agriculture only influences a small proportion of the total land area (Supplementary Table 3), and milk is the main produce (based on a phone interview of the local agricultural advisor, Markku Heikkilä). Land use is influenced more by reindeer husbandry and forestry than agriculture. Semi-wild reindeer roam freely and influence vegetation by for example browsing more on angiosperm than conifer seedlings. Forestry practices are similar throughout Finland, and the intensive version of it is based on soil treatment, mainly planting native *Pinus sylvestris* and *Picea abies* trees, pre-commercial thinning, and a couple commercial thinnings before final felling, with a rotation period less than a century in the south and more than a century in the north. Less intensive management is similarly based on stands a couple of hectares in size, but might be based on natural regeneration and thinnings might not be included. Forest management is optimized mainly towards the production of wood for saw and pulp mills, but non-timber forest products and services are acknowledged and have some impact on management. The state government owns most of the forestry land in Kolari, but management practices are also similar on private lands.

Forest carbon is discussed actively in the research community and in the planning agencies at the country level in Finland, but so far it has not influenced much practical forest management. Even the minority of forest owners trying to minimize their carbon footprints during their everyday lives do not normally consider the carbon impact of their forest management actions. Despite this, forest carbon has increased in Finland, and is expected to increase further in coming decades due to increased growth because of peatland draining, afforestation of marginal cropland, and possibly increased nitrogen deposition and a warmer climate[45], and on the other hand due to less logging partly because less intensive management has been favoured to conserve biodiversity and aesthetic values.

FinlandNorth was not optimal for CarboScen simulations as the landscape consisted mainly of only one land use class. We adopted a simplistic approach with only two main land uses. Because increasing ecosystem carbon thanks to the payments would more likely happen mainly through an increase in carbon on forestry land and not via land use changes, we set two artificial land uses with 50% more carbon in both biomass and soil than in normal forestry land and cropland. The interviewees were supposed to imagine how such changes could come about, but the interviewer provided some help if asked to do so. Biomass could be increased on forestry land by lengthening the rotation period, fertilizing, reducing the number and intensity of thinnings, and by shortening the length of the slow-growth period at the beginning of the rotation[46]. Soil carbon would be more difficult to increase, and the techniques differ in drained, previously waterlogged peatlands and dryer mineral soils. Increasing litter input and avoiding tilling is common for both landscapes, but lifting the height of the water table is operational only on drained sites.

As explained in the Methods section, even large biases in the baseline scenarios are expected to only have a minor impact on the results, as the objective was to study the difference in the baseline scenario and not the actual carbon densities of the carbon payment scenarios. Therefore our modelling was only at an approximate level.

We obtained forest biomasses from the Finnish national forest inventory and estimated the increasing carbon density based on datasets[21] from 1993 and 2009. We added root biomass[47], dead wood volume[48], and necromass based on an assumed wood density of 300 kg $m^{-3}$ consistent with published data[49]. We set forestry land soil carbon density by assuming that the top 0.3-m layer used in our study contained 80% of the carbon in published values for the top 0.7-m layer[50]. We assumed that most of the croplands are on mineral soils, and that soil carbon decreases roughly following published data[51] and that the top 0.3- m layer contains 50% more carbon that the top 0.15-m layer.

During the interviews in many cases we understood that some of the set values were unrealistic, but could not modify these without beginning the interviews again. In the case of FinlandNorth, we realized that the transition speed of 0.02 for soil is far too high when cropland is converted into forestry land or its high-carbon version. However, as the interviewees focused on differences in the baseline scenarios, the biases caused by such errors were minor. We carried out the interviews in Helsinki during a period from 2nd September to 7th November 2014.

Supplementary Table 3. Set carbon values in FinlandNorth (top six rows) and land use based on simulations. Biomass and soil carbon density values at the beginning are reported only if they differ from equilibrium values.

| | *Forestry land* | *Forestry land (high carbon)* | *Cropland* | *Cropland (high carbon)* |
|---|---|---|---|---|
| ***Biomass carbon density at equilibrium (Mg ha$^{-1}$)*** | 55 | 83 | 0 | 0 |
| ***Soil carbon density at equilibrium (Mg ha$^{-1}$)*** | 100 | 150 | 60 | 90 |
| ***Biomass transition speed*** | 0.015 | 0.015 | NA | |
| ***Soil carbon transition speed*** | 0.020 | 0.020 | 0.020 | 0.020 |
| ***Biomass carbon density at start (Mg ha$^{-1}$)*** | 30 | 83 | NA | |
| ***Soil carbon density at start (Mg ha$^{-1}$)*** | NA | | 93 | 90 |
| ***Area in 2015, (%)*** | 99.5 | 0.0 | 0.5 | 0.0 |
| ***Area in 2045, baseline scenario (%)*** | 99.6 | 0.0 | 0.4 | 0.0 |
| ***Area in 2045, scenarios perceived by the interviewed experts A, B, C, D, E, F, G, and H based on an imagined payment of US$1 (%)*** | 74.8 | 24.8 | 0.1 | 0.2 |
| | 99.6 | 0.0 | 0.4 | 0.0 |
| | 85.9 | 13.9 | 0.2 | 0.0 |
| | 49.7 | 50.1 | 0.2 | 0.0 |
| | 83.1 | 16.5 | 0.3 | 0.0 |
| | 92.4 | 7.2 | 0.4 | 0.0 |
| | 52.7 | 46.9 | 0.4 | 0.0 |
| | 83.2 | 16.5 | 0.3 | 0.0 |
| ***Area in 2045, scenarios perceived by the interviewed experts A, B, C, D, E, F, G, and H based on an imagined payment of US$10 (%)*** | 59.6 | 40.1 | 0.0 | 0.3 |
| | 29.4 | 70.5 | 0.0 | 0.0 |
| | 40.0 | 59.9 | 0.0 | 0.0 |
| | 29.4 | 70.4 | 0.1 | 0.1 |
| | 56.1 | 43.7 | 0.2 | 0.0 |
| | 54.3 | 45.3 | 0.3 | 0.0 |
| | 0.0 | 99.8 | 0.2 | 0.0 |
| | 4.2 | 95.7 | 0.1 | 0.0 |
| ***Area in 2045, technical maximal scenario (%)*** | 0.0 | 100.0 | 0.0 | 0.0 |

**FinlandSouth**

We chose the municipality of Kouvola to represent southern Finland. Kouvola is located some fifty km from the Gulf of Finland in the Baltic sea, and has an area of 2833 $km^2$ when water is included[40]. As with FinlandNorth, we excluded water bodies and settlements from our landscapes, and the simulations began with 1720 $km^2$ of forestry land and 470 $km^2$ of cropland[41]. The geology of the landscape is split into the flat southern plains roughly 50 m above sea level, approximately half of which are cropland, and the sparsely populated and hilly northern part with less fertile soils, more lakes and forest at roughly 100 m above sea level.

The population density of the entire municipality was 43.0 $km^{-2}$ in 2014, more than double the national average[44]. The landscape encompasses several significant urban centres with diverse economies, including plenty of forest industry. The rural economy is based on intensive agriculture mainly producing grains, and extensive private forestry as elsewhere in southern Finland. Forestry is similar to FinlandNorth, but more intensive and productive, and more variable due to a larger number of forest owners, also including forest industry companies.

As in FinlandNorth, we used the simplistic approach with forestry land and cropland, and their high carbon versions with 50% higher carbon density. Unlike FinlandNorth, increasing carbon by afforestation is potentially a significant option.

We obtained carbon data from the same sources as for FinlandNorth, but using region or municipality -specific values. We carried out the interviews in Helsinki and Kouvola during a period from 30th September to 30th October 2014.

