Perennial-GHG: A new generic allometric model to estimate biomass accumulation and greenhouse gas emissions in perennial food and bioenergy crops

Manuscript Details

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Abstract

Agriculture, and its impact on land, contributes almost a third of total human emissions of greenhouse gases (GHG). At the same time, it is the only sector which has significant potential for negative emissions through offsetting via the supply of feedstock for energy and sequestration in biomass and soils. Perennial crops represent 30% of the global cropland area. However, the positive effect of biomass storage on net GHG emissions has largely been ignored. Reasons for this include the inconsistency in methods of accounting for biomass in perennials. In this study, we present a generic model to calculate the carbon balance and GHG emissions from perennial crops, covering both bioenergy and food crops. The model can be parametrized for any given crop if the necessary empirical data exists. We illustrate the model for four perennial crops – apple, coffee, sugarcane, and Miscanthus.

Keywords	above ground biomass; below ground biomass; carbon; carbon dioxide; greenhouse gas emissions; modelling

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Suggested reviewers	Wilson Ancelm, Alessio Boldrin, Cesar Perez-Cruzado, Felipe Crecente

Submission Files Included in this PDF

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Dear Editor:

Many thanks for considering the manuscript entitled "Perennial-GHG: a new generic allometric model to estimate biomass accumulation and greenhouse gas emissions in perennial food and bioenergy crops" for publication. We found the reviewers' and Editor's questions and concerns very interesting and helpful. The manuscript has been revised following reviewers' comments taking into account most comments and answering those not included (see details below). The changes to the old version of the manuscript have been highlighted in blue. In addition to the suggested changes, we have also corrected some additional typos and have made the following improvements:

- The model now deals with intercropping systems. Formerly it only worked for single crops.
- We have added a new table detailing all the model variables (Table 3)
- We have added a new subsection called "model parametrization ", in order to provide more information about parametrization - following the editor and reviewer's suggestions.
- R code has been done with R-markdown, easier to read and understand.
- We have clarified the model boundaries and application. We could see from the reviewer's comments that it was not very clear.

As a final note, several researchers have already expressed an interest in the model and the R code. Accordingly, we think that this study would be broadly read and the paper well cited.

Sincerely,

Alicia Ledo in behalf of all authors

Comments from the editors and two reviewers:

-Editor

EDITOR: The topic of this manuscript is within scope of EMS and is relevant to international research needs with respect to climate change and GHG accounting. Comments from two reviewers are included that must be addressed. Comments from one of the reviewers indicates some confusion about the role of this model in overall GHG accounting. Please seek ways to clarify this.

AUTHORS: We have answered to all the reviewers' comments, and have added into the manuscript the clarifications and concerns suggested by the reviewers. The suggested modifications that we have not incorporated were: the soil carbon model (rev. 1) and the GHG mitigation is the substitutive effect (rev. 2). Detailed reasons are in their respective answers' to comments. We have clarified the model boundaries and added information about the carbon in the system beyond the model boundaries, providing details on complementary models that can be used to calculate extra GHG emissions.

EDITOR: There is no description of the parameterisation of the model beyond the R code and tables of data. Additionally, and importantly, there is no verification that the fitted parameter values are in any way applicable beyond the data used for fitting. This information must be included for the manuscript to progress. Inclusion of this information is essential but will add to an already long description.

AUTHORS: We have added a new section called "model parametrization" right after the "model definition" section (details in answers to rev 2). The model is data-driven and the performance of the model will depend on the quality of the data, of course. We totally agree with the Editor on this point, and we acknowledge this issue in the manuscript (see, for example, lines 754-755). We have used global data for the crops we have parametrized to have an initial global-valid estimation. It is worth reiterating that we did not use data from a single site, but rather combined data from multiple sites, and from different world regions (the data are given in S2). We did not retain data for validation, since it was more valuable to use the data for model fitting. However, it should be noted that we compared the values of biomass obtained in our model with values given in different studies that used either empirical evidence or used a different modelling approach, with no deviations from the reported values (see case studies, lines 716-720, 727,731). We have also specified that for more accurate estimations, more empirical data are needed. The model can be even parametrized at farm scale (lines 757-761). Yet, for the managed ecosystem our model covers, management will be probably quite determinant in plant biomass. And the biomass removed and or left in the plants is not model parameter dependent but depends on the management indicated by the used, which is a model input and therefore, already considered in the model.

EDITOR: Consider ways of consolidating the presentation of the equations to condense the length.

AUTHORS: We are afraid that we don't know how to consolidate the equations. They could be included all in a table. But in this case, the explanation and the equations won't be together and therefore the manuscript will be more difficult to follow (the reviewers pointed that the current manuscript is easy to read and follow). Do you have any suggestions for how we could consolidate the presentation and retain the readability?

EDITOR: The arguments about the desirability of process-based v's empirical models is weak and should be bolstered. For example daily weather is increasing availability from global databases (e.g. AgMERRA). Are process-based 'internal parameters' (the values of which might be deduced from pre-existing knowledge) actually more difficult to obtain than realistic empirical parameters which must be known for each proposed location (weather-soil combination) and management for each cultivar etc.? These topics require discussion/ justification.

AUTHORS: We have now justified and explained better the reasons behind using an empirical model in this particular case. Now it reads "The Perennial-GHG model is data-driven and based on allometric relationships of biomass increment as a function of time. Although physiological crop process-based models are common in agricultural research, the input data required, such as daily meteorological data, and internal parameters such as photosynthesis and evapotranspiration rate, means that they are not easy to apply outside the research community. Process based models can give accurate simulations of daily plant growth and yield, making them more accurate, but also more complex and computationally demanding, which makes them unsuitable for use by farmers / land-managers, and unsuitable for inclusion in most decision support systems." lines 141-144. It is true that global data is more available, but using it is still prohibitive for non-researcher users, while weighing or measuring plants is feasible. Effect of location, variety, climate is now more deeply discussed. More details in answers to rev.2

EDITOR: Other points:

L138 - qualify that the ranking is for the UK please – the statement is misleading

AUTHORS: This has been incorporated (line 166)

L145 - and vertically the bottom of the root zone?

AUTHORS: We have added this clarification: "The model includes the total plant biomass: the above ground (trunk, branches, leaves and fruits) and below grown (the root system and rhizome)." (lines 176-177).

L155 - I was surprised about the statement that it was not necessary to take account of inter-annual variability of climate. Such climate variability is a key driver of plant death which must materially affect biomass accumulation. Please justify or clarify.

AUTHORS: We do acknowledge that climate drives differences and it must be considered. In the ABM, the yield is a model input. The effect of climate on the plant is already reflected in the inter-annual yield variation and therefore there is no need to account for it again. The case is different in the IBM but we do not say that the effect of inter-annual variation should be dismissed. For crops with rotation 10-20 years, as is the case, so positive and negative effects of the climate variability will largely cancel out over time. This is also detailed in lines 196-199. Regarding the effect of climate on tree mortality, the number of trees that die is an input in the model too, it was already considered.

L185 and Table1/2 suggest that there is no time, management or locality component to N concentration in organs. Please justify.

AUTHORS: There is no time in these parameters, since they are the parameters of power law functions which in turn calculate biomass as a function of time. And is therefore included indirectly, e.g. the parameters in the tables describe the curve that predicts biomass as a function of time.

The carbon (C) and nitrogen (N) values are at harvesting time as mentioned in the text (line 676). We have now specify this in the table captions too "The carbon (C) and nitrogen (N) values are at harvesting time."

Management and locality components have not been parametrized yet, due to the lack of data. See answers to rev. 2 for more details.

L432 - "demanding"? "damaging" perhaps?

AUTHORS: No, we meant demanding. Then we clarified that is uncommon. It is true that it is also damaging, but this practise is not common because is very expensive, time consuming and doesn't give any short term advantage like, i.e. increasing the actual yield.

-Reviewer 1

REV1: In general it is a very interesting publication. However, for me a major issue is, that it doesn't discuss what happens with the SOC after the plantation resp. cultivation time. Most of the CO_2 savings (as shown in Figure 2) are caused by the roots. The stability of the SOC in the soil though is highly dependent how the land is used after the cultivation of the perennial crops. Furthermore for example if the soil has a high SOC content the accumulation rate is different from soil with a low SOC content. This issue should be discussed much more in detail.

AUTHORS: We totally agree, the stability of SOC in the system will depend on land use after and before the cultivation, and also on the management and climate. We recognise the importance of soil C (lines 83-84, 94-95 among others) but it is not our intention to model it in this paper where we focus specifically on plant biomass. We are currently conducting a related study to review SOC under perennial crops (mentioned in lines 813-816) but that work is not yet finished and is too large to incorporate in this study, which is already quite long (even longer in this second review). Therefore, modelling SOC is beyond the scope of the model, which is farm-level focused. There are other models that can be used to estimate SOC in the systems, in particular in the soil. We have acknowledged and incorporated this issue, see answers to rev.2 for a deeper explanation. Besides, we have added details about the stability of the SOC in the system through the entire Ms, and in larger detail in in the discussion section (lines 799-807). Besides, the GHGs protocols for product life cycle accounting, for various reasons, do not consider soil carbon stock changes or biomass accumulation in carbon footprint calculations.

