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Software notes

# CarboScen: a tool to estimate carbon implications of land-use scenarios

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Land use directly impacts ecosystem carbon and indirectly influences atmospheric carbon. Computing ecosystem carbon for an area experiencing changes in land use is not trivial, as carbon densities change slowly after land-use changes. We developed a tool, CarboScen, to estimate ecosystem carbon in landscapes. It is a simple tool typically used with an annual time step, and is based on carbon pools and densities. It assumes that carbon density asymptotically approaches a value, which is set for the land-use type in question. We recommend CarboScen for landscapes with spatially relatively homogenous soils and climate, multiple land uses, and changes between these leading to slow changes in carbon densities because either soil organic carbon is included in the analysis or afforestation occurs. Thanks to its simplicity, it is particularly suitable for participatory planning, rapid assessment of REDD+ project potential, and educational use.

## Currently available tools

Understanding the carbon implications of land-use change is essential to optimally mitigate climate change. Quantifying biomass carbon density, i.e. carbon stocks per unit area, is surprisingly demanding in the field. Simply measuring tree diameter (Cushman et al. 2014) or height (Larjavaara and Muller-Landau 2013) can be unexpectedly challenging, and more systematic and random errors may arise from the estimation of wood density (Plourde et al. 2015) and whole-tree biomass from allometric equations (Chave et al. 2014). Quantifying soil organic carbon (hereafter 'soil carbon') is also demanding (Schrumpf et al. 2011). Because measuring and estimating carbon density are difficult and time-consuming in the field, most larger scale ecosystem carbon quantifications are based on combining data by multiplying area and carbon density estimations of similar land-use classes obtained elsewhere (Carlson et al. 2012). This land-use class-based approach not only simplifies the quantification, but it is also the only option when temporal carbon trends are studied and only land-use data are available. In addition, this land-use class-based carbon estimation enables the estimation of other climate impacts if models are available. These other climate impacts include the emission of other greenhouse gases, such as ozone and methane, and changes in albedo and volatile organic compound composition (Unger 2014).

The IPCC guidelines contain instructions for greenhouse gas accounting based on land-use classes (IPCC 2006), and dozens of tools have already been developed to facilitate computation (Denef et al. 2012). These range in complexity, land uses and regions covered, spatial scale of use, inclusion of greenhouse gases, indirect impacts included, interface type, and range of intended users. Their potential uses have been divided into education, reporting, and predicting the future (Colomb et al. 2013). Most of these tools focus on emissions from agricultural land uses, are designed to quantify sequestration for offsetting from afforestation, or focus on helping to choose the correct IPCC default carbon densities (Denef et al. 2012). We describe some of these tools below under 'CarboScen compared to other approaches'.

Carbon densities change in dynamic landscapes experiencing changes in land use. Carbon density values can be modeled simply based on sudden changes e.g. from rangeland to young secondary forest, then to old secondary forest, and finally to old-growth forest. However, it is more realistic to set gradual changes. Carbon can accumulate above ground for centuries following afforestation (Luyssaert et al. 2008), and for even longer periods in the soil (Wardle et al. 2012). Land-use changes are important as illustrated by the 7–14% gross share of anthropogenic carbon emissions originating from tropical deforestation alone (Harris et al. 2012) despite this being partly compensated by reforestation. Because understanding ecosystem carbon is vital, it is important to have a range of tools built from various perspectives to quantify both the positive and negative impacts at various scales. Therefore, we attempted to develop a relatively simple tool, CarboScen, based on equilibrium carbon densities given for land-use classes.

## Carbon density in CarboScen

Surprisingly, none of the existing landscape carbon calculation tools that we reviewed utilized the possibly most natural approach to quantifying carbon in landscapes. Local carbon density data are currently available for numerous land uses. By simply assuming that carbon density asymptotically approaches a land-use-dependent set value at a land-use-dependent set rate or speed relative to the remaining carbon density difference, landscape carbon dynamics can presumably be modeled with a high realism to complexity ratio. Mathematically, carbon density in a given land use at a given moment of time ($\rho_c$) can be calculated from

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

where $\rho_s$ is carbon density at the start of the examination period, $\rho_e$ is the equilibrium carbon density of the land-use type in question, $e$ is Euler's number, $f$ is a parameter on transition rate, and $t$ is time since the start of the examination period. The remainder of this section contains justification for our choice of using this exponential rise or fall model (Eq. 1) in CarboScen.