Supplementary Table 4. Set carbon values in FinlandSouth (top six rows) and land use based on simulations. Biomass and soil carbon density values at beginning are reported only if they differ from equilibrium values.

| | ***Forestry land*** | ***Forestry land (high carbon)*** | ***Cropland*** | ***Cropland (high carbon)*** |
|---|---|---|---|---|
| ***Biomass carbon density at equilibrium (Mg ha$^{-1}$)*** | 75 | 113 | 0 | 0 |
| ***Soil carbon density at equilibrium (Mg ha$^{-1}$)*** | 56 | 84 | 60 | 90 |
| ***Biomass transition speed*** | 0.022 | 0.022 | NA | |
| ***Soil carbon transition speed*** | 0.030 | 0.030 | 0.030 | 0.030 |
| ***Biomass carbon density at start (Mg ha$^{-1}$)*** | 57 | 113 | NA | |
| ***Soil carbon density at start (Mg ha$^{-1}$)*** | NA | | 93 | 90 |
| ***Area in 2015, (%)*** | 78.7 | 0.0 | 21.3 | 0.0 |
| ***Area in 2045, baseline scenario (%)*** | 78.7 | 0.0 | 21.3 | 0.0 |
| ***Area in 2045, scenarios perceived by the interviewed experts A, B, C, D, E, F, G, and H based on an imagined payment of US$1 (%)*** | 70.3 | 11.2 | 18.5 | 0.2 |
| | 74.1 | 4.6 | 17.8 | 3.5 |
| | 71.9 | 6.8 | 20.7 | 0.6 |
| | 58.2 | 23.2 | 15.7 | 2.8 |
| | 46.7 | 37.0 | 13.6 | 2.6 |
| | 69.7 | 10.6 | 19.6 | 0.0 |
| | 74.5 | 6.9 | 16.9 | 1.7 |
| | 58.3 | 20.5 | 21.3 | 0.0 |
| ***Area in 2045, scenarios perceived by the interviewed experts A, B, C, D, E, F, G, and H based on an imagined payment of US$10 (%)*** | 52.1 | 29.2 | 15.9 | 2.8 |
| | 54.7 | 23.9 | 0.9 | 20.5 |
| | 42.9 | 40.6 | 11.6 | 4.9 |
| | 42.9 | 40.6 | 11.6 | 4.9 |
| | 31.2 | 58.7 | 6.3 | 3.8 |
| | 56.5 | 24.8 | 15.9 | 2.8 |
| | 39.4 | 47.0 | 9.2 | 4.4 |
| | 55.7 | 26.0 | 18.3 | 0.0 |
| ***Area in 2045, technical maximal scenario (%)*** | 0.0 | 100.0 | 0.0 | 0.0 |

**IndonesiaEast**

The landscape of IndonesiaEast is located on the island of Borneo, in the province of Central Kalimantan and in the district of Kapuas. The landscape was chosen to represent the most carbon-dense peatlands in Indonesia, and was the project area of a financially large REDD+ demonstration landscape called Kalimantan Forests and Climate Partnership (KFCP). This project began in 2010, but was heavily criticized by the media, even at the international level, and was stopped in 2014 without significant actual changes occurring in the landscape[52]. The landscape has an area of 1200 $km^2$, and is covered by peatlands with the exception of riparian forest and agricultural land. The landscape is flat and at very low elevations, as the peat deposits have been developed as a result of sea-level changes during the past millenia[53].

The human population density was 7.5 $km^{-2}$ in 2009, with the population living along the rivers bordering the landscape[52]. They received their income from rubber tapping, rice cultivation, and fishing[52], which all are concentrated on the narrow strip bordering the rivers. The northern part of the landscape, covering more than half of the land, is covered in semi-natural forest where selective logging has occurred in the past. This was based on floating logs in hand-dug ditches, which still drain the forest[54]. The southern part is very different, as it was part of the so-called Mega-Rice Project aiming at converting forested peatland into cropland. This project was implemented in 1996 and 1997, and large areas were deforested and ditched with a network of canals and ditches and is now open little-used land that burns regularly, which prevents or slows down succession towards a forest. These fires not only burn vegetation and litter, but cause huge carbon emissions from burning peat[55]. In addition, the ditching triggers the decomposition of peat and releases emissions even without fires[56]. The concept of REDD+ is familiar to an exceptionally large group of people in the region, and has been discussed for years as a potentially important income source. However, land tenure and the distribution of revenues from land-based activities has been disputed for decades, and even various governmental organizations often have conflicting plans.

We estimated the carbon densities as in most landscapes by gathering all available relevant data and assigning weights based on our protocol (Supplementary Box 1). The data for all eight tropical landscapes are available as Supplementary Data Carbon Density. Because, the variable units and definitions we had to commensurate these.  We assumed that half of biomass was carbon[57], that there was 20.0 Mg $ha^{-1}$ of coarse woody debris in forests[58] and 3.0 Mg $ha^{-1}$ in non-forests, that there was 2.6 Mg $ha^{-1}$ litter in forests and 8.0 in non-forests, that below-ground biomass was 67.3 Mg $ha^{-1}$ in forests[59] and 33.7 Mg $ha^{-1}$ in non-forests. Furthermore we assumed that the biomass of trees smaller than 50 mm at 1.3 m height was 5.0 Mg $ha^{-1}$ and that of trees smaller than 100 mm was 15.0 Mg $ha^{-1}$. In the case of mineral soils we converted soil carbon in the top 1 m to soil carbon in the top 0.3 by multiplying with 0.5[(60)].

We obtained areas of various land use classes and the baseline change from a report of the KFCP project[61]. Simulations were based on dividing the landscape into peatland and riparian land uses that cannot convert from one to the other, and for example the technical maximal carbon scenario assumed that all peatland will convert to the peatland class with the highest carbon density and the riparian areas to the riparian class with the highest carbon density.

As with many of our study landscapes, we observed some unrealistic assumptions or errors during the interviews. In the first interviews we accidentally simulated land use change only up to 2044, and not to 2045 as in other landscapes, but this error does not influence the results, as the interviewees based their responses on the final areas and not on the speeds of land use change.

We carried out most of the interviews in Palangkaraya on 22–24 September 2014, but one abroad on 5th December 2014.

Supplementary Table 5. Set carbon values in IndonesiaEast (top six rows) and land use based on simulations. Biomass and soil carbon density values at the beginning are reported only if they differ from equilibrium values.