REV1: In the following more comments in detail to the manuscript:

REV1: L23 Change *gasses* to gases

AUTHORS: This has been done (line 23)

REV1: L38 This is after my opinion not really a highlight of the current paper, too general

AUTHORS: This has been removed and replaced by some highlights from the current paper (see new highlights)

REV1: L44 It would be nice to include some results of the case studies in the highlights

AUTHORS: We have added new highlights. Points 3 and 4 are based on our results (see new highlights)

REV1: L49 In the keywords "GHG emissions" fits better instead of "carbon dioxide" because you also included CH_4 and N_2O in your model

AUTHORS: We have added the keyword “greenhouse gas emissions”

REV1: L62 CO_2 instead of *CO2*

AUTHORS: This has been changed.

REV1: L72-73 “*all of which may in part be attributed to management without regard for GHG emissions, and potential for GHG mitigation*” meaning not clear, please clarify this sentence
AUTHORS: We have corrected this sentence. Now it reads: “These emissions can be reduced or reversed, so management is a potential tool for GHG mitigation (Smith et al., 2008, 2014). To enable judicious management to be prescribed, sources of GHG emission first need to be identified and quantified.” (lines 73-76)

REV1: L78 Water probably strongly depends on the perennial crop you are looking at. Furthermore I cannot find *Dohleman and Long 2009* in the references

AUTHORS: We agree with the comment. We have added a more accurate description: “Besides, some perennial crops, and in particular perennial grasses like Miscanthus, are more effective at intercepting and utilizing water and CO_2 resources (Dohleman and Long 2009),” (lines 86-88). The reference is now included

REV1: L94 The problem regarding the *permanence of biomass carbon stores* is after my opinion not discussed enough in this paper

AUTHORS: This is a very good point. It is now deeply discussed in the discussion section, lines 807-810, and also mentioned in the equations description section and in the case example.

REV1: L105 Clarify that you only look at the cultivating stage on the farm

AUTHORS: We have clarified our statement. Now it reads: “In this paper, we present a generic model, Perennial-GHG, to calculate the carbon balance and GHG emissions from perennial crops at farm level that does not require the level of site information necessary to run a detailed, process-based model. This model covers the cultivation period and the residue management for both food and bioenergy crops, also considering intercropping, the combination of two or more perennial crops.” (lines 134-116)

REV1: L107 The space before hyphens is different

AUTHORS: This has been corrected.

REV1: L113 Something is missing in the sentence "*intended to estimate biomass when yield is known*". Do you talk here about biomass carbon? Please specify. Often you use the wording "*biomass*" when you talk about the carbon stored in the biomass

AUTHORS: This sentence has been clarified. Now it reads: "Importantly, yield is also an input in the Perennial-GHG model. The Perennial-GHG model does not aim to predict yield, as physiological crops and process-based models do, but to estimate biomass and GHG emissions in perennial crops based on expected / previously recorded / estimated yield." (lines 132-135)

REV1: L124 In which category fall woody perennials, such as willow and poplar, for energy production?

AUTHORS: Those trees are in the IBM category. In this new version of the manuscript, we have included them in deeper detail and parametrize them (see comments to editor)

REV1: L171 N_2O instead of N_4O

AUTHORS: This mistake has been corrected

REV1: L192 Do you also account for pre-harvest losses?

AUTHORS: Yes, this biomass was accounted for. It has been added in line 230. The ABM also accounts for it, we have added this too, line 233.

REV1: L200 What happens with the rhizomes after recultivation in this model?

AUTHORS: Details about what happen with all plant parts are given in the next subsection, in the plant biomass model description.

REV1: L208-209 *If plant parts are taken away - effectively outside the farm boundary, this is considered to be neutral*. Sounds a bit over-simplified.

AUTHORS: We had explained farm boundaries in the introduction section (lines 79, 115, among others). Nevertheless, we have clarified a bit more here. All calculators have finite scope and we believe we have defined ours clearly in the paper. But we do not suggest that biomass or emissions cease to exist outside the farm boundary or the duration of the plantation, simply that that is beyond the scope of our model whose intention is to exploit important driving data to reliably model biomass growth and retention within the farm boundary. Other methods exist currently downstream which we do not wish to duplicate. This also applies to the question of fossil fuel offsets raised by the second reviewer below – there are multiple ways to use biomass products which impact on downstream emissions but these do not impact on farm level quantification which is our goal here.

REV1: L214-216 In case the biomass is used to produce biobased products such as bioplastics or biobased building material this assumption is not valid.

AUTHORS: This is a very good point. We have included this in the Ms, lines 256-258: “However, this is not the case if is the harvested products are used to produce bio-based products such as bio-plastic or bio-based building materials; these are not accounted for in the model..”

REV1: L261 Do you mean branches?

AUTHORS: Yes, this mistake has been corrected.

REV1: L303 coarse roots instead of *coarse root*

AUTHORS: This change has been made.

REV1: L310 1996 instead of *996*

AUTHORS: Mistake corrected.

REV1: L317-318 What is the ratio between roots which will be decomposed and roots which add to the soil organic carbon pool?
AUTHORS: The decomposition curve is specified in the next section. We have added this information here: “The decomposition rate and equations are specified in the section “calculation of GHG emissions”. Lines 367 – 368. And also for the ABM, lines 472-473.

REV1: L341 Sometimes Kg (Table 3) is used, and sometimes kg. Better stay consistent.

AUTHORS: We have changed Kg to kg through the whole manuscript.

REV1: L375-376 Is it possible for example for Miscanthus to differentiate between green harvest in autumn and harvest in spring?

AUTHORS: Yes, the model can be parametrized for either case. As we only have good data for parametrize Miscanthus harvested in autumn, we decided to give values of only autumn harvest for all the presented crops. This information has been added in lines 399-400: “The yield can be either the autumn or spring harvest. In this study, we have parametrized for the autumn harvest (Table 2)” – lines 399-401.

REV1: L428 Here again the problem of the (temporal) storage of carbon in biobased products

AUTHORS: We have added information about bio-based products (lines 487-488). However, here there is not problem anymore. For bio-based products biomass is harvested and falls in that category.

REV1: L437 It should be explained how the model treat the fact that it is quite unsure, how long this “stable” carbon stays in the soil. Especially in the case of land-use change

AUTHORS: This is true. We have added information about carbon persistence in the systems (see comments in the general comments’ section). Nevertheless, we have added a sentence here to clarify any possible misunderstanding: "These root soil input material will stay in the soil afterward for a time that depends on the soil conditions and climate" Lines 499-502

REV1: L480 However, if the chips are used to produce energy and substitute fossil energy and thus generate an additional carbon mitigation potential.

AUTHORS: This is true and we agree. But we do not account for substitution in this manuscript because is beyond the scope (see above and answers' to general comments for more details)

REV1: L568 GHGs instead of *GHGS*

AUTHORS: This has been changed

REV1: L588 "*For the perennial grasses, sugarcane and Miscanthus, most of the negative GHGs are due to litter left on the ground followed by root biomass accumulation.*" Is it not the other way round that the root biomass accumulation is most important (see Figure 2).

AUTHORS: Yes, we have corrected this and clarified: "For the perennial grasses, sugarcane and *Miscanthus*, most of the negative GHGs are due to root biomass accumulation followed by litter left on the ground. The amount of litter is larger but it mainly decomposes in the following years while the root biomass persists for longer." (lines 684-687)

REV1: L618+619 Hyphens are missing

AUTHORS: We have corrected this.

REV1: L691 See above

Table 3: Which pesticides are applied at *Miscanthus* other than herbicides?

AUTHORS: No. In our example, only herbicides were applied, the first year (see Table 4)

Is it realistic that four different management systems have the same energy input? Even if there management steps as some are fertilized and others not. Please explain.

AUTHORS: This is a fair point. We have re-constructed the examples using a different energy value (details in Table 4)

Figure 3: Ground instead of *grond.* Abbreviation *unprod_soil* is not explained in the text

AUTHORS: The typo has been corrected, and there is no need for extra explanations in the caption.

-Reviewer 2

REV2: The manuscript reports the development of a generic model to estimate GHG balance for perennial agricultural crops. The model considers the C accumulation in several fractions of living biomass and residues, as well as several alternatives of residual management. The model is based on allometric relationships which must be calibrated for each crop type. The prediction step is one year, and the scale of prediction is one hectare, even though the model allow estimations for individual plants for the living biomass pools. Model parameters for different woody perennial crops (apple trees, citrus, cocoa, coffe and tea) and herbaceous perennial crops (Miscanthus, sugarcane and switchgrass) are provided. The paper is easy to read and the topic is timely and relevant. Based on my judgement, I recommend accepting this paper after the major changes suggested below.

General aspects:

One of the main advantages of bioenergy crops for GHG mitigation is the substitutive effect. This is due to the fact that the amount of energy produced by bioenergy crops is substituting energy produced from fossil fuels. This is a direct reduction of fossil C emissions, and in my opinion, it should be taken into account in the model. This is a not difficult task. Firstly you should estimate the amount of energy produced at the end of the rotation for each crop type. This can be derived from the crop yield as well as the net calorific value of the biomass (see Pérez et al (2006) DOI: 10.1016/j.tca.2006.08.009). Then, the C emissions for such amount of energy have to be estimated from the non-renewable source of energy (i.e. coal-based thermic plant).