Carbon density change in CarboScen is based on only one parameter, $f$. This naturally restricts how closely biomass and soil carbon changes can be modeled. The form of this model can be assessed critically both by comparing it to field observations and conceptually. Changes are often rapid when biomass decreases, e.g. when forest is cleared for agriculture. The exact form of decreasing biomass is unimportant if the drop is rapid relative to the calculation period, as a potential bias is a significant influence for only a brief period of time. More important is the form of biomass recovery related to slow tree growth. Biomass occasionally changes after reforestation is described with an S-shaped or sigmoid curve with a slow beginning. This could be caused by delayed seed arrival, occupation by other plants, such as shrubs (Larjavaara 2015), and the time needed for the trees to grow to a size in which they are able to spread their branches and reach maximal leaf area and 'canopy closure'. When trees have reached their maximal leaf area they begin utilizing all the radiation that they are able to, thus maximizing their gross primary productivity and biomass accumulation rate. Growth slowdown is inevitable as a significant part of the energy produced is consumed by the tree itself during autotrophic respiration. By definition, living tissue consumes energy and therefore, more of it consumes more energy and less is spared for net primary production. Additional reasons for growth slowdown have been presented and tested related to hydraulic path length and gravitational potential (Ryan et al. 2006), phloem transportation distance (Jensen et al. 2012), and increased energy allocation on reproduction (Thomas 2011). Interestingly, assuming that the decelerating growth is caused by the first mentioned need to support more living tissue and that autotrophic respiration per unit biomass does not vary, then growth would follow Eq. 1 supporting its use in CarboScen.

Without land-use changes soil carbon is often assumed to be in balance so that inputs from litter, root mortality, woody debris, and moss senescence are in balance with outputs due to decomposition (Wutzler and Reichstein 2007). Both inputs and outputs along with their interactions are directly affected by land-use change. If equilibrium soil carbon is increased e.g. when a cropland is afforested, the increase can initially be negative e.g. if agricultural crops are cleared and trees do not reach a significant size for many years, and inputs therefore remain minimal (Paul et al. 2002). In a different scenario soil carbon may begin rising instantaneously when trees appear in addition to the agricultural crops, but as in the biomass case the change may follow a more sigmoid curve due to the slow increase in inputs rather than Eq. 1. When soil carbon decreases, the assumed Eq. 1 is perhaps more acceptable theoretically than e.g. an extreme case where, as the inputs drop to zero, the remaining carbon from the previous land use will decompose but with decreasing rate, as the most easily decomposable material decomposes first and the process continuously slows down (Liski et al. 2005). When fire consumes soil carbon, the process is completely different as the oxidation is then obviously very rapid.

Choosing just one model for the carbon density transition rate obviously limits how realistically landscape carbon changes can be described. The material that we present in the appendices helps to evaluate whether our simplistic approach is realistic. An alternative option for Eq. 1 could have been a more complicated function with slow onset at the very beginning, rapid change soon after, and then a lengthy approach to the new equilibrium. This 'asymmetric sigmoid' approach would have fitted part of the situations well, but Eq. 1 seems more justifiable overall. Moreover, Eq. 1 simplifies the computations, as using it enables basing carbon density change calculations on average carbon density (proof not shown analytically here).

The above discussion was concerned with the form of the model based on which carbon density approaches its new equilibrium. Another question is whether the transition rate should depend only on the new land use and the distance to the equilibrium carbon density. It is easy to think of situations where this CarboScen assumption is unrealistic. For example, the approach from cropland can be very slow due to slow tree growth compared to a potentially rapid decrease e.g. due to logging. This could be the case in a landscape with alternating cropland and low- and high-carbon forests, where low-carbon forest areas are increasing while both other land uses are decreasing in size. Similarly, soil carbon can drop rapidly to its new equilibrium, but an increase from a lower carbon density can take much longer (Poeplau et al. 2011). Having only one value for this rate of change is a problem in some situations, but for overall simplicity we chose to incorporate only one transition rate for one land-use type. If some of the simulated land-use classes require several transition rates, these classes could be separated into several individual ones with identical equilibrium carbon densities but varying transition rates.