| | *Peat forest (canals blocked, zero logging)* | *Peat forest (some logging)* | *Peat forest (severe logging)* | *Peat shrub land* | *Peat fern or grass* | *Peat oil palm* | *Riparian forest* | *Riparian agroforest* | *Riparian cropland or settlement* |
|---|---|---|---|---|---|---|---|---|---|
| ***Biomass carbon density at equilibrium (Mg ha$^{-1}$)*** | 367 | 220 | 149 | 41 | 14 | 90 | 243 | 102 | 43 |
| ***Soil carbon density at equilibrium (Mg ha$^{-1}$)*** | 5024 | 4773 | 4295 | 3014 | 3014 | 2512 | 113 | 113 | 68 |
| ***Biomass transition speed*** | 0.022 | 0.020 | 0.018 | 0.080 | 0.120 | 0.060 | 0.020 | 0.060 | 0.100 |
| ***Soil carbon transition speed*** | 0.0002 | 0.003 | 0.003 | 0.030 | 0.040 | 0.050 | 0.030 | 0.050 | 0.080 |
| ***Biomass carbon density at start (Mg ha$^{-1}$)*** | NA | | | | | 45 | NA | | |
| ***Soil carbon density at start (Mg ha$^{-1}$)*** | NA | 4898 | 4773 | 4521 | 4521 | 4521 | NA | | |
| ***Area in 2015, (%)*** | 0.0 | 30.7 | 26.3 | 16.7 | 21.3 | 0.0 | 3.0 | 1.0 | 1.0 |
| ***Area in 2045, baseline scenario (%)*** | 0.0 | 24.9 | 23.0 | 7.5 | 39.6 | 0.0 | 3.0 | 1.0 | 1.0 |
| ***Area in 2045, scenarios perceived by the interviewed experts A, B, C, D, E, F, G, and H based on an imagined payment of US$1 (%)*** | 0.0 | 25.1 | 61.4 | 4.7 | 3.7 | 0.0 | 3.0 | 1.0 | 1.0 |
| | 0.0 | 25.1 | 39.4 | 7.0 | 23.5 | 0.0 | 3.0 | 1.0 | 1.0 |
| | 0.0 | 30.7 | 48.0 | 5.6 | 10.7 | 0.0 | 3.0 | 1.0 | 1.0 |
| | 0.0 | 24.9 | 23.0 | 7.5 | 39.6 | 0.0 | 3.0 | 1.0 | 1.0 |
| | 0.0 | 24.9 | 23.5 | 7.5 | 39.1 | 0.0 | 3.0 | 1.0 | 1.0 |
| | 0.0 | 24.9 | 50.0 | 7.7 | 12.4 | 0.0 | 3.0 | 1.0 | 1.0 |
| | 0.0 | 24.9 | 61.7 | 4.8 | 3.6 | 0.0 | 3.0 | 1.0 | 1.0 |
| | 2.8 | 24.2 | 22.3 | 7.3 | 38.5 | 0.0 | 3.0 | 1.0 | 1.0 |
| ***Area in 2045, scenarios perceived by the interviewed experts A, B, C, D, E, F, G, and H based on an imagined payment of US$10 (%)*** | 73.5 | 5.6 | 5.2 | 1.7 | 9.0 | 0.0 | 3.0 | 1.0 | 1.0 |
| | 0.0 | 25.1 | 39.4 | 7.0 | 23.5 | 0.0 | 3.0 | 1.0 | 1.0 |
| | 52.7 | 6.6 | 30.1 | 2.7 | 2.9 | 0.0 | 3.0 | 1.0 | 1.0 |
| | 0.0 | 24.9 | 23.0 | 7.5 | 39.6 | 0.0 | 3.0 | 1.0 | 1.0 |
| | 0.0 | 24.9 | 23.5 | 7.5 | 39.1 | 0.0 | 3.0 | 1.0 | 1.0 |
| | 49.1 | 5.3 | 26.7 | 3.9 | 10.0 | 0.0 | 3.0 | 1.0 | 1.0 |
| | 89.8 | 1.0 | 1.9 | 0.4 | 1.8 | 0.0 | 3.0 | 1.0 | 1.0 |
| | 9.5 | 22.4 | 20.7 | 6.7 | 35.7 | 0.0 | 3.0 | 1.0 | 1.0 |
| ***Area in 2045, technical maximal scenario (%)*** | 95.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 5.0 | 0.0 | 0.0 |

**IndonesiaWest**

The borders of the landscape IndonesiaWest do not follow administrative or project borders as in the case of IndonesiaEast. Instead, the delimitation was performed for the participatory workshop. The landscape is composed of two separate areas close to but not including the town of Ketapang on the island of Borneo, province of West Kalimantan and district of Ketapang. The land area of the landscape was 2602 $km^2$, and consisted of mineral soils close to the sea in the west and a larger peatland-dominated proportion in the east. However, peat depths are thinner than in IndonesiaEast and are interrupted by hills.

The landscape is much more densely populated than IndonesiaEast and the proximity of the town of Ketapang enables a large range of rural professions. Much of the peatland has been cleared, and has already been converted or is waiting to become planted with economically very profitable[62] oil palm. Forest fires burn a large proportion of the landscape at the end of the dry season, and many of the ignitions are intentional to clear vegetation for future planting of oil palm or other crops.

Our understanding of the land use economics and current land use, and development of the baseline scenario were at a rough level, based mainly on a single remote sensing study on a larger landscape encompassing our landscape[63]. Key publications to set parameter values concerning peat dynamics were the same as those used in IndonesiaEast.

During the interviews we noted that the soil carbon density equilibrium value for oil palm plantation on peatlands was too high.

We carried out most of the interviews in Ketapang on 17–18 September 2014, but one was later carried out abroad on 5th December 2014.

Supplementary Table 6. Set carbon values in IndonesiaWest (top six rows) and land use based on simulations. Biomass and soil carbon density values at the beginning are reported only if they differ from equilibrium values.

| | ***Degraded burned peatland*** | ***Degraded land on mineral soil*** | ***Forest on mineral soil*** | ***Forest on peat*** | ***Non-forest on mineral soil*** | ***Oil palm plantation on mineral soil*** | ***Oil palm plantation on peat*** | ***Restored forest on peat*** |
|---|---|---|---|---|---|---|---|---|
| ***Biomass carbon density at equilibrium (Mg ha$^{-1}$)*** | 41 | 41 | 204 | 166 | 74 | 78 | 78 | 249 |
| ***Soil carbon density at equilibrium (Mg ha$^{-1}$)*** | 1246 | 81 | 113 | 2077 | 102 | 81 | 1869 | 5538 |
| ***Biomass transition speed*** | 0.100 | 0.100 | 0.020 | 0.022 | 0.100 | 0.060 | 0.060 | 0.022 |
| ***Soil carbon transition speed*** | 0.030 | 0.030 | 0.030 | 0.015 | 0.030 | 0.030 | 0.030 | 0.0002 |
| ***Biomass carbon density at start (Mg ha$^{-1}$)*** | NA | | | | 59 | 39 | 39 | NA |
| ***Soil carbon density at start (Mg ha$^{-1}$)*** | 2492 | 102 | NA | 2769 | NA | 102 | 2492 | NA |
| ***Area in 2015, (%)*** | 34.3 | 9.5 | 6.6 | 26.4 | 13.0 | 1.0 | 9.2 | 0.0 |
| ***Area in 2045, baseline scenario (%)*** | 29.7 | 7.7 | 3.0 | 9.6 | 9.4 | 10.0 | 30.6 | 0.0 |
| ***Area in 2045, scenarios perceived by the interviewed experts A, B, C, D, E, F, G, and H based on an imagined payment of US$1 (%)*** | 2.2 | 7.7 | 3.0 | 11.2 | 9.4 | 10.0 | 45.7 | 10.8 |
| | 18.8 | 7.7 | 3.0 | 11.3 | 9.4 | 10.0 | 26.6 | 13.3 |
| | 29.7 | 7.7 | 3.0 | 9.6 | 9.4 | 10.0 | 30.6 | 0.0 |
| | 29.7 | 7.7 | 3.0 | 9.6 | 9.4 | 10.0 | 30.6 | 0.0 |
| | 10.2 | 1.5 | 9.7 | 37.5 | 10.9 | 8.0 | 22.2 | 0.0 |
| | 29.7 | 7.7 | 3.0 | 9.6 | 9.4 | 10.0 | 30.6 | 0.0 |
| | 29.7 | 7.7 | 3.0 | 9.6 | 9.4 | 10.0 | 30.6 | 0.0 |
| | 29.0 | 7.7 | 3.0 | 9.6 | 9.4 | 10.0 | 30.3 | 1.0 |
| ***Area in 2045, scenarios perceived by the interviewed experts A, B, C, D, E, F, G, and H based on an imagined payment of US$10 (%)*** | 0.7 | 7.7 | 3.0 | 11.2 | 9.4 | 10.0 | 10.7 | 47.3 |
| | 7.6 | 3.4 | 3.0 | 9.6 | 13.7 | 10.0 | 21.3 | 31.4 |
| | 15.4 | 6.1 | 10.9 | 29.4 | 5.1 | 8.0 | 25.1 | 0.0 |
| | 9.1 | 9.0 | 5.2 | 19.3 | 11.6 | 4.3 | 13.2 | 28.3 |
| | 1.6 | 0.2 | 11.3 | 51.5 | 11.6 | 7.1 | 16.8 | 0.0 |
| | 25.5 | 6.2 | 4.6 | 15.3 | 9.7 | 9.6 | 29.2 | 0.0 |
| | 13.7 | 7.7 | 3.0 | 8.4 | 14.1 | 5.3 | 24.5 | 23.4 |
| | 23.2 | 7.7 | 3.0 | 9.6 | 9.4 | 10.0 | 28.3 | 8.8 |
| ***Area in 2045, technical maximal scenario (%)*** | 0.0 | 0.0 | 30.1 | 0.0 | 0.0 | 0.0 | 0.0 | 69.9 |

**MexicoEast**

The landscape MexicoEast is located in the states of Yucatan and Campeche, and has a large land area of 12 563 $km^2$. Despite abundant precipitation (Supplementary Table 1), the tallest trees in even the most pristine forests are of relatively low stature due to soils with only low water holding capacities[64]. The landscape is mostly plain, at roughly an elevation of 100 m above sea level but including some hillier areas.