AUTHORS: For reasons stated above and in the manuscript, we do not include this substitutive effect. But we restate again here:

1) This is not in the model boundary border we have defined (farm level). In this regards, we have clarified more the model boundaries (see comments to rev 1)
2) The substitution effect is totally dependent upon what is being substituted, where, and how (the biomass to energy supply chain). This is not a trivial task to be addressed, and is not relevant to the quantification of biomass accumulation on farm. If somebody wished to conduct a more detailed analysis of the fate of the biomass beyond the farm gate, we do, of course, with this model provide the biomass estimates which can be used in such an.

Besides, we provide the embedded emissions associated with production and transport. We have also clarified this in the Ms (see comments to rev 1).

Finally, the fuel substitution can be calculated using current tools. The aim of our paper is to give new, inexistent tools, like the biomass model.

REV2: Another aspect which may increase the interest of this paper for end-users is the inclusion of the transport emissions of the final goods produced. Circular economy has received an enormous attention recently, and the effect of long-distance transportation on agricultural crops has not been estimated properly. I would suggest the authors to make an effort and include a separate module for estimate the C emissions due to transportation.

AUTHORS: This is not considered in the Perennial-GHG model, but it is already included in the Cool Farm Tool in which we will embed this model. Maybe this was not clearly explained. We used the equations from Hillier et al 2012 to account for the emissions from machinery, transport, etc. (paragraph starting in line 159, line 671). We did not present the equations because this is not novel in this study, not because we ignored these emissions. We have also pointed out that this model will be incorporated as a part of the Cool-Farm-Tool (line 163), which accounts for more source of GHGs, such as land use change, etc.

REV2: The growth model considered (L266) assumes a power growth across the rotation length of the crop. This is a risky assumption, as it is well known that the growth of living individuals in any dimension is related with age with a sigmoid-shape model, with an horizontal asymptote which shows the maximum development stage achievable by an individual (or an stand) due to ontogeny. If you decide to keep your power model as the basis for biomass growth, you should state clearly what are the limitations and assumptions behind this model formulation.

AUTHORS: The reviewer is totally right, a sigmoid-shape curve has been demonstrated to be the most adequate for modelling plant growth. However, in the mentioned equation, we are not modelling tree growth but biomass accumulation. And the curve commonly used for biomass accumulation as a function of time is a power law function (see examples Chave et al 2015, Global change Biology; Feldpausch et al 2012, Biogeosciences; Mascaro et 2011, Biotropica). Besides, it has been recently demonstrated (Stephenson et al, 2014, Nature) that trees accumulate biomass following an exponential curve. This justifies once again the use of a power law. On an additional note, our model works on an annual bases, and therefore it is not easy to reflect the early growth differences from empirical annual data. Besides, we tried few curves to check with one accommodate better, and the power law was the best one (lines 308-312).

The power law can be asymptotic some times. One of the cases is for small alpha values, like the ones we have. In addition, management in this particular case will avoid an unlimited growth, especially in crops and trees which life-spam is not very long, like in farms. We have added this idea “Contrary to natural ecosystems, the shape of the trees in farmland is mainly the result of the management actions, i.e. pruning, and controlled by climatic conditions to a lesser extent” (lines 146-148).

REV2: The model formulation considered assumes that the growth of the aboveground part and the belowground part is independent. This is due to the fact that the alpha1 and beta1 parameters (AGB model) and the alpha2 and beta2 parameters (BGB model) are independent. The most evident consequence of this is that the Total biomass does not follow the additivity property. This is: the sum of the belowground part and the aboveground part equals the total biomass. This problem can be solved by keeping the actual model formulation, as long as the alpha1, beta1, alpha2 and beta2 parameters are obtained simultaneously in the same fitting process. This can be done by Seemly Unrelated Regression (SUR) techniques. I strongly recommend the authors to suggest the use of this technique for estimating the values of the parameters.

AUTHORS: We agree with the point the reviewer has made. We had decided to have the AGB and BGB model separately to accommodate for those cases in which the ABG and BGB do not have the same age. This is quite common in agriculture, in which the AGB is harvested more often than the BGB. A clear example are SRC. Tree crowding is also a common practice in fruit trees, i.e. apples and citrus, and also in vineyards. Also in some production systems above ground plants are grafted onto different rootstock which dramatically affects the correlation between AGB and BGB. In natural forest, there is no doubt AGB and BGB should be linked. But in perennial cropping systems it is less clear. We have also clarified that the age of the above part and below part can be different (details in the answers' to the next question).

REV2: Why the ABM does not include correction factors for soil fertility and water availability as IBM does? If you decide to include these two correction factors for the IBM, you should do it as well for the ABM. But, on the other hand, it could be argued whether it makes sense to include the growth correction factors for any of the two approaches. As the yield of the crop must be parameterized with site-specific empirical data, the training data will have implicit into account the two correction factors above mentioned.

AUTHORS: Because the ABM calculates biomass as a function of the annual yield, which is a model input. The annual yield is already a result of the soil fertility and climate conditions. This cannot be reflected in the IBM yield, since the response of yield to nutrients and climate is not directly related with the biomass response to the same factors. We have clarifies this in the discussion section, lines 498-502. We have also clarified that the age of the above part and below part can be different and gave an explanation "Where *year* is the crop life year at which the plantation starts, in years, starting in 1. The parameter *age* and *year* may be the same if the plant is planted on the farm at age 0" (lines 322-323, 414-415).

REV2: In several parts of the MS the paper of Liski et al (2005) is quoted. This paper develops a process-based soil model (YASSO) which could easily be implemented as a separate module of your model. I would strongly recommend the authors to incorporate the YASSO model in your C accounting model.

AUTHORS: In this paper, we wanted to present the new model to account for GHG from plant biomass and residues. The paper is already quite long and a model for SOC changes in beyond the scope of this paper. However, we have clarified and pointed out that for evaluating SOC a complementary model can and should be used. It reads: "Yet, the outputs of our model can be used as inputs for a SOC model such us RothC (Coleman and Jenkinson 1996), ECOSSE (Smith et al. 2010), or YASSO (Liski et al. 2005)." Lines 185-187. Besides, as we indicated in the discussion (lines 810-814), we are working on an empirical model of SOC changes in perennials. This is a quite complex model and will need a full dedicated paper to it. Nonetheless, this model is not mean to replace robust models like the aforementioned.

REV2: Regarding the notation, many formulas use "i", "age" and "year" for indexing the same. I would recommend reviewing the notation to make it consistent thorough the text.

AUTHORS: We have now used "year" through the Ms. However, for the AGB we have age, because that refers to the age of the crops, which may or may not be the same as the plantation crop year. To avoid confusions and be more accurate, we have defined age and year. This difference can be now easily spotted thanks to the new Table 3 we have added (see comments to the editor for details).

Specific aspects:

REV2: Figure 1. There are CO2 in grey and in black (right end part of the diagram). It is not clear for the reader the meaning of both types of CO2, even after a deep review of the paper.

AUTHORS: This is a very fair point. We have added explanation in the figure caption: "The emissions in plane black are positive emissions, GHGs released to the atmosphere. Emissions in grey are neutral emissions, the uptaken CO2 equals the released CO2. Emissions in bolt are negative emissions, atmospheric carbon fixed in the system."

REV2: L24-25. Use of agricultural crops for producing energy supposes a deep ethical controversy, as many areas in the globe are suffering of hungry. Please, include some comments on this.

AUTHORS: We do agree with the reviewer. But the use of land and crop prices are beyond the scope of this study which does not inform the debate in any material way. We therefore make no reference to this food vs fuel debate.

REV2: L39-41. This Highlight is too long. Please shorten it.

AUTHORS: This highlight has been rewritten (see highlights and answers to rev. 1)

REV2: L65-68 This sentence is confusing, please rephrase it.

AUTHORS: This sentence has been rephrased (details in answers to rev. 1)

REV2: L71 Please, include "and livestock" after "rice production".

AUTHORS: This has been included

REV2: L107 Please, replace "apples" by "apple trees".

AUTHORS: We have changed this and substitute apples by "apple", which is the name of the crop.

REV2: L116 Please, replace "crop" by "based".

AUTHORS: We have added "process-based" models, line 114

REV2: L109-130. This paragraph is too long and the same ideas are repeated (i.e. trees and grasses are considered in the model L108 and L123). I would recommend shorten this paragraph. The paper is quite long and it will help to reduce the MS length.

AUTHORS: This paragraph has been changed, according to rev.1

REV2: L131 Please add "the" after "develop".

AUTHORS: This has been added.

REV2: L151-152. "and the final outcome….on the user's imput.". I would remove this last part of the sentence, as it is a generic statement which applies to all models.

AUTHORS: This sentence has been removed

REV2: L194-200 This description does not correspond exactly with Figure 1, where there are a lesser number of residues.

AUTHORS: True, Figure 1 is an example. Not all the residues will be always present.

REV2: L273 and elsewhere (L289, L297, L328, L334, etc…): The notation of the sum must be changed to FROM: i=1 TO N, instead of FROM 1 TO N.