An equilibrium carbon density is a problematical concept in several situations. Biomass cannot normally accumulate forever and e.g. the data of Luyssaert et al. (2008) does not show an increase for forests older than a few hundred years. However, due to global change it is likely that biomass gradually changes even in old-growth forests such as primary tropical rain forests (Phillips et al. 1998). However, it seems likely that these global change-driven changes are extremely slow (Chave et al. 2008) compared to successional changes (Supplementary material Appendix 1). Soil carbon is different as its continuous accumulation is possible in some conditions. If all soil carbon in peatland down to the mineral soil is included in the examination, most of this soil carbon is typically in an anaerobic condition, decomposing very slowly and accumulating carbon for millennia. Mineral forest soils are typically assumed to be roughly in balance (Wutzler and Reichstein 2007). However, the accumulation of soil carbon can also be equally rapid as in peatlands, with the difference that peatlands have burned less, as supported by some evidence (Wardle et al. 2012). In landscapes where the carbon density equilibrium value is irrelevant for some land uses and carbon density accumulates during the examination period, a CarboScen user should use the 'Carbon density differs at start' option and set the transition rate start value to such that carbon density accumulation is realistic. Considering all e.g. managed forests as one 'normal forest' (equal area of all age classes) with equilibrium carbon density as the average of all age classes is advisable in landscapes with rotational carbon dynamics, e.g. due to soil carbon accumulation, until a sudden fire causes a drop or until a drop occurs due to logging in managed forests with biomass accumulation.

## Data needed

Equilibrium carbon density values can be set based on national inventories or more local studies conducted e.g. to assess REDD+ potential. If multiple reliable values are available, we recommend using all of them. Instead of an arithmetic mean it is often advisable to calculate the mean by weighting based on the trustworthiness of the study, and the similarity of the studied ecosystem and the land-use class in CarboScen. Users can naturally define biomass and soil carbon as they wish. However, to uphold some consistency between users we recommend defining biomass to include above-ground biomass, below-ground biomass, and coarse woody debris. Soil carbon then includes litter and soil carbon down to 300 mm, or down to the mineral soil layer in organic soils. Because of the equilibrium carbon density approach transitional land-use classes, such as secondary forest, are not recommended. Instead, if this secondary forest is not influenced by humans and is approaching the general 'forest' or 'natural forest' carbon density, then the secondary forest should be considered 'forest' or 'natural forest' that has not yet reached that state.

Transition rate values are more challenging to set than equilibrium carbon densities, as local data are typically not available. We have therefore prepared materials that should help users define biomass transition rates in tropical forests (Supplementary material Appendix 1) and soil carbon (Supplementary material Appendix 2). Naturally potential land uses are countless, and these are just selected examples of transition rates of slow changes that are most important for accurate modeling.

Land use is described based on a land-use change matrix or matrices. These report the land conversion rates at which a land-use class converts to other land-use classes. We discuss potential sources of these matrices and practical questions related to equilibrium carbon density values and transition speed values below under 'CarboScen applications'.

## CarboScen versions published with this note

We first developed a rough spreadsheet version of CarboScen (Supplementary material Appendix 3). This CarboScen version (ver. xlsx) can be useful in teaching or if researchers wish to make modifications in a spreadsheet program.

The CarboScen version recommended for most (ver. 1.0.1) is downloadable from a website: <www.cifor.org/toolboxes/carboscen>. CarboScen ver. 1.0.1 has a graphical user interface and contains numerous additional features compared to the ver. xlsx. The number of land uses is restricted to ten in ver. xlsx, but has no limitation in ver. 1.0.1. Similarly the number of land-use change periods is restricted to two in ver. xlsx, but has no limitation in ver. 1.0.1. Ver. 1.0.1 contains an option for setting the land-use change to linear in addition to the standard that follows Eq. 1, but so that the 'equilibrium area' of the original land use approaches zero. Version 1.0.1 contains an option for quantifying uncertainty based on Monte Carlo simulation (Mooney 1997) derived either by a normal distribution or bootstrapping (Mooney et al. 1993) from the possibilities of area or carbon density. This bootstrapping can be based e.g. on several possible values for carbon densities due to several contradictory inventories. Users are recommended to apply varying weights if some of the carbon density values are e.g. from more trustworthy sources.

CarboScen is based on a discrete, typically annual, time interval. Therefore the 'transition speed' in CarboScen is somewhat faster than parameter $f$ in Eq. 1 and the appendices that are based on continuous functions.

## CarboScen applications

We developed CarboScen to compare carbon implications of future land-use scenarios in tropical landscapes roughly the size of a couple of hundred thousand hectares and consisting of five to ten land-use classes. These scenarios were developed in two-day participatory capacity building workshops in 2014 and 2015 (Ravikumar et al. 2014). The CarboScen computations were conducted during the night in between the two workshop days. Participants needed to not only understand the carbon implications of future land use but also how these were computed.