The landscape is moderately densely populated with agricultural communities concentrated along the main roads. Most of the cropland is sown for maize, which is managed with medium intensity. These fields are typically taken care of by individuals and the larger forest areas by communities. Mexico has a compensation system developed prior to the REDD-era, where financial compensation is awarded for keeping forests as forests, and these payments for ecosystem services together with income from honey enable weighty revenue from the forested land.

We did most parts of the carbon density calculation as in the case of the Indonesian landscapes but naturally the used carbon density values were different as can be seen in the Supplementary Data Carbon Density. We used somewhat differing values to correct original data values to those that we entered in our dataset. We assumed 10.0 Mg $ha^{-1}$ of coarse woody debris in forests[65] and 4.0 Mg $ha^{-1}$ in non-forests[65], 2.0 Mg $ha^{-1}$ litter in closed forests[65], 1.0 Mg $ha^{-1}$ in open forests and 0.5 Mg $ha^{-1}$ in other land uses. To compute below-ground biomass we used above-ground to below-ground ratios of 0.2 in forests, 0.5 in scrublands and 1.0 in grasslands. We computed 0.3 m soil carbon based on factors which we used to multiply the original data values. Those were 0.8 for 0.5 m, 0.7 for 0.6 m, 0.5 for 1.0 m and 0.3 for 1.5 m[60].

We obtained the land use and land use change for the baseline scenario from the Mexican forest inventory. Because of the relative stability in the area of the land uses, we assumed no change in the baseline scenario.

We carried out the interviews in the towns of Oxkutzcab, Ticul, and Mérida on 9–11 September 2015. We could not interview the planned eight experts due to a cancellation, and obtained data from only seven experts.

Supplementary Table 7. Set carbon values in MexicoEast (top six rows) and land use based on simulations. Biomass and soil carbon density values at the beginning are reported only if they differ from equilibrium values. The English translations for the land use classes are from left to right: Medium-stature forest, Low-stature forest, Medium-stature secondary forest, Low-stature secondary forest, Agriculture, Urban and settlements, Secondary scrubland, and Pasture and savannah.

| | *Selva mediana* | *Selva baja* | *Vegetacion secundaria arborea mediana* | *Vegetacion secundaria arborea baja* | *Agricultura* | *Zona urbana y asentamientos humanos* | *Vegetacion secundaria arbustiva* | *Pastizal y sabana* |
|---|---|---|---|---|---|---|---|---|
| ***Biomass carbon density at equilibrium (Mg ha$^{-1}$)*** | 91 | 69 | 45 | 32 | 23 | 23 | 23 | 30 |
| ***Soil carbon density at equilibrium (Mg ha$^{-1}$)*** | 145 | 131 | 117 | 103 | 90 | 90 | 89 | 80 |
| ***Biomass transition speed*** | 0.040 | 0.050 | 0.060 | 0.080 | 0.600 | 0.200 | 0.100 | 0.400 |
| ***Soil carbon transition speed*** | 0.030 | 0.030 | 0.030 | 0.030 | 0.030 | 0.030 | 0.030 | 0.030 |
| ***Biomass carbon density at start (Mg ha$^{-1}$)*** | NA | | | | | | | |
| ***Soil carbon density at start (Mg ha$^{-1}$)*** | NA | | | | | | | |
| ***Area in 2015, (%)*** | 0.7 | 0.5 | 72.3 | 5.3 | 10.9 | 0.4 | 7.4 | 2.5 |
| ***Area in 2045, baseline scenario (%)*** | 0.7 | 0.5 | 72.3 | 5.3 | 10.9 | 0.4 | 7.4 | 2.5 |
| ***Area in 2045, scenarios perceived by the interviewed experts A, B, C, D, E, F, G, and H based on an imagined payment of US$1 (%)*** | 0.7 * | 1.0 | 72.3 | 11.0 | 5.2 | 0.4 ** | 7.4 | 2.0 |
| | 2.2 | 0.5 | 72.3 | 5.3 | 9.4 | 0.4 | 7.4 | 2.5 |
| | 6.4 | 0.5 | 72.3 | 5.3 | 5.2 | 0.4 | 7.4 | 2.5 |
| | 0.7 | 0.5 | 72.3 | 5.3 | 10.9 | 0.4 | 7.4 | 2.5 |
| | 1.3 | 0.5 | 72.3 | 5.3 | 10.3 | 0.4 | 7.4 | 2.5 |
| | 0.7 | 0.5 | 72.3 | 5.3 | 10.9 | 0.4 | 7.4 | 2.5 |
| | 19.6 | 19.3 | 40.2 | 3.0 | 10.9 | 0.4 | 4.1 | 2.5 |
| | NA | | | | | | | |
| ***Area in 2045, scenarios perceived by the interviewed experts A, B, C, D, E, F, G, and H based on an imagined payment of US$10 (%)*** | 8.7 * | 0.9 | 72.3 | 11.0 | 5.2 ** | 0.4 ** | 0.3 | 1.2 |
| | 6.7 | 0.5 | 72.3 | 5.3 | 6.1 | 0.4 | 7.4 | 1.4 |
| | 60.2 | 0.5 | 22.1 | 1.6 | 5.2 | 0.4 | 7.4 | 2.5 |
| | 0.7 | 0.5 | 73.2 | 5.3 | 10.9 | 0.4 | 7.4 | 1.6 |
| | 44.8 | 0.5 | 36.8 | 2.7 | 9.8 | 0.4 | 3.8 | 1.3 |
| | 0.7 | 0.5 | 72.3 | 5.3 | 10.9 | 0.4 | 7.4 | 2.5 |
| | 20.4 | 20.2 | 40.2 | 3.0 | 9.7 | 0.4 | 4.1 | 2.0 |
| | NA | | | | | | | |
| ***Area in 2045, technical maximal scenario (%)*** | 100.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

* Biomass carbon density at equilibrium assumed to increase to 100 Mg ha$^{-1}$

** Biomass carbon density at equilibrium assumed to increase to 30 Mg ha$^{-1}$

**MexicoWest**

The landscape of MexicoWest is located in the mountainous part of the state of Chiapas. The southern and eastern parts of the landscape are at an elevation of approximately 500–1000 m above sea level, and are dominated by cropland and have a dense human population. The northern and eastern parts are much less populated, have extensive maize cultivation, pastures, and forests, and a significant portion is above the elevation of 1000 m above sea level. The total land area is 5791 $km^2$.

As in the case of MexicoEast, we obtained the areas of various land use classes from the Mexican forest inventory and because of the slow changes assumed no change in the area of the land uses.

We explained how we did the carbon density calculations in the previous chapters and the landscape specific values are available in the Supplementary Data Carbon Density. To correct original data values we used the same assumptions as for MexicoEast, except that coarse woody debris was assumed 11.0 Mg $ha^{-1}$ in forests[66,67] and only 2.0 Mg $ha^{-1}$ in other land uses. Participants of the workshops criticized the soil carbon equilibrium values being too high for this specific landscape and therefore we multiplied these values by 0.7.