AUTHORS: This has been changed, and following the notation according to the general comment (see answers to general comments)

REV2: L310 (1996)

AUTHORS: This has been change (details in answers to rev.1)

REV2: L312 and 313 Shouldn't be either "BGBi" or "BGBage" in both formulas?

AUTHORS: This has been change through the manuscript (details in answers to rev.1)

REV2: L333 These values are not provided in Table 1.

AUTHORS: True, we have added a new column including these values

REV2: L366 Please replace "one unit" by "as a fraction of one".

AUTHORS: This has been changed through the Ms

REV2: L375 Please, replace "use" by "used".

AUTHORS: This has been replaced

REV2: L143. This information is not included in Table 2.

AUTHORS: It has been included now

REV2: L432 "is uncommon in agriculture" This is not true for apple trees and citrus trees.

AUTHORS: We are not aware of many cases in which this practice is common. This is not common in apple and citrus in many cases, ie. UK.

REV2: L471 This parameter of the YASSO model was obtained for boreal soils, and it is well known that it does not work well for other climates. As the authors claim about the broad applicability of the model, the consideration of this parameter must be taken with caution, and admitting that it is not valid for all climates.

AUTHORS: Yes, this is a very fair point and it was not clear enough in the paper. We have clarified in better. This also applies to other decomposition parameters. We have added this idea into the manuscript, i.e. lines 499 (general), 509,555,556 (decomposition), among others

REV2: L573 Please, explain what GWP is.

AUTHORS: Global Warming Potential (GWP), it was explained in line 205.

REV2: L588. Harvesting-derived emissions are not taken into account here.

AUTHORS: Yes, they were, but it was not well explained. This item has been clarified in the manuscript (check answers to rev1)

REV2: L610. Please replace “right” by “left”

AUTHORS: This change has been made

REV2: L623. Please replace “right” by “left”

AUTHORS: This change has been made

REV2: L627. Please replace “left” by “right”

AUTHORS: This change has been made

REV2: L661-662 as well as harvesting operations.

AUTHORS: Information added.

REV2: P32 It would be nice to have here a deep dissertation on the data necessary to parameterize the model, as well as the details of the sampling design necessary for gathering such data: time period for obtaining the biomass empirical data, etc..

AUTHORS: This is a very fair point. We have added a new subsection called “model parametrization” including such information (lines 646-663).

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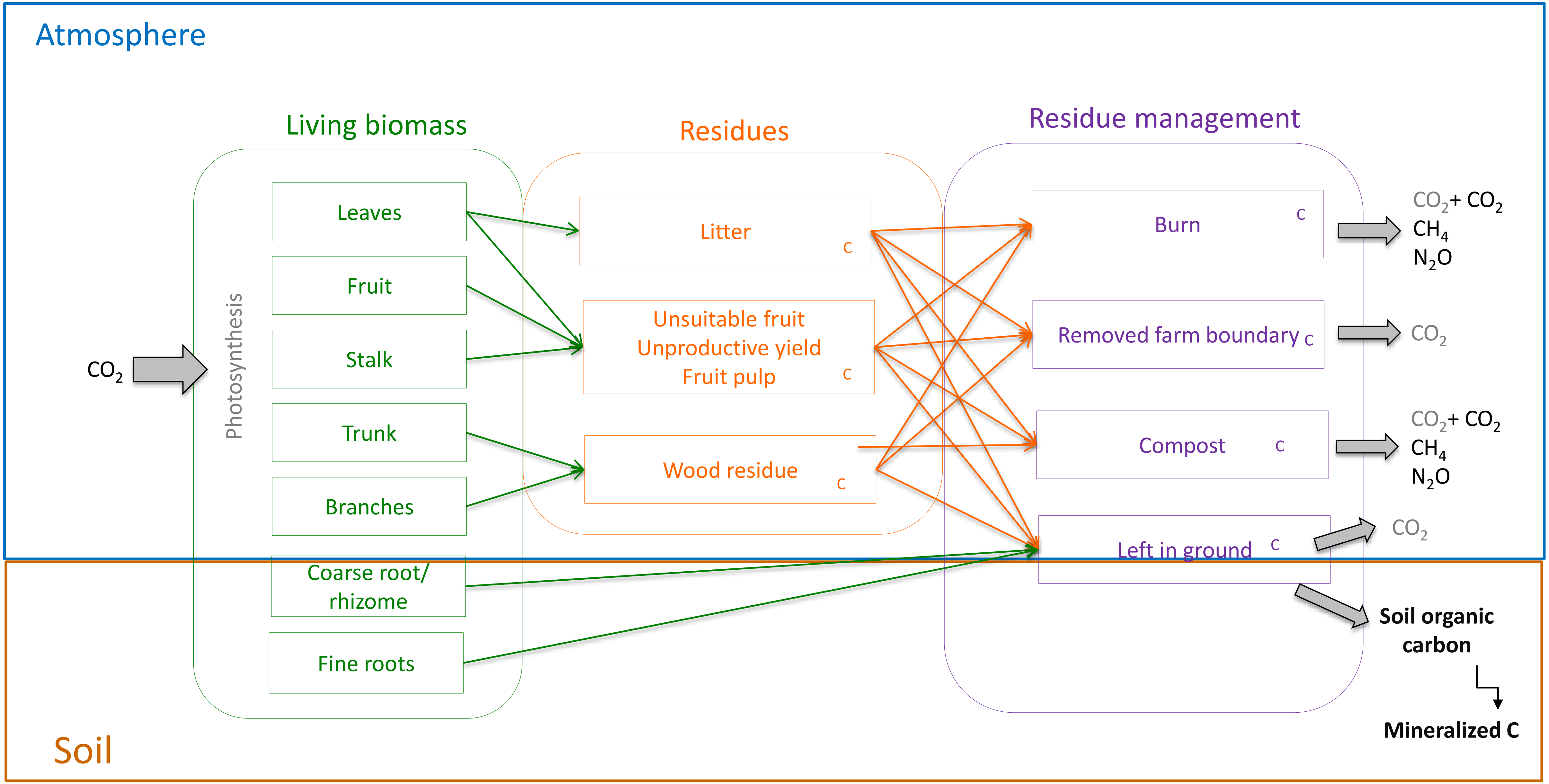
Atmosphere
Living biomass
Residues
Residue management
Leaves
Fruit
Stalk
Trunk
Branches
Coarse root/ rhizome
Fine roots
Photosynthesis
CO_2
Litter
C
Unsuitable fruit
Unproductive yield
Fruit pulp
C
Wood residue
C
Burn
C
Removed farm boundary C
Compost
C
Left in ground
C
CO_2+ CO_2
CH_4
N_2O
CO_2
CO_2+ CO_2
CH_4
N_2O
CO_2
Soil organic carbon
Mineralized C
Soil

Perennial-GHG: a new generic allometric model to estimate biomass accumulation and greenhouse gas emissions in perennial food and bioenergy crops

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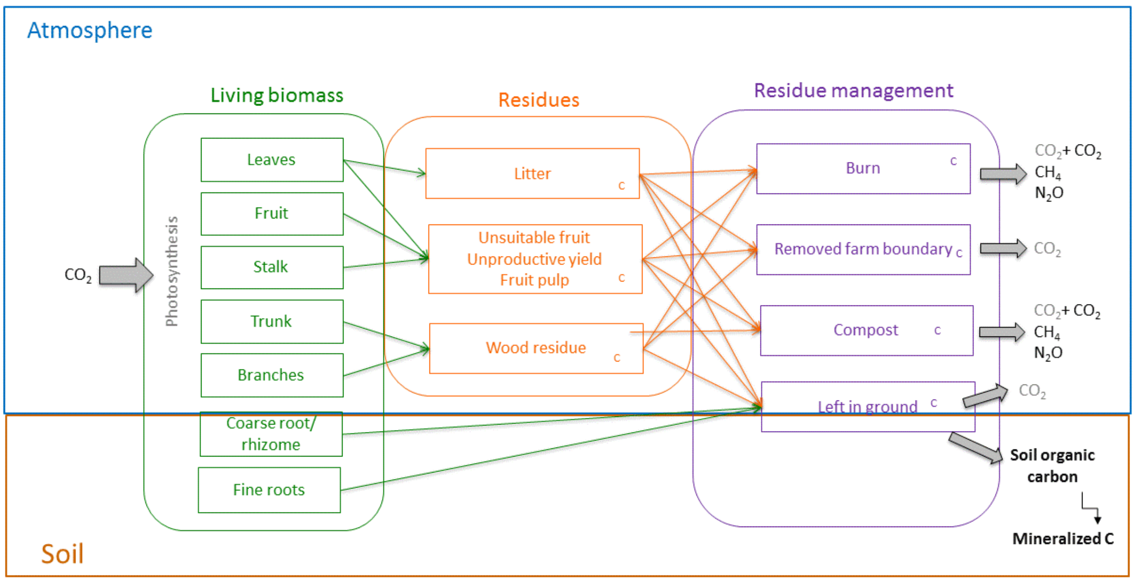
Abstract

Agriculture, and its impact on land, contributes almost a third of total human emissions of greenhouse gases (GHG). At the same time, it is the only sector which has significant potential for negative emissions through offsetting *via* the supply of feedstock for energy and sequestration in biomass and soils. Perennial crops represent 30% of the global cropland area. However, the positive effect of biomass storage on net GHG emissions has largely been ignored. Reasons for this include the inconsistency in methods of accounting for biomass in perennials. In this study, we present a generic model to calculate the carbon balance and GHG emissions from perennial crops, covering both bioenergy and food crops. The model can be parametrized for any given crop if the necessary empirical data exists. We illustrate the model for four perennial crops – apple, coffee, sugarcane, and *Miscanthus*– to demonstrate the importance of biomass in overall farm GHG emissions.