The second time CarboScen was used in face-to-face expert interviews in 2014 and 2015 regarding the potential impact of carbon payments on land use (Larjavaara et al. unpubl.). The interviews were conducted in ten landscapes, in five countries around the world. The CarboScen computation results were required during the interviews.

The computation of carbon implications for each new scenario could therefore not last more than a minute, which was achieved with CarboScen ver. xlsx.

The following uses for CarboScen have been educational. Course participants at the Univ. of Helsinki, Finland and Hamelmalo College of Agriculture Eritrea, first participated in lectures, and then performed computations for a couple of hours using CarboScen ver. 1.0.1 and an earlier version, on the potential land-use change caused by carbon changes.

We have not observed any significant problems in the use of CarboScen. The first minor challenge was to explain to workshop participants, interviewees, and students how the computation cannot be based on land-use classes with no equilibrium carbon density such as 'secondary forest'. Secondly, complications occurred when the soil or climate varied significantly within a landscape. To make sure that unrealistic land-use changes are not accidentally simulated, edaphically or climatically homogenous parts of the landscape could be separated into two simulations. Finally, users should be careful with the depth at which soil carbon is included, a problem common in all carbon calculation models. The ecosystem carbon stock increases with chosen soil depth and it is impossible to set any general rules. Normally, layers influenced by future land uses should be included, but these depend on how much influence is present and how far into the future the simulation assesses.

We recommend CarboScen for various distinct uses. Its comparative advantage is in landscapes with land-use changes and gradual changes in carbon density, e.g. related to soil carbon if biomass change is sudden, as typically occurs in deforestation. The distinct uses range from educational to rapid expert assessments, typically simulating future carbon stocks in a landscape. CarboScen could be used in future carbon calculations when planning or releasing advance payments in REDD+ or other programs aiming to increase ecosystem carbon. The main payments are then typically released only after results documented in the field. CarboScen could naturally also be used to compute prior landscape carbon dynamics.

The challenges in parameterization of CarboScen naturally depend on the application. In educational use, when the objective is not to create realistic scenarios but rather to demonstrate hypothetical simplistic carbon dynamics, as in Fig. 1, the objectives are often equally met with a large range of values used for equilibrium carbon density and transition rate. On the contrary, when historical development, or more typically a continuation of the historical development as a business-as-usual scenario is simulated (Larjavaara et al. unpubl.), numerous challenges arise.

When a realistic simulation is the objective, the parameterization process should begin by defining the land-use classes. This could be done from two directions. Perhaps in the more typical case when land-use data are scarce, it is better to define the land-use classes based on the available land area data. An ideal example would be a remote sensing study conducted earlier at two points in time covering the landscape with identical methods (Kukkonen and Käyhkö 2014) for land-use reporting. Such a study would typically report changes from each land use to all other land uses between the two points in time and this change would be divided evenly over the time period to gain the land-use matrix used by CarboScen. In this approach, equilibrium carbon density values would then be sought for these same land-use classes, preferably based on local data available e.g. from field inventories conducted to survey REDD+ potential.

In some cases it is better to define the land-use classes based on carbon equilibrium data. This could be the case e.g. when a reliable carbon equilibrium value study is available and when resources can be used to carry out a new remote sensing study optimized for this purpose, therefore avoiding many of the potential sources of error (Verburg et al. 2011). Independent of which of the two directions is taken, it is crucial that the land-use classes for the area and carbon