We carried out the interviews in Tuxtla Gutiérrez, San Cristóbal de las Casas, and Oxkutzcab on 4–8 September 2015. Due to a time limitation for the stay we could arrange only six interviews instead of the planned eight.

Supplementary Table 8. Set carbon values in MexicoWest (top six rows) and land use based on simulations. Biomass and soil carbon density values at the beginning are reported only if they differ from equilibrium values. The English translations for the land use classes are from left to right: Cloud forest, Oak and pine forest, Tropical rain forest, Secondary forest, Agriculture, Urban and settlement, Pasture and savannah, and Secondary scrubland.

| | Bosque mesófilo de montana | Bosque de encino y pino | Selva | Vegetacion secundaria arborea de bosque y de selva | Agricultura | Zona urbana y asentamientos humanos | Pastizal sabana y sabanoide | Vegetacion secundaria arbustiva de bosque y de selva |
|---|---|---|---|---|---|---|---|---|
| ***Biomass carbon density at equilibrium (Mg ha$^{-1}$)*** | 58 | 69 | 60 | 42 | 23 | 23 | 23 | 15 |
| ***Soil carbon density at equilibrium (Mg ha$^{-1}$)*** | 91 | 76 | 56 | 57 | 62 | 62 | 57 | 60 |
| ***Biomass transition speed*** | 0.020 | 0.030 | 0.030 | 0.040 | 0.300 | 0.100 | 0.100 | 0.080 |
| ***Soil carbon transition speed*** | 0.020 | 0.030 | 0.030 | 0.030 | 0.030 | 0.030 | 0.030 | 0.030 |
| ***Biomass carbon density at start (Mg ha$^{-1}$)*** | NA | | | | | | | |
| ***Soil carbon density at start (Mg ha$^{-1}$)*** | NA | | | | | | | |
| ***Area in 2015, (%)*** | 1.0 | 10.7 | 5.0 | 21.5 | 20.8 | 1.0 | 20.3 | 19.8 |
| ***Area in 2045, baseline scenario (%)*** | 1.0 | 10.7 | 5.0 | 21.5 | 20.8 | 1.0 | 20.3 | 19.8 |
| ***Area in 2045, scenarios perceived by the interviewed experts A, B, C, D, E, F, G, and H based on an imagined payment of US$1 (%)*** | 1.0 | 10.7 | 5.0 | 37.5 | 15.4 | 1.0 | 9.6 | 19.8 |
| | 1.0 | 10.7 | 5.0 | 21.5 | 20.8 | 1.0 | 20.3 | 19.8 |
| | 1.0 | 10.7 | 5.0 | 21.5 | 20.8 | 1.0 | 20.3 | 19.8 |
| | 1.0 | 10.7 | 5.0 | 21.5 | 20.8 | 1.0 | 20.3 | 19.8 |
| | 1.0 | 10.7 | 5.0 | 21.5 | 20.8 | 1.0 | 20.3 | 19.8 |
| | 1.0 | 10.7 | 5.0 | 21.5 | 20.8 | 1.0 | 20.3 | 19.8 |
| | NA | | | | | | | |
| | NA | | | | | | | |
| ***Area in 2045, scenarios perceived by the interviewed experts A, B, C, D, E, F, G, and H based on an imagined payment of US$10 (%)*** | 1.0 | 25.0 | 11.6 | 17.1 | 15.4 | 1.0 | 9.2 | 19.8 |
| | 1.0 | 15.1 | 21.3 | 21.4 | 16.3 | 1.0 | 9.2 | 14.6 |
| | 1.0 | 12.8 | 16.5 | 21.2 | 14.5 | 1.0 | 13.2 | 19.8 |
| | 1.0 | 10.7 | 5.0 | 21.5 | 25.9 | 1.0 | 20.3 | 14.6 |
| | 1.0 | 29.6 | 24.1 | 10.3 | 16.3 | 1.0 | 13.4 | 4.3 |
| | 1.0 | 16.4 | 5.0 | 21.4 | 17.9 | 1.0 | 17.6 | 19.8 |
| | NA | | | | | | | |
| | NA | | | | | | | |
| ***Area in 2045, technical maximal scenario (%)*** | 9.3 | 44.2 | 46.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

**PeruNorth**

The landscape PeruNorth is located in the northwestern corner of San Martin region on the eastern slopes of the Andean mountains. It is the most rugged of the ten landscapes, with peaks overtopping elevations of 3000 m while the central valley lies below the elevation of 1000 m above sea level. The area is 1467 $km^2$ in size, and the borders partly follow the administrative borders of the region.

The central valley is moderately densely populated, but the upper slopes of the Alto Mayo protection forest are uninhabited. The main agricultural activities focus on intensive rice cultivation in the valley bottom, and coffee and cattle in the valley and lower slopes. A typical land use change pattern begins with clearing forest for coffee, which is later converted to pasture due to soil degradation. Deforestation for coffee is typically performed by recent migrants without tenure to the cleared area. REDD+ has been discussed actively in the landscape.

The used carbon density values are available in the Supplementary Data Carbon Density. As in the case of the other landscapes, minor corrections or modifications were needed in the original data to fit our data criteria. These were the same as in the case of IndonesiaEast except that we assumed below-ground biomass to be 20.0 Mg $ha^{-1}$ in forests and 10.0 Mg $ha^{-1}$ in non-forests.

We estimated land use and its change based on unpublished inventories in 2011 and 2015.

We carried out the interviews in Moyobamba and Nueva Cajamarca on 1–3 December 2014. Due to a misunderstanding in planning the interviews, three of the interviewees worked in the same governmental organization. However, they represented different branches and had clearly differing perspectives to the posed questions.

Supplementary Table 9. Set carbon values in PeruNorth (top six rows) and land use based on simulations. Biomass and soil carbon density values at the beginning are reported only if they differ from equilibrium values.