Graphical abstract



Highlights

- Inconsistency in methods of accounting for biomass in perennial crops impedes quantification of positive effects of perennial crops on net greenhouse gas (GHG) emissions.
- We present a generic model to calculate the carbon balance and GHG emissions from perennial crops, covering both bioenergy and food crops. We illustrate the model for four perennial crops.
- Different crops and different management practices for a given crop lead to very different emissions of GHGs, which can be either positive or negative.
- We show the importance of biomass in overall farm GHG emissions. Under judicious management, perennials have significant potential for negative emissions and are thus important for climate change mitigation.

Keywords: above ground biomass; below ground biomass; carbon; carbon dioxide; decomposition; greenhouse gas emissions; modelling.

Introduction

Agriculture is an essential human activity but at the same time a substantial emitter of greenhouse gas (GHG) emissions (Robertson et al., 2000). With a rising global population, the need for agriculture to provide secure food and energy supply is one of the main human challenges (Smith et al., 2010). Agriculture contributes about 4.6-5.4 Gt CO_2-equivalent per year, which is 9-11% of global GHG anthropogenic emissions in 2010 (Tubiello et al., 2013; Smith et al., 2014), and the value approaches a third of total emissions if the indirect impacts of land use change, and land degradation (Wollenberg et al., 2013) are considered. At the same time it, and the other land based sectors, are the only ones which have significant potential for negative emissions through the sequestration of carbon and offsetting *via* the supply of feedstock for energy production.

In addition to land use change, major sources of GHG emissions from crop production include N_2O emission from the production and use the use of fertilizers (Robertson et al., 2000), methane emissions from paddy rice production and livestock (Yan et al., 2005), and the loss of stored biomass and soil carbon, all of which may in part be attributed to management. These emissions can be reduced or reversed, so management is a potential tool for GHG mitigation (Smith et al., 2008, 2014). To enable judicious management to be prescribed, sources of GHG emission first need to be identified and quantified.

Perennial crops such as fruit trees or bioenergy grasses like *Miscanthus* are often not differentiated from annual crops when estimating agricultural GHG emissions. However, in contrast to annual cropping systems which most often have positive GHG emissions, perennials may have net zero or even negative emissions (Glover et al., 2010; Robertson et al., 2000:2016, McCalmont et al.; 2015). Perennial agricultural management also reduces soil disturbance since annual cultivation is not required, and it adds more carbon inputs to the soil and improves soil conditions (Paustian et al. 2000; Cox et al. 2006). This, in turn, allows soil carbon to be stabilised, hence reducing emissions of carbon dioxide to the atmosphere *via* mineralization in those cases in which the soil is not saturated with carbon (Dawson & Smith, 2007). Besides, some perennial crops, and in particular perennial grasses like Miscanthus, are more effective at intercepting and utilizing water and CO_2 resources (Dohleman and Long 2009), and some need less or no fertilizer application (Hastings et al. 2009:2017; Davies et al. 2012). This may have vital implications for GHG and mitigation options in the future; hence it is timely to develop generic, consistent, and scalable models to account for often overlooked biomass accumulation, particularly in perennial production systems.

Perennial crops accumulate carbon during their lifetime, in above and below ground components, and enhance organic soil carbon increase *via* root senescence and litter inputs. However, inconsistency in accounting for this stored biomass undermines efforts to assess the benefits of such cropping systems when applied at scale. Common product foot-printing standards e.g. the Publicly Available Standard 2020:2011 (PAS2050), the EU renewable Fuel Directive (RED), and the GHG protocol for product life cycle accounting, for various reasons, do not consider soil carbon stock changes or biomass accumulation in carbon footprint calculations (Whitaker et al., 2010). The major concerns appear to be, firstly, the lack of reliable methods to quantify carbon stocks in the various plant components, and secondly, issues around permanence of the biomass carbon stored (Brandão et al*.,* 2013). A consequence of this exclusion is that efforts to manage this important carbon stock are neglected. Detailed information on carbon balance is crucial to identify the main processes responsible for greenhouse gas emissions in order to develop strategic mitigation programmes. Perennial cropping systems represent 30% of the area of total global crop systems (Glover et al., 2010). Furthermore, they have a major role both in the global food (i.e. oil palm, coffee, fruit and cocoa) and bioenergy (i.e. *Miscanthus*, switchgrass, sugarcane, short rotation coppice) industries. At the same time, an increase in perennial crops or 'perennialization', is one of FAO's (Food and Agriculture Organization of the United Nations) strategies to enhance food security and ecosystem service delivery (Glover et al., 2010; Rai et al., 2011).

In this paper, we present a generic model, Perennial-GHG, to calculate the carbon balance and GHG emissions from perennial crops at farm level that does not require the level of site information necessary to run a detailed, process-based model. This model covers the cultivation period and the residue management for both food and bioenergy crops, also considering intercropping, the combination of two or more perennial crops. GHG emissions can be either positive (emissions to the atmosphere) or negative (carbon uptake from the atmosphere). Plant biomass is formed *via* carbon uptake from the atmosphere; consequently, it is stored as a negative GHG emission in the model while it is living material in the plant. Once the plant or plant part is removed or naturally released, it becomes a residue (see Fig.1).

We then use this model to illustrate the importance of biomass in the estimation of overall GHG emissions from four important perennial crops - coffee, apple, *Miscanthus* and sugarcane – which were chosen to give examples from tropical and temperate regions, trees and grasses, and energy and food supply. We propose a model that has wide applicability and can be used both in research environments and for decision support among industry, farming, and NGO stakeholders, to evaluate actual agriculture practises, and support efforts to reduce the GHG intensity of agricultural products by accounting for biomass storage and decomposition, and persistence of carbon in the system. Plant biomass is in large part carbon fixed from the atmosphere by photosynthesis and stored in the plant. The model runs using inputs supplied by the farmer or land manager, including the cultivated area, crop or crops, and the main management options (the list of inputs is presented in Supplementary information S3). Importantly, yield is also an input in the Perennial-GHG model. The Perennial-GHG model does not aim to predict yield, as physiological crops and process-based models do, but to estimate biomass and GHG emissions in perennial crops based on expected / previously recorded / estimated yield.

The Perennial-GHG model is data-driven and based on allometric relationships of biomass increment as a function of time. Although physiological crop process-based models are common in agricultural research (Priesack and Gayler, 2009), the input data required, such as daily meteorological data, and internal parameters such as photosynthesis and evapotranspiration rate, means that they are not easy to apply outside the research community. Process based models can give accurate simulations of daily plant growth and yield, making them more accurate, but also more complex and computationally demanding, which makes them unsuitable for use by farmers / land-managers, and unsuitable for inclusion in most decision support systems.

Contrary to natural ecosystems, the shape of the trees in farmland is mainly the result of the management actions, i.e. pruning, and controlled by climatic conditions to a lesser extent. At the end of the crop cycle, tree woody biomass often reflects human actions. The generic model we are presenting is composed of two simple sub-models, to cover grasses and other perennial plants. The first is a generic individual-based sub-model (IBM) covering both woody crops in which the yield is the fruit and the plant biomass is an unharvested residue, and short rotation coppice (SRC). Trees, shrubs and climbers fall into this category. The second model is a generic area-based sub-model (ABM) covering perennial grasses, in which the harvested part includes some of the plant parts in which the carbon storage is accounted. Most second generation perennial bioenergy crops fall into this category. Both generic sub-models presented in this paper can be parametrized for different crops, and we have parametrized the sub-models for a list of crops using published empirical data. The model can also account for different varieties, geographical locations and rate of applied fertilizer, and for fine-scale analysis, it can be parametrized at farm level.

For use outside the research community, so-called "carbon calculators" have been developed. Although there are several of these, the accounting for stored biomass is relatively limited (Whittaker et al., 2013). The models we develop in this study have been co-designed with the Cool Farm Alliance to be ready for insertion in to the Cool Farm Tool (CFT, www.coolfarmtool.org) - a free-to-use, farmer-oriented GHG calculator, which has been widely used globally by industry and farming to assess GHG emissions, and identify positive interventions to mitigate GHG emissions. The CFT performed best among all farm GHG emissions calculators in the UK (Whittaker et al., 2013), and the incorporation of improved accounting for biomass in perennials will enable wider use in the bioenergy sector. The methodology, however, could also be used in other GHG emission calculators, to improve their functionality on representing perennials.