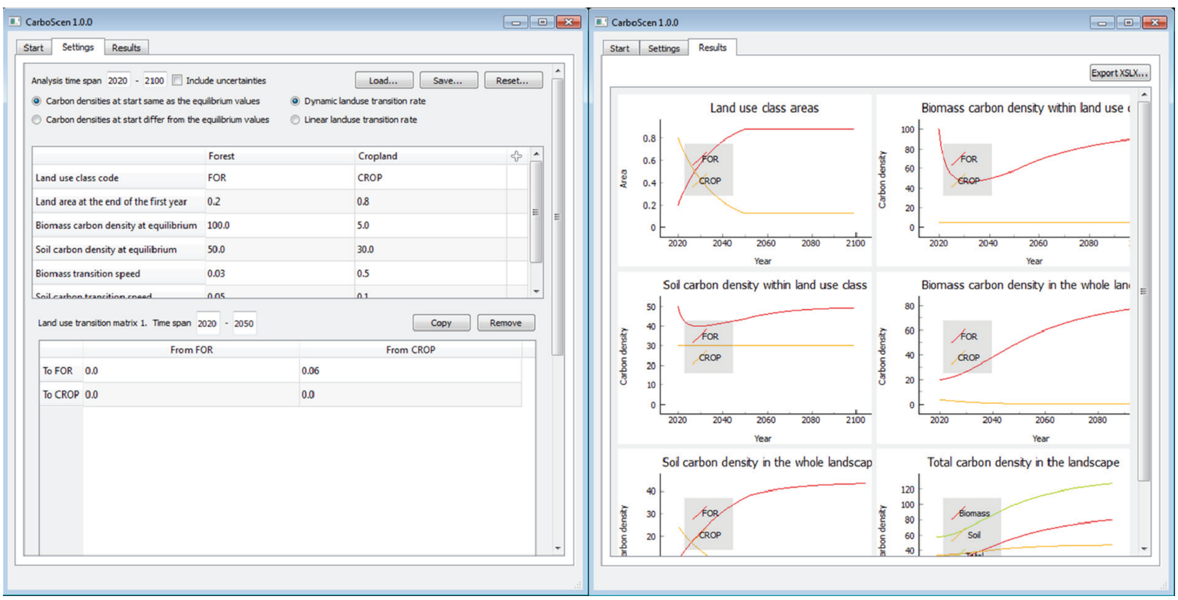


Figure 1. A simple hypothetical example of CarboScen ver. 1.0.1 with just two land uses and increasing forest area.

equilibrium value correspond to each other. This is often easy in small-scale landscapes in rich countries when land tenure is clear and borders of relatively homogenous patches are sharp. In contrast, avoiding bias due to mismatch between land uses in land area and carbon computations requires good field knowledge of the entire landscape in large and heterogeneous landscape when land uses gradually change from one to another.

Setting the transition rates for carbon density can be demanding. Luckily, most biomass changes are rapid and therefore a bias in the transition rate does not significantly influence total ecosystem carbon in longer simulations. When reforestation is important in the landscape, changes in biomass are slow and setting the transition rate should be done with more care and not relying solely on academic studies. The set values should be confirmed based on information obtained from local foresters in the case of timber plantations or local biologists in the case of natural succession. Setting transition rates for soil carbon are more challenging and local actors rarely have experience with this and the parameterization is therefore best performed based on published studies.

## Examples

Figure 1 shows the settings (left) and results (right) of an extremely simple CarboScen ver. 1.0.1 simulation containing only two land uses, cropland and forest, and where 6% of the cropland is converted annually to forest for thirty years. Results (right) show how forest area (red) increases and cropland area (yellow) decreases (top left of the six plots). As a great deal of young forests have recently been converted from cropland, biomass carbon density in the forest drops significantly during the period with land-use change and increases slowly afterwards (top right). A similar, but smaller drop can be seen in soil carbon as a smaller carbon density difference was assumed for soil carbon than biomass carbon (middle left). When area is multiplied by carbon density all carbon in the landscape for the land-use classes is obtained for biomass carbon (middle right) and soil carbon (bottom left). These are then added to obtain all ecosystem carbon in the landscape (bottom right), showing how more carbon was initially present in the soil (yellow) than biomass (red), but the situation changes with afforestation.

Figure 2 shows a more complex simulation for a Mexican landscape with eight land-use classes and land-use changes for thirty years from the starting year described by an interviewed expert (Larjavaara et al. unpubl.). These changes lead to a modest increase in both biomass and soil carbon (bottom right).

## CarboScen compared to other approaches

We compared CarboScen to three out of eighteen landscape-scale calculators reviewed by Colomb et al. (2013). Only five of the eighteen calculators were not country-specific, one did not include forests, and one was still under construction. In addition, we compared CarboScen to the widely used modeling framework CO2FIX (Masera et al. 2003).