| | ***Montane Forest*** | ***Pre-Montane Forest*** | ***Low Hill Forest*** | ***Wetland Forest*** | ***Eco-coffee*** | ***Montane shrubland*** | ***Other Agriculture*** | ***Coffee*** | ***Pasture*** | ***Rice*** |
|---|---|---|---|---|---|---|---|---|---|---|
| ***Biomass carbon density at equilibrium (Mg ha$^{-1}$)*** | 157 | 149 | 123 | 99 | 71 | 25 | 20 | 11 | 11 | 8 |
| ***Soil carbon density at equilibrium (Mg ha$^{-1}$)*** | 76 | 59 | 41 | 57 | 40 | 76 | 20 | 30 | 30 | 30 |
| ***Biomass transition speed*** | 0.020 | 0.030 | 0.030 | 0.040 | 0.060 | 0.070 | 0.500 | 0.100 | 0.040 | 0.800 |
| ***Soil carbon transition speed*** | 0.030 | 0.040 | 0.040 | 0.050 | 0.050 | 0.020 | 0.120 | 0.080 | 0.050 | 0.100 |
| ***Biomass carbon density at start (Mg ha$^{-1}$)*** | NA | | | | | | | | | |
| ***Soil carbon density at start (Mg ha$^{-1}$)*** | NA | | | | | | | | | |
| ***Area in 2015, (%)*** | 50.3 | 12.0 | 0.3 | 1.0 | 0.0 | 2.1 | 15.3 | 13.2 | 1.3 | 4.4 |
| ***Area in 2045, baseline scenario (%)*** | 47.4 | 10.8 | 0.3 | 0.1 | 0.0 | 2.1 | 16.1 | 17.1 | 1.3 | 4.9 |
| ***Area in 2045, scenarios perceived by the interviewed experts A, B, C, D, E, F, G, and H based on an imagined payment of US$1 (%)*** | 47.4 | 10.9 | 0.3 | 0.1 | 8.2 | 2.1 | 16.0 | 8.7 | 1.3 | 4.9 |
| | 48.8 | 11.4 | 0.3 | 0.2 | 4.1 | 2.1 | 15.7 | 11.3 | 1.3 | 4.7 |
| | 48.9 | 11.4 | 0.3 | 0.2 | 3.7 | 2.1 | 15.7 | 11.5 | 1.3 | 4.7 |
| | 47.8 | 10.9 | 0.3 | 0.1 | 8.1 | 2.1 | 16.0 | 8.5 | 1.3 | 4.9 |
| | 47.6 | 11.1 | 0.3 | 0.1 | 1.0 | 2.1 | 16.0 | 15.6 | 1.3 | 4.9 |
| | 47.4 | 18.5 | 4.1 | 0.7 | 7.9 | 2.1 | 12.3 | 2.7 | 1.3 | 3.0 |
| | 47.4 | 10.8 | 0.3 | 0.1 | 0.0 | 2.1 | 16.1 | 17.1 | 1.3 | 4.9 |
| | 47.8 | 11.1 | 0.3 | 0.1 | 8.1 | 2.1 | 16.0 | 8.5 | 1.1 | 4.9 |
| ***Area in 2045, scenarios perceived by the interviewed experts A, B, C, D, E, F, G, and H based on an imagined payment of US$10 (%)*** | 48.8 | 11.5 | 9.7 | 0.3 | 12.6 | 2.1 | 6.9 | 3.3 | 0.0 | 4.8 |
| | 50.3 | 12.0 | 0.6 | 1.0 | 7.6 | 2.1 | 15.3 | 5.6 | 1.0 | 4.4 |
| | 50.3 | 12.0 | 0.4 | 1.0 | 6.6 | 2.1 | 15.3 | 6.6 | 1.2 | 4.4 |
| | 47.9 | 11.0 | 0.5 | 0.5 | 12.2 | 2.1 | 16.0 | 4.7 | 1.1 | 3.9 |
| | 48.1 | 11.4 | 3.2 | 0.1 | 13.2 | 2.1 | 11.9 | 6.7 | 0.1 | 3.2 |
| | 48.8 | 27.7 | 4.1 | 0.7 | 0.0 | 2.1 | 12.4 | 2.7 | 1.3 | 0.1 |
| | 50.1 | 11.6 | 11.3 | 0.3 | 11.2 | 2.1 | 3.8 | 4.3 | 0.6 | 4.7 |
| | 48.3 | 11.4 | 0.3 | 0.1 | 11.9 | 2.1 | 15.9 | 4.3 | 1.0 | 4.8 |
| ***Area in 2045, technical maximal carbon scenario (%)*** | 62.0 | 22.5 | 7.9 | 5.4 | 0.0 | 2.1 | 0.0 | 0.0 | 0.0 | 0.0 |

**PeruSouth**

The landscape of PeruSouth is located in the southeastern part of the Madre de Dios region immediately southwest from the town of Puerto Maldonado. The land area is 1456 $km^2$, and most of the landscape is part of the vast Amazon plateau and is at an elevation of 200–250 m above sea level, but the very westernmost part includes areas of the easternmost Andean foothills.

The landscape is sparsely populated and southern parts of it are part of the buffer zone of Tambopata Natural Reserve, but include small patches of cropland, and the forests have been selectively logged. The landscape is delimited in the north by a paved highway, the surroundings of which are deforested. Illegal gold mining operated mainly by immigrants from the mountains is by far the land use causing the most dynamics in recent years. Most gold mining is illegal and the open pit methodology leaves a barren ground after the site has been exhausted of gold.

As with the other tropical landscapes, carbon density data is available in the Supplementary Data Carbon Density. We used the same corrections for the data values as in the case of PeruNorth. We assumed that the equilibrium carbon density was twenty percent lower for the logged forest relative to the unlogged forest.

Our land use data was mainly based on a recent study in the same landscape [68]. Many of the interviewees regarded the assumed rapid forest succession in the baseline scenario as unrealistic, and believed that the mined areas will remain open.

We carried out the interviews in Puerto Maldonado on 26–27 November 2014.

Supplementary Table 10. Set carbon values in PeruSouth (top six rows) and land use based on simulations. Biomass and soil carbon density values at the beginning are reported only if they differ from equilibrium values.

| | *Montane Forest* | *Unlogged forest* | *Logged forest* | *Shrub and Bamboo Vegetation* | *Agriculture and Pastures* | *Mining* |
|---|---|---|---|---|---|---|
| ***Biomass carbon density at equilibrium (Mg ha$^{-1}$)*** | 181 | 163 | 130 | 121 | 45 | 5 |
| ***Soil carbon density at equilibrium (Mg ha$^{-1}$)*** | 60 | 50 | 50 | 55 | 35 | 5 |
| ***Biomass transition speed*** | 0.04 | 0.05 | 0.05 | 0.06 | 0.70 | 0.80 |
| ***Soil carbon transition speed*** | 0.05 | 0.06 | 0.06 | 0.07 | 0.15 | 0.50 |
| ***Biomass carbon density at start (Mg ha$^{-1}$)*** | NA | | | | | |
| ***Soil carbon density at start (Mg ha$^{-1}$)*** | NA | | | | | 35 |
| ***Area in 2015, (%)*** | 1.0 | 0.0 | 79.6 | 5.4 | 11.6 | 2.5 |
| ***Area in 2045, baseline scenario (%)*** | 0.7 | 0.0 | 81.1 | 4.5 | 11.8 | 1.9 |
| ***Area in 2045, scenarios perceived by the interviewed experts A, B, C, D, E, F, G, and H based on an imagined payment of US$1 (%)*** | 0.7 | 21.8 | 64.9 | 4.1 | 6.9 | 1.6 |
| | 0.7 | 1.9 | 80.1 | 4.5 | 11.0 | 1.9 |
| | 0.7 | 9.2 | 72.6 | 4.3 | 11.5 | 1.8 |
| | 0.7 | 9.3 | 74.3 | 4.4 | 9.8 | 1.6 |
| | 0.7 | 0.0 | 84.5 | 4.6 | 8.3 | 1.9 |
| | 0.7 | 11.4 | 71.5 | 4.3 | 10.4 | 1.7 |
| | 0.6 * | 32.1 | 54.7 | 3.9 | 7.2 | 1.4 |
| | 0.7 | 25.1 | 64.7 | 4.1 | 3.9 | 1.5 |
| ***Area in 2045, scenarios perceived by the interviewed experts A, B, C, D, E, F, G, and H based on an imagined payment of US$10 (%)*** | 0.6 * | 44.3 | 45.2 | 3.6 | 5.0 | 1.3 |
| | 0.6 * | 42.8 | 42.9 | 3.6 | 9.3 | 0.8 |
| | 0.7 | 50.7 | 38.8 | 2.4 | 7.3 | 0.1 |
| | 0.7 | 23.4 | 61.8 | 4.1 | 8.5 | 1.6 |
| | 0.7 | 23.3 | 63.7 | 4.1 | 6.6 | 1.6 |
| | 0.8 | 43.5 | 47.1 | 3.7 | 3.6 | 1.3 |
| | 0.8 | 44.9 | 46.5 | 3.6 | 4.1 | 0.1 |
| | 0.6 * | 43.4 | 47.2 | 3.7 | 3.9 | 1.3 |
| ***Area in 2045, technical maximal scenario (%)*** | 0.4 * | 99.6 | 0.0 | 0.0 | 0.0 | 0.0 |

* Area of the most carbon-rich land use decreases as an artefact caused by the assumed proportion the non-forested land uses directly converting into Montane forests, and as their area decreases less new Montane forest appears.