<FIGURE 1>

Model definition

The Perennial-GHG model we present in this study estimates values of GHG emissions derived from the plant biomass for the entire cultivated crop area. It is a generic model that describes biomass accumulation and release, and calculates associated GHG emissions and removals. The model includes the total plant biomass: the above ground (trunk, branches, leaves and fruits) and below grown (the root system and rhizome). The model allows farm level management to be taken into account, and the system boundary is the farm gate (Hillier et al. 2011). GHG emissions arising from supplementary management options, machinery, farm electricity and goods transport need to be considered in the overall farm emissions, and for these we used the equations presented in Hillier et al. 2011 (not presented here). Regarding the below ground compartment, the model estimates plant biomass input to the soil and subsequently decomposition. Perennial-GHG is a biomass model and does not include a soil module (which is the subject of ongoing work), so does not estimate changes in soil organic carbon (SOC). Yet, the outputs of our model can be used as inputs for a SOC model such us RothC (Coleman and Jenkinson 1996), ECOSSE (Smith et al. 2010), or YASSO (Liski et al. 2005).

In the Perennial-GHG model, biomass accumulation is described using different generic allometric curves, which have to be parametrized for each crop, and estimates biomass as a function of time (in years). In farmlands, most of the biomass released is due to human management interventions, such as grapping or pruning. The model specifies the contribution of each different plant part and/or residue to GHG emissions and details the annual GHG emission values. This allows investigation of the inter-annual variation in terms of biomass increment/decrease and GHGs and the contribution of each separate plant part or residue type to GHG emissions. We did not consider it necessary to take into account the effect of seasonal and inter-annual variability of climate for the following reasons: for the IBM, crop rotations are longer than 5-10 years, so positive and negative effects of the climate variability will largely cancel out over time (Harris et al 2014). In the ABM this effect is directly accounted for by the input values of yield given by the user.

In the Perennial-GHG model, both the IBM and the ABM sub-models are comprised of different modules, which we present in the following subsections. The required model inputs are listed in Supplementary information S3. The model calculates emissions of the different GHG gases: CO_2, N_2O and CH_4. As is common-practise, the emissions from all those GHG gases are transformed into CO_2 equivalents using Global Warming Potential (GWP) values as follows:

$$CO_2eq\,(CH_4) = CH_4 * GWP_{CH_4} \quad \text{[eq. 1]}$$

$$CO_2eq\,(N_2O) = N_2O * GWP_{N_2O} \quad \text{[eq. 2]}$$

$$CO_2eq = CO_2 + CO_2eq\,(CH_4) + CO_2eq\,(N_2O) \quad \text{[eq. 3]}$$

The model includes two different set of values for GWP, the widely used 2001 IPCC values (IPCC 2001), and the most recent IPCC GWP over a 100-year time horizon presented in Myhre et al. (2013). Different values could be also specified by the user.

Information about annual GHG balance of each plant part, and for each residue, is stored in a matrix in the model. In addition, it should be noted that in the following, biomass always refers to the dry biomass, the weight of the plant excluding the water content. The percentage of C in the different plant organs is also required for the sub-models. Although not a focus of this study it should be noted that the model additional calculates the N balance in the plant.

$$Biomass = fresh\ weight * \ dry\ matter \quad \text{[eq. 4]}$$

where $dry\ matter = 1 - water\ content$, as a fraction of one.

$$Carbon_{organ} = Biomass_{organ} * Carbon\ content_{organ} \quad \text{[eq. 5]}$$

$$Nitrogen_{organ} = Biomass_{organ} * Nitrogen\ content_{organ} \quad \text{[eq. 6]}$$

Specific values of water, C and N content in different plant organs and species and are presented in Table 1 and 2.

A first set of modules estimate biomass accumulation as a function of time, in which different plant parts are modelled separately and stored as annual values. The IBM defined for the woody crops therefore consists of the following modules: biomass from woody parts, leaf biomass, below ground biomass (accounting for the coarse and fine roots separately), biomass pulp for those crops that have to be de-pulped, and biomass of the yield discarded for quality reasons. This includes the total biomass produced by the plant, including all the pre-harvest biomass. In parallel, the ABM consists of modules for: above ground and stalk biomass, leaf biomass and below ground biomass (accounting for the rhizomes and roots with turnover separately). Once again, it includes all the pre-harvest biomass. Subsequently, a second set of modules estimate GHG emissions both from the plant parts and from the residues and/or the biomass naturally released from the plant. Five kinds of residue are accounted for in the IBM: litter from the leaves, woody parts from pruning, trees that die and the final tree cut, the fruit discarded and fruit pulp, and fine roots that die. In the ABM, three kinds of residue are accounted for: the leaves, if it is not a commodity, total above ground biomass (AGB) of the unproductive initial(s) year(s), and roots that die. The total GHG emissions from residues can be either positive or negative and this strongly depends on the residue management, which is a model input indicated by the user.

The Perennial-GHG model incorporates different residue management options. Options for wood residues are: burning, chipping followed by spreading, or chipping followed by removal. For litter, the options are either burning or litter left on the ground. For discarded fruits and pulp the management options are either: left on the ground or removed. In either case, burning will always result in positive GHG emissions but residue incorporation into the soil will result in negative emissions. If plant parts are taken away - effectively outside the farm boundary, this is considered to be neutral consistent with our farm-gate boundary (as described in the introduction), which was fixed to limit the model scope to processes over which farmers have control. Perennial-GHG allows a mix of different management techniques for each residue source, for example, 50% of the pruning residues chipped and 50% burnt.

As a final step, outputs from the modules are summed to obtain the total field level estimation of GHG emissions. The carbon in harvested products, exported beyond the farm gate is, excluded from the accounting since it is generally considered in bioenergy, food and drink sectors to be available for combustion or consumption, and thus most likely returned to the atmosphere in the short carbon cycle. However, this is not the case if is the harvested products are used to produce bio-based products such as bio-plastic or bio-based building materials; these are not accounted for in the model.

For the IBM, the field CO_{2eq} is calculated by multiplying the individual value by the number of trees of each species. For monocultures, only one species is included. For intercropping or multi-cultures, the CO_{2eq} from each species is gathered:

$$Field\ CO_{2eq_{biomass_{year}}} = (\textstyle\sum_{s=1}^{s=S} Ind\ CO_{2eq_{biomass_{year}}} * N_S) * A \quad \text{[eq. 7.1]}$$

Where S in the number of species, S=1 in monocultures. $Ind\ CO_{2eq_{biomass_{year}}}$ are the individual values of CO_{2eq} containing separate information about the aforementioned plant biomass and residue for each year per species s. The modules for estimated plant and residue biomass will be detailed in the forthcoming section. N_s is the number of trees per ha of each species s. This number does not equal the number of planted trees because some trees will die during the crop life period. If gapping (replacement of dead trees) is not present, then $N = N_{planted\ trees} - N_{trees\ die}$. If gapping is present, N is equal to the number of planted trees. In both cases, the percentage of trees that die is an input to the model. The model assumes a constant mortality ratio during the period: $N_{trees\ die} = N_{planted\ trees} * {}^{\%\ trees\ die}\!/_{100}$. A is the total cultivated area in ha.

For the ABM, the field CO_{2eq} is calculated by multiplying the per hectare value by the total area:

$$Field\ CO_{2eq_{biomass_{year}}} = \sum_{s=1}^{s=s} Area\ CO_{2eq_{biomass_{year}}} * A \quad \text{[eq. 7.2]}$$

Where s in the number of species, s=1 in monocultures $Area\ Co2eq_{mass_{year}}$ are the per-ha values of CO_{2eq} containing separate information about each species s of plant biomass or residue and year. The modules for estimated plant and residue biomass will be detailed in the forthcoming section. A is the cultivated area in ha of each species.

For farms than contain both crops that fall in the ABM and the IBM categories, the field CO_{2eq} is calculated by adding the GHG derived from those crops (eq. 7.1 and eq. 7.2).

$$Field\ CO_{2eq_{biomass_{year}}} = \left(Field\ CO_{2eq_{biomass_{year}}}\right)_{IBM} + \left(Field\ CO_{2eq_{biomass_{year}}}\right)_{ABM} \quad \text{[eq. 7]}$$

The annual values are then summed to derive the overall CO_2eq values from each plant part or residue each year of the crop lifecycle in the entire cultivated field:

$$Field\ CO_{2eq_{biomass}} = \sum_{year=1}^{year=Years} Field\ CO_{2eq_{biomass_{year}}} \quad \text{[eq. 8]}$$

And the overall CO_{2eq}, regardless of plant part or residues, is:

$$Field\ CO_{2eq} = \sum Field\ CO_{2eq_{biomass}} \quad \text{[eq. 9]}$$

Finally, CO_{2eq} equivalent per tonne of finished product is given by:

$$CO_{2eq}\ per\ tonne\ of\ final\ product = Field\ CO_{2eq} / \sum_{year=1}^{year=Years} yield_{year} \quad \text{[eq. 10]}$$

Where total yield is a model input.

In this section, only the equations for CO_{2eq} are shown, but a similar approach exists for individual GHGs. All the functions provide values of CO_{2eq} in kg.

Definitions of all the parameters included in the model are detailed in Table 3. The R code for the main model including all the modules is provided in S1 and the figshare archive doi <*to be added*>. The database of empirical values used to parametrize the model is provided in S2 and figshare archive doi <*to be added*>. The required model inputs to run the Perennial-GHG model are provided in S3.