The Cool Farm Tool (<https://coolfarmtool.org/coolfarmtool/greenhouse-gases/> accessed 13 October 2016) is an online calculator to compute a greenhouse gas assessment or carbon footprint on active farms. It focuses on emissions caused by fertilizer and pesticide applications, energy use, and manure management, and appears to be fast to use. EX-ACT (Bernoux et al. 2010) is a spreadsheet-based calculator that, just as Cool Farm Tool, includes non-$CO_2$ greenhouse gases, which is often the case for calculators focusing on agriculture. The USAID AFOLU Carbon Calculator (<http://afolucarbon.org/> accessed 13 October 2016) is designed for forested landscapes with potentially decreasing carbon density. This calculator

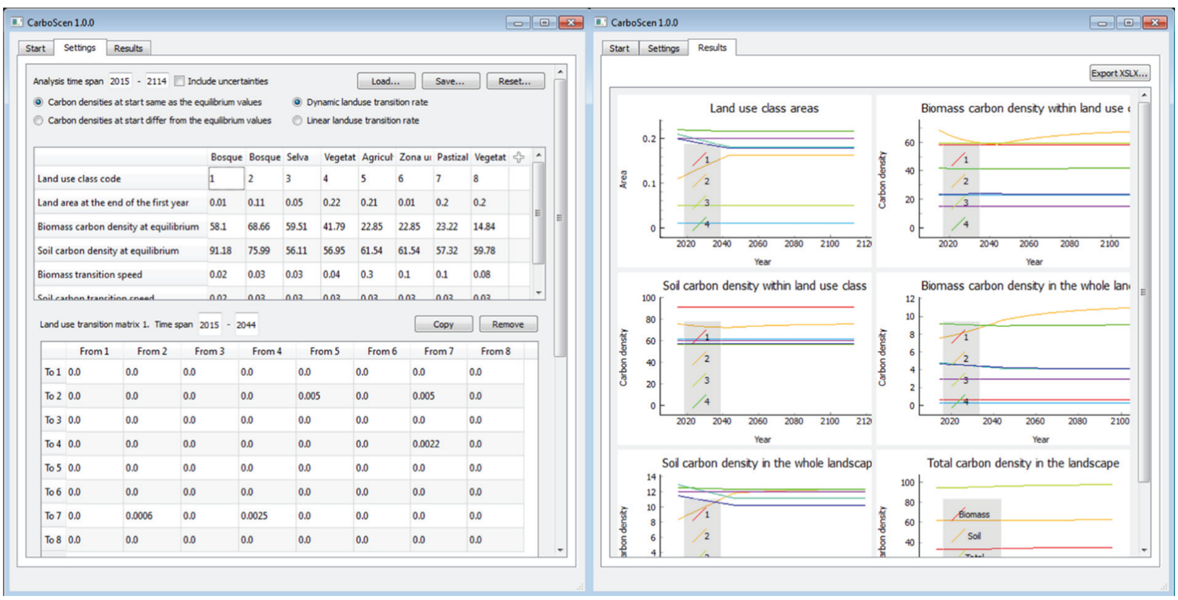


Figure 2. A real example of CarboScen ver. 1.0.1 based on the land-use classes of a Mexican landscape and future changes expected by an interviewed expert.

computes emissions from deforestation, fire, and logging, which can then be compared to e.g. a REDD+ conservation scenario. CO2FIX (Masera et al. 2003) also has a forest focus, but contrastingly to the USAID tool it was developed to quantify carbon sequestration associated to afforestation and forest management activities and based on setting mean annual increments.

The approaches are so different that comparing them quantitatively could be misleading. Using same set of settings to all of them would not be possible due to different approaches and the differences in the outputs would be caused by differences in settings. None of the reviewed models was based on equilibrium carbon densities or land-use change matrices. CarboScen is simplistic and has focus only on carbon and land-use change unlike any of the reviewed other tools.

### Potential ways of expanding CarboScen

CarboScen could be made more inclusive in many ways. One option is to include the carbon in wood products (Perez-Garcia et al. 2005). This could be done e.g. by adding an additional 'land-use class' representing carbon in wood products. Input to this carbon pool could be based e.g. on tree plantation area and output based on an exponential decrease. Secondly, the climate impact of other greenhouse gases, such as methane and nitrous oxide, could be added. In this case e.g. paddy rice cultivation with significant methane emissions would lead to a worse scenario than corn cultivation from the climate point of view, even if carbon densities were assumed identical. Thirdly, other land-use-dependent climate impacts, such as albedo and volatile organic compounds, could be included (Unger 2014). Leakage (Eichner and Pethig 2011) could be taken into account in all three paths.

To cite CarboScen or acknowledge its use, cite this Software note as follows, substituting the version of the application that you used for 'version 0':

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Supplementary material (Appendix ECOG-02576 at <www.ecography.org/appendix/ecog-02576>). Appendix 1–3.