**TanzaniaEast**

The landscape TanzaniaEast is the main island of Zanzibar (Unguja), excluding the most urban area of Zanzibar City. The land area is 1560 $km^2$ and the highest hills overtop the height of 100 m above sea level. The soils are mainly composed of sandy deposits in the West and coral rag in the East[69]. This soil division has caused a landscape pattern where permanent agriculture, agroforestry and fruit tree plantations dominate the West, while the East is mostly covered by natural coral rag vegetation combined with crop rotation and shifting cultivation[41]. Natural forests are rare in the western part, and the forests in the coral rag are largely degraded to scrubs. Agroforestry practices are widespread, as planting trees has historically strengthened land tenure[70]. There are few larger government managed forest plantations, but smallholder plantations of *Casuarina* have been spreading in the coral rag area during recent decades.

Compared to the nine other landscapes, TanzaniaEast is much more densely populated than all the others, with a population density of over 200 $km^{-2}$ [71]. Majority of the population lives in the west, where the rural economy is very diverse with a large range of agricultural crops and vicinity of Zanzibar City provides additional livelihood opportunities[69]. The hydromorphic valleys are used for commercial irrigated rice cultivation, while the agroforestry areas are mainly divided between smallholders[70]. In the unfertile eastern part, shifting cultivation is the dominant form of agriculture and done essentially for subsistence reasons[41]. However, coastal tourism as well as fishery and collection forest products provide additional incomes to this otherwise poor region. Unfortunately, due to vast degradation of the coral rag forests, the forestry products are largely limited to low-income goods such as fuelwood and pole wood.

As in other tropical landscapes, the carbon density data is available the Supplementary Data Carbon Density. For the corrections we followed largely the values and factors used in MexicoEast except that coarse woody debris values for mangroves was 0.1 Mg $ha^{-1}$, for other forests was 1.6 Mg $ha^{-1}$ and for non-forests 0.1 Mg $ha^{-1}$ as reported[72]. The value for litter in mangroves was 1.4 Mg $ha^{-1}$[73]. Below-ground biomasses were 1.4 Mg $ha^{-1}$ for mangroves, 5.1 Mg $ha^{-1}$ for other forests and 1.8 Mg $ha^{-1}$ for non-forests based on the same report[73]. Because of the scarcity of small trees in the forests of TanzaniaEast, we halved the assumed biomass of trees below 50 mm in diameter at 1.3 m height to 2.5 Mg $ha^{-1}$.

To measure current land-use and its change we combined data from two sources. The current land use and land cover data was based on results of Zanzibar Woody Biomass Survey –project[72], where land cover mapping was done via visual interpretation of high resolution (5 m) RapidEye images of 2012. We modified this detailed land use and land cover classification of Zanzibar Woody Biomass Survey –project for the purposes of this study by combining classes to more generalized categories. We did also some modifications to the original delineations of settlement areas as they contained significant amount of surrounding non-urban areas within them. Then we analysed the land use and land cover changes of Zanzibar between 1996 and 2012. Kukkonen and Käyhkö[74] had already analysed the forest cover changes of Unguja between 1996 and 2009 with a method combining automated and visual change detection techniques and it had relatively high overall accuracy (87%) and kappa (0.846). We updated this information by overlaying the 1996–2009 change data with the

2012 land use and land cover classification and satellite images and we digitized manually areas changed after 2009 in the scale of 1:30000 with minimum mapping unit size of 1.44 ha. We did not update shifting cultivation related changes, namely clearings and regrowth, as these were not considered to influence the quantities of land use and land cover classes significantly and we also did not map changes between categories with low carbon density differences, as between agriculture and barren. We determined the current land use and land cover class of the changed areas by their category in the modified classification of 2012, while the class in 1996 was determined by guided interpretation process. First, we divided the changed areas to two regions based on soil data, as forests in the coralline soils belong to coral rag categories, while they belong to agroforest or high forest in the clay soils. Then we determined the final 1996 class of each change area with a visual interpretation of 1996 SPOT image as well as the aerial images of 2004 and 1987 of limited coverage. The classification process was also guided by literature and in-depth spatial knowledge about the most significant land cover changes in the study area, i.e. concentrations of forest plantations. Finally, we turned these datasets into a transition matrix indicating changes between all categories from 1996 to 2012.

We carried out the interviews in various parts of Unguja Island on 26-27 February 2015. As in all landscapes, we did not allow interviewees to hear interviews of others prior to their own interview. However, in TanzaniaEast we made one exception to this but the interviewee assured that the heard interview did not influence his or her views.

Supplementary Table 11. Set carbon values in TanzaniaEast (top six rows) and land use based on simulations. Biomass and soil carbon density values at the beginning are reported only if they differ from equilibrium values.

| | *Agriculture* | *Agroforestry* | *Barren* | *Coral rag forest* | *Coral rag scrub* | *Forest tree plantation* | *High forest* | *Mangrove* | *Settlement* | *Forest tree plantation planted to replace coral rag scrub* |
|---|---|---|---|---|---|---|---|---|---|---|
| ***Biomass carbon density at equilibrium (Mg ha$^{-1}$)*** | 4 | 27 | 2 | 24 | 3 | 23 | 57 | 26 | 22 | 20 |
| ***Soil carbon density at equilibrium (Mg ha$^{-1}$)*** | 9 | 82 | 2 | 117 | 68 | 35 | 94 | 97 | 105 | 73 |
| ***Biomass transition speed*** | 0.300 | 0.030 | 0.500 | 0.030 | 0.200 | 0.080 | 0.030 | 0.050 | 0.030 | 0.030 |
| ***Soil carbon transition speed*** | 0.150 | 0.100 | 0.300 | 0.010 | 0.010 | 0.080 | 0.050 | 0.030 | 0.010 | 0.010 |
| ***Biomass carbon density at start (Mg ha$^{-1}$)*** | NA | | | | | | | | | |
| ***Soil carbon density at start (Mg ha$^{-1}$)*** | NA | | | | | | | | | |
| ***Area in 2015, (%)*** | 16.7 | 22.7 | 0.9 | 3.1 | 40.4 | 1.9 | 0.7 | 3.4 | 10.3 | 0.0 |
| ***Area in 2045, baseline scenario (%)*** | 18.4 | 21.3 | 1.1 | 2.5 | 38.4 | 2.1 | 0.7 | 3.4 | 12.2 | 0.0 |
| ***Area in 2045, scenarios perceived by the interviewed experts A, B, C, D, E, F, G, and H based on an imagined payment of US$1 (%)*** | 18.4 | 21.3 | 1.1 | 2.5 | 38.4 | 2.1 | 0.7 | 3.4 | 12.2 | 0.0 |
| | 17.8 | 21.7 | 1.1 | 2.5 | 31.6 | 2.0 | 0.7 | 3.4 | 12.1 | 7.2 |
| | 17.0 | 21.3 | 1.1 | 2.7 | 39.6 | 2.1 | 0.7 | 3.4 | 12.2 | 0.0 |
| | 18.0 | 21.3 | 1.1 | 2.5 | 27.5 | 2.0 | 0.7 | 3.4 | 12.1 | 11.6 |
| | 13.0 | 26.1 | 1.0 | 2.5 | 19.4 | 1.9 | 0.7 | 3.4 | 12.2 | 19.9 |
| | 17.7 | 21.9 | 1.1 | 2.5 | 35.2 | 2.1 | 0.7 | 3.4 | 12.2 | 3.4 |
| | 18.4 | 21.3 | 1.1 | 2.5 | 38.4 | 2.1 | 0.7 | 3.4 | 12.2 | 0.0 |
| | 14.6 | 25.2 | 1.1 | 2.5 | 36.2 | 2.0 | 0.7 | 3.4 | 12.3 | 2.1 |
| ***Area in 2045, scenarios perceived by the interviewed experts A, B, C, D, E, F, G, and H based on an imagined payment of US$10 (%)*** | 18.2 | 21.3 | 1.1 | 2.5 | 33.2 | 2.0 | 0.7 | 3.4 | 12.2 | 5.5 |
| | 12.9 | 26.7 | 1.1 | 2.5 | 28.4 | 2.0 | 0.7 | 3.4 | 12.3 | 10.3 |
| | 15.2 | 22.2 | 1.0 | 2.9 | 20.3 | 1.9 | 0.7 | 3.4 | 12.1 | 20.3 |
| | 11.2 | 25.8 | 1.0 | 2.9 | 19.1 | 2.3 | 0.7 | 3.4 | 12.2 | 21.5 |
| | 12.5 | 26.0 | 1.0 | 2.5 | 8.3 | 1.7 | 0.7 | 3.4 | 12.0 | 32.0 |
| | 17.3 | 22.3 | 1.1 | 2.5 | 34.1 | 2.0 | 0.7 | 3.4 | 12.2 | 4.5 |
| | 15.9 | 23.5 | 1.1 | 2.5 | 28.6 | 2.0 | 0.7 | 3.4 | 12.2 | 10.3 |
| | 11.9 | 27.7 | 1.1 | 2.5 | 27.5 | 2.0 | 0.7 | 3.4 | 12.3 | 11.1 |
| ***Area in 2045, technical maximal scenario (%)*** | 0.0 | 0.0 | 0.0 | 43.5 | 0.0 | 0.0 | 53.1 | 3.4 | 0.0 | 0.0 |