Plant biomass modules

Individual based sub-model (IBM) for perennial woody crops

Functions in this subsection estimate biomass accumulation as a function of time in the different plant parts. They represent cumulative amounts, in units of kg per plant.

< TABLE 1 >

Biomass in wood module

This module provides the above ground biomass of the woody parts (AGBW) as a function of time. The AGBW comprises the stem plus all the branches, including twigs. Power relationships are generally used in biomass estimation (Stephenson et al., 2014) and in this case, the power law provided the best fit to the crop-growth empirical data for different crops we have (data reproduced in S2). The power law was not only the best fit for single crops in most cases, but also the best single function that accommodated all crops.

$$AGBW = (\alpha_1 age^{\beta_1}) * Rw_{AGB} * Rf_{AGB} \quad \text{[eq. 11]}$$

where *age* is the age of the above-ground plant part, in years. α_1 and β_1 are specific parameters (see Table 1). The Rw_{AGB} and Rf_{AGB} account for water and nutrient limitation – i.e. the growth limiting effect of lack/excess of water, and lack of fertilizers, respectively. To date, data on robust empirical Rw_{AGB} and Rf_{AGB} values for perennial crops are rare, and thus are set to 1 in the current model.

If pruning is practiced, as is common for many perennial crops, the values of AGBW are corrected to actual AGBW (actAGBW):

$$actAGBW_{year} = (AGBW - Pruning)_{year} \quad \text{[eq. 12]}$$

Where *year* is the crop life year at which the plantation starts, in years, starting in 1. The parameter *age* and *year* may be the same if the plant is planted on the farm at age 0. The model allows two kinds of inputs regarding pruning values: the values can be specified either in fresh weight of pruned residues per year or as the percentage of crown removed per year.

The cumulative values of pruned biomass are:

$$AGBpruning_{year} = \sum_{year = SPrun}^{year = Years} (Pruning)_{year} + (Pruning)_{year-1} \quad \text{[eq. 13]}$$

where *SPrun* is the year in which pruning starts. This function assumes that pruning is always executed once it starts.

Biomass in leaves module

Two sub-models are defined for leaves, one for deciduous species and a one for evergreens. The deciduous plants module is:

$$Annual\ Leaves\ Biomass_{dec} = \alpha_2 actAGBW^{\beta_2} \quad \text{[eq. 14.1]}$$

where α_2 and β_2 are specific parameters (Table 1). Leaf biomass is therefore a function of actAGBW. eq. 14.1 is applied annually to have the annual leaf biomass. Cumulative leaf biomass is thus given by:

$$Leaf\ Biomass_{dec} = \Sigma_{year=1}^{year=Years}(Annual\ Leaf\ Biomass_{dec})_{year} + (Annual\ Leaf\ Biomass_{dec})_{year-1} \quad \text{[eq. 15.1]}$$

The module for evergreen plants is mathematically similar to eq. 14.1, except that the current leaf biomass does not correspond to the annual production.

$$Annual\ Leaf\ Biomass_{ev} = \alpha_2 actAGBW^{\beta_2} \quad \text{[eq. 14.2]}$$

where α_2 and β_2 are specific parameters (Table 1).

The cumulative value of leaf biomass in this second case is:

$$Leaf\ Biomass_{ev} = \Sigma_{year=1}^{year=Years} Annual\ Leaf\ Biomass_{ev} + {Annual\ Leaf\ Biomass_{ev}}/{l} \quad \text{[eq. 15.2]}$$

where *l* is the average lifespan of the leaves.

Below-ground biomass module

Below-ground biomass refers to the entire root system, including both the coarse roots and the fine roots. The module to calculate root biomass is:

$$BGB = (\alpha_3 age_{root}^{\beta_3}) * Rw_{BGB} * Rf_{BGB} \quad \text{[eq. 16]}$$

where age_{root} is the plant root age, in years. The age_{root} can be equal during the first crop rotation but they will differ after biomass removal and re-growth. α_3 and β_3 are specific parameters

(Table 1). This model also includes the theoretical parameters $Rw_{BGB} * Rf_{BGB}$ to account for lack and excess of water and lack of fertilizers, not parametrized yet and set equal to 1.

For estimating the percentage of fine roots as a function of plant age, the equation proposed by Kurz et al. (1996) is used. It can be seen that the proportion of fine roots (*Prop fine roots*) decreases with age:

$$Prop\ fine\ roots_{age_{root}} = 2.73 * age_{root}^{\ -0.841} \quad \text{[eq. 17]}$$

$$Fine\ root_{root} = \frac{Prop\ fine\ roots_{age_{root}}}{100} * BGB_i \quad \text{[eq. 18]}$$

Where $Prop\ fine\ roots_{age_r}$ is the proportion of fine roots at a particular plant root age, in years.

The fine roots have a short life (Withington et al., 2006). We therefore assumed the fine roots die every year and new fine roots are produced, while the coarse roots remain (Guo et al., 2006; Withington et al., 2006). The fine roots that die will either decompose to emit short cycle CO_2 or add to the soil organic carbon pool. The decomposition rate and equations are specified in the section "calculation of GHG emissions".

Crop yield residue module

Crop yield is not predicted in the model. It is a model input that should be indicated by the user. However, some crop yield is discarded because it does not meet required quality standards. If this is the case, the model accounts for this crop biomass, which becomes a residue instead of a commodity. The user indicates the actual harvested crop yield biomass, but the actual plant yield is:

$$Total\ yield = harvested\ yield + (harvested\ yield * {\%\ discarded}/{100}) \quad [eq.\ 19]$$

Where $\%\ discarded$ is the percentage of unharvested yield. Hence:

$$Discarded\ biomass_{year} = \sum_{year=SProd}^{year=Years}(Harvest\ yield * {\%\ discarded}/{100})_{year} + (Discarded\ biomass)_{year-1} \quad [eq.\ 20]$$

Where $SProd$ is the year in which production starts.

A second important residue derived from the fruit is the pulp for those crops in which de-pulping is necessary, such as for coffee. The pulp biomass is calculated as a function of the yield indicated by the user. The percentage of pulp/seed is a specific parameter (Table 1).

$$Pulp\ biomass_{year} = \sum_{year=SProd}^{year=Years}({yield_{year}}/{Perc\ seed} * Perc\ pulp)_{year} + ({yield}/{Perc\ seed} * Perc\ pulp)_{year-1} \quad [eq.\ 21]$$

where $Perc\ seed$ is the percentage in one of the seeds with respect to the entire fruit (seed plus pulp). And $Perc\ pulp$ is the percentage in the pulp with respect to the entire fruit.

Area based sub-model (ABM) for perennial grasses biomass

In the ABM, biomass values are modelled in tonnes per ha per year and may subsequently be converted to kg for consistency with the IBM model.

<TABLE 2>

Stalk and above ground biomass module

The AGB for perennial grasses is calculated using the yield information provided by the user. The model does not predict yield but uses the provided yield information to calculate plant biomass. The user can provide the yield as either fresh plant weight, right after harvesting the plant, or plant weight after leaving it dry on the ground, along with the moisture content at that particular time or dry biomass, the plant weight excluding the water. The yield can be either the autumn or spring harvest. In this study, we have parametrized for the autumn harvest (Table 2). Two modules are defined for estimating AGB. In either case, the model considers that the plants are annually harvested and consequently a new above-ground part grows every year. The first module should be used for those species in which the harvested part is only the stalk and the leaves are hence residues, such as sugarcane.

The annual stalk biomass is:

$$Stalk\ biomass_{age} = Yield_{age} * dry\ matter \quad \text{[eq. 22]}$$

where *age* is the plant aboveground age, $dry\ matter$ is a specific values for fresh plant, given in Table 2, if the values of yield are included in the model as a fresh weight. If the yield values are input as semi-dry weight, the $dry\ matter = 1 - moisture\ content$. If the yield values are input as dry weight, the yield will equal the stalk biomass, hence $dry\ matter = 1$.

The total stalk production is hence:

$$Stalk\ biomass = \sum_{year=1}^{year=Years} (Yield_{year} * dry\ matter)_{year} + (Stalk\ biomass)_{year-1} \quad \text{[eq. 23].}$$

Where *year* is the crop life year at which the plantation starts, in years, starting in 1 and *N* is the last year of the crop cycle. The parameter *age* and *year* may be the same if the plant is planted on the farm at age 0.

The above ground biomass:

$$AGB_{year} = {Stalk\ biomass_{year}}\big/{stalk{:}AGB} \quad \text{[eq. 24.1]}$$

where $stalk{:}AGB$ is the ratio, as a fraction on one, of the stalk with respect to the total AGB, a specific value (Table 2).

The cumulative values of AGB were also calculated at the end of the crop lifecycle, as in eq. 23.

In this case, [eq. 24.1] is used to calculate AGB, since the stalk biomass (from eq. 23) and the $stalk{:}AGB$ values (Table 2) are known parameters. Importantly, the plant organ ratio parameters change not only among crops, but also for the harvesting times. The model can consider those differences by using different crops specific parameters.

The second module should be used for those species in which the harvested yield includes both the stalk and the leaves, such as switchgrass.

$$AGB_{age} = Yield_{age} * dry\ matter \quad \text{[eq. 24.2]}$$

The cumulative values of AGB were also calculated at the end of the crop lifecycle, as in eq. 23.