**TanzaniaWest**

The landscape TanzaniaWest is located in Southern Highlands in southwestern Tanzania in Iringa region and in Kilolo district. The landscape does not follow administrative borders but was delimited to cover the transitional area from agricultural zone in west and forested zone in east covering a land area of 1232 $km^2$. Elevation ranges mostly between 1500 and 2000 m above sea level. The area is mainly covered by highland farmland. Part of the eastern half is covered in forest reserves with natural cloud forest detached from the Udzungwa National Park while the western part covers mainly land transformed for agricultural purposes.

Population density is 52 $km^{-2}$ [(75)] comparable to the national average[71]. People are primarily engaged in agriculture and livestock husbandry. Maize is the most important crop followed by beans and cash crops. Typically land-use is patchy and diverse around the villages shifting to more intensive agricultural land closer to Iringa town in the west. TanzaniaWest has traditions and wide interest in small scale timber plantations on species belonging mainly to genera *Pinus* and *Eucalyptus*.

Carbon densities are available in Supplementary Data Carbon Density. To correct some of the original data values to match our definitions we used the same values as for MexicoEast except that we assumed 2.0 Mg $ha^{-1}$ of coarse woody debris in forest plantations, 1.0 Mg $ha^{-1}$ in woodland and bushland and 9.5 Mg $ha^{-1}$ in montane forests[76]. The ratio of below-ground biomass to above-ground biomass was 1.9 for grasslands[77].

We obtained the current land use information from the National Forest Resources Monitoring and Assessment land use and land cover classification with some small modifications that were based on a field work done in February 2015. We could not execute land cover change analysis with the National Forest Resources Monitoring and Assessment land use and land cover data because the data was designed on a coarser spatial level suited for the multifunctional landscape. Land cover changes in the area are not spatially vast and distinct in regional level but more small scale and diffuse degradation. We did land cover change analysis between 1990 and 2014 with Landsat images (Landsat 5 TM 15.10.1990 and Landsat 8 OLI 1.10.2014) acquired in dry season using standard post classification methods[78]. We created the classification nomenclature based on the knowledge of the area and aims of the project. We designed rough classification as the landscape is heterogeneous and very prone to classification errors. The training sites and validation sites were delineated based on high resolution satellite images in Google maps and field visit done in February 2015. Overall accuracy of the analysis was 78% and kappa 0.74. We computed annual changes for each class assuming linear regression.

Biomass data from National Forest Resources Monitoring and Assessment training plots were linked to 2014 Landsat image with kNN-method resulting continuous biomass raster of the area. Biomass trend of the landscape was then reconstructed based on the composition of the previous classification classes within the modified National Forest Resources Monitoring and Assessment classes.

We carried out the interviews in Iringa on 4–6 March 2015.

Supplementary Table 12. Set carbon values in TanzaniaWest (top six rows) and land use based on simulations. Biomass and soil carbon density values at the beginning are reported only if they differ from equilibrium values.

| | Broadleaf | Coniferous | Woodland | Grassland | Bushland | Barren / burned land | Agricultural / open land |
|---|---|---|---|---|---|---|---|
| ***Biomass carbon density at equilibrium (Mg ha$^{-1}$)*** | 63 | 33 | 27 | 9 | 15 | 9 | 2 |
| ***Soil carbon density at equilibrium (Mg ha$^{-1}$)*** | 86 | 71 | 34 | 43 | 29 | 25 | 25 |
| ***Biomass transition speed*** | 0.035 | 0.050 | 0.040 | 0.100 | 0.080 | 0.100 | 0.400 |
| ***Soil carbon transition speed*** | 0.035 | 0.040 | 0.050 | 0.070 | 0.070 | 0.070 | 0.120 |
| ***Biomass carbon density at start (Mg ha$^{-1}$)*** | NA | | | | | | |
| ***Soil carbon density at start (Mg ha$^{-1}$)*** | NA | | | | | | |
| ***Area in 2015, (%)*** | 18.4 | 2.0 | 6.1 | 15.6 | 36.4 | 2.6 | 18.9 |
| ***Area in 2045, baseline scenario (%)*** | 19.5 | 1.9 | 5.4 | 14.1 | 35.1 | 2.4 | 21.5 |
| ***Area in 2045, scenarios perceived by the interviewed experts A, B, C, D, E, F, G, and H based on an imagined payment of US$1 (%)*** | 22.9 | 6.4 | 5.3 | 13.7 | 30.7 | 2.4 | 18.6 |
| | 19.5 | 1.9 | 5.4 | 14.1 | 35.1 | 2.4 | 21.5 |
| | 20.1 | 4.2 | 3.1 | 14.1 | 34.7 | 2.4 | 21.4 |
| | 26.5 | 1.9 | 5.4 | 13.6 | 35.1 | 2.4 | 15.1 |
| | 27.7 | 7.2 | 7.4 * | 12.9 | 23.9 | 2.4 | 18.6 |
| | 22.2 | 10.3 | 5.4 | 11.4 | 32.4 | 2.5 | 15.9 |
| | 29.1 | 30.0 | 5.3 | 6.3 | 18.1 | 2.5 | 8.8 |
| | 25.6 | 20.8 | 5.2 | 7.3 | 20.3 | 2.4 | 18.4 |
| ***Area in 2045, scenarios perceived by the interviewed experts A, B, C, D, E, F, G, and H based on an imagined payment of US$10 (%)*** | 25.1 | 7.6 | 5.2 | 13.6 | 27.8 | 2.4 | 18.3 |
| | 22.0 | 10.1 | 5.2 | 13.7 | 26.0 | 2.4 | 20.5 |
| | 23.9 | 11.5 | 2.5 | 12.3 | 34.9 | 2.5 | 12.4 |
| | 27.2 | 11.7 | 5.7 | 12.5 | 35.8 | 2.6 | 4.6 |
| | 38.6 | 15.0 | 6.7 ** | 5.6 | 16.7 | 2.4 | 15.1 |
| | 15.9 | 63.4 | 4.9 | 0.8 | 1.6 | 2.5 | 10.9 |
| | 31.5 | 46.6 | 5.0 | 2.6 | 4.7 | 2.4 | 7.2 |
| | 30.0 | 31.8 | 5.2 | 4.4 | 15.0 | 2.4 | 11.3 |
| ***Area in 2045, technical maximal scenario (%)*** | 100.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

* Biomass carbon density at equilibrium assumed to increase to 60 Mg ha$^{-1}$

** Biomass carbon density at equilibrium assumed to increase to 70 Mg ha$^{-1}$

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