Species specific values of dry matter for fresh plants are shown in Table 2. If the yield values are input as semidry weight, $dry\ matter = 1 - moisture\ content$. If the yield values are input as dry weight, the yield will equal the stalk biomass, hence $dry\ matter = 1$. In either case, if the plant is cut but not harvested in the first year(s) of it cycle, the potential yield is treated as a residue.

Leaf biomass module

This module estimates the biomass of leaves, in tonnes per ha and year.

$$Leaves\ biomass_{age} = AGB_{age} * (1 - stalk{:}AGB) \quad \text{[eq. 25]}$$

The cumulative values are also calculated at the end of the crop lifecycle, as in eq. 23.

When the perennial grasses harvest is after senescence, much of the life material becomes litter and is therefore considered in this section. This actually improves the quality of the harvested biomass as it has less ash and potassium without the leaves.

Below-ground biomass module

The below-ground biomass of the grasses comprise not only the roots but sometimes a rhizome. The rhizome is a storage organ which grows as the plant establishes, but it remains the same size in mature established crops. What we call below-ground biomass in this study includes both the rhizome and the roots, if both organs are present in the crops. Roots are about 20% of the below-ground biomass for most bioenergy crops (Dohleman et al., 2012). Previous research shows that the below-ground biomass in agricultural perennial grasses does not change appreciably over time after establishment (Dohleman et al., 2012; Ebrahim et al., 1998), and is independent of senesced rate (Amougou et al., 2011). Consequently, this sub-model assumes that from year 1 after planting, the entire root system and the rhizome are developed, and in the subsequent years the biomass of new roots is equal to the biomass of roots that senesce. For some individuals or crop varieties rhizome development may take up to three years, but the model does the aforementioned assumption for simplicity. This below-ground biomass module is always used in this form, including for the first unproductive years, if present.

The below ground biomass is hence:

$$BGB = Biomass_{roots} + Biomass_{rizhome} \quad \text{[eq. 26]}$$

The BGB module for year 1 is:

$$BGB_1 = AGB_1 * (AGB{:}BGB) \quad \text{[eq. 27]}$$

where the $AGB{:}BGB$ is the specific value at harvesting age, values in Table 2.

For subsequent years:

$$BGB_{ratoon_{year}} = BGB_1 * rsen \quad \text{[eq. 28]}$$

where *rsen* is the root senescence ratio, values in Table 2.

The cumulative values were also calculated at the end of the crop lifecycle, as in eq. 23. The roots that die during the year will either decompose to emit short cycle CO_2, or add to the soil organic carbon pool. The decomposition rate and equations are specified in the following section, “calculation of GHG emissions”.

< TABLE 3 >

Calculation of GHG emissions

Henceforth values of CO_2, N_2O and CH_4 are subsequently converted into CO_2 equivalents using equations eq. 1 to 3.

Aerial biomass

The equation to estimate annual CO_2 absorbed from the atmosphere and converted into biomass from living plant parts is:

$$CO_{2_{organ}} = Biomass_{organ} * CF_{organ} * \frac{44}{12} (-1) \quad \text{[eq. 29]}$$

The plant biomass values derive from the corresponding equation in section "Plant biomass modules". CF_{organ} is the carbon fraction in the organ (Tables 1,2).

Plant biomass is accumulated through time, but at the end of the crop life cycle, only the root biomass prevails. The entire AGB is either harvested, i.e. if the plant is used to produce biofuel or bio-based products, or becomes residue, i.e. if the only the fruit is used, like in top-fruit trees.

Below-ground parts

The Perennial-GHG model does not consider root removal once the crop cycle is completed (Hastings et al 2017), since it is a very demanding practice and is uncommon in agriculture. Consequently, plant roots remain underground after plant harvest and become part of the soil organic carbon. Some roots die during the production period. This dead biomass will either decompose or stay as a stable component in the soil, henceforth incorporated as part of the soil organic carbon pool (Schulze and Freibauer, 2005). The roots that decompose are neutral in terms of carbon, and the remaining biomass is a negative emission accounted for in the model. It is important to note that the Perennial-GHG estimates biomass and plant residues, and derives GHGs during the crop cycle. These root soil input materials will stay in the soil for some time, depending on the soil conditions and climate (Powlson et al., 2013). Nevertheless, subsoil or tillage operations are considered in the additional management options, and the roots removed through these operations are included.

To calculate the remaining biomass of roots that die for the IBM, we used the widely-used decay function proposed by Aber et al. (1990):

$$mass = e^{-k\,t} \quad \text{[eq. 30]}$$

Where *mass* is the remaining mass, k is the decay constant and t is the time in years. For woody crops k =0.51 (Guo et al., 2006). The remaining root biomass at year i is:

$$Remaining\ mass_{roots_i} = Original\ mass_{roots} * e^{-0.51\,i} \quad [eq.\ 31]$$

The k parameter we provide is general and can be refined for different crops and climates when robust empirical data are available.

For the ABM, root senescence is available (Table 2).

In either case, remaining biomass decreases with time and this effect is also included in the model.

The module for estimating root GHG emissions:

$$CO_2\ BGB = (BGB_{end\ period} + Remaining\ mass_{roots_{end\ period}}) * CF_{root} * \frac{44}{12}(-1) \quad [eq.\ 32]$$

BGB is derived fom eq. 16 in IBM and eqs. 26, 27 and 28 in the ABM. CF_{root} is the carbon fraction in the root, a specific parameter (Table 1,2).

AGB and BGB values are fitted independently in the model. In natural plants AGB and BGB have to be considered together to account for biomass distribution and resource allocation. This is not the case for farm plants. First, management changes the above ground part and therefore overall plant carbon allocation no longer follows the natural rule. Second, and more importantly, the common practice of harvesting the AGB part but not the BGB (i.e., bioenergy crops, SRC, cropping practices in fruit trees) creates an unbalanced plant age, with the belowground system frequently older than that above ground. To reflect these differences the model needed, in turn, a separate estimator for above and belowground biomass.

Wood residues that are burnt

GHG emissions from burning wood residues are estimated using the following equations, presented in Akagi et al. (2011):

$$1\ Kg\ burnt\ wood\ biomass = (1.509\ Kg\ CO_2 * {}^{\%\ residual\ burnt}/_{100}) - wood\ biomass\ CO_2$$

[eq. 33]

$$1\ Kg\ burnt\ wood\ biomass = 0.00568\ Kg\ CH_4 * {}^{\%\ residual\ burnt}/_{100} \quad \text{[eq. 34]}$$

$$1\ Kg\ burnt\ wood\ biomass = 0.00038\ Kg\ N_2O * {}^{\%\ residual\ burnt}/_{100} \quad \text{[eq. 35]}$$

Where $wood\ biomass$ is derived from equations eq. 13 for pruning residues or eq. 12 for the tree at the end of the cycle and/or trees that die during the period. The $\%\ residual\ burnt$ is the percentage of residues that are burnt. This is an input of the model (see the explanation at the beginning of section "Model definition" for details). Short cycle CO_2 stored in plant biomass as organic carbon is not accounted here as it is taken up by the plant and returned shortly after.

Wood residues that are chipped

If the woody parts are chipped and spread on the soil, they either add to the soil organic carbon pool (Weedon et al., 2009) or decompose to emit CO_2, which is effectively carbon neutral. To calculate the remaining soil organic carbon, we used a decay function [eq. 30]. For wood chips, the decomposition constant k = 0.3 (Liski et al., 2005). Hence, at year $=i$ the remaining mass of chips is:

$$Remaining\ mass_{chip_i} = Original\ mass_{chip} * e^{-0.3\,i} \quad \text{[eq. 36]}$$

And the module for estimating CO_2 is:

$$CO_2\,chips_i = Remaining\ mass_{chip_i} * CF_{wood} * {}^{\%\ wood\ spread}\!/_{100} * \frac{44}{12} * (-1) \quad \text{[eq. 37]}$$

Where $Remaining\ mass_{chip_i}$ is derived from eq. 36 applied after eq. 13 for pruning residues or eq. 36 applied after eq. 12 for the tree at the end of the cycle and/or trees that die during the period. CF_{wood} is the faction of carbon in the biomass (Table 1). The $\%\ wood\ spread$ is the percentage of the residues that are chipped and spread (see section "Model definition"). The *k* parameter was developed to be used in temperate climates. We use it as a general value here, but it can be refined for different crops and climates when robust empirical data are available.

If the woody parts are chipped and the chips are removed, they are regarded as neutral in terms of carbon and therefore the plant emissions are equated to zero in the Perennial-GHG model.

Litter burning

GHGs from litter burning are estimated using the IPCC values for biomass burnt with GHGs for agricultural residues, Table 2.5 in Chapter 2, Volume 4 of the original document (IPCC, 2006).

$$1\ Kg\ burnt\ litter\ biomass\ = (1.515\ Kg\ CO_2 * {}^{\%\ litter\ burnt}\!/_{100})) - wood\ biomass\ CO_2 \quad \text{[eq. 38]}$$

$$1\ Kg\ burnt\ litter\ biomass\ = 0.027\ Kg\ CH_4 * {}^{\%\ litter\ burnt}\!/_{100} \quad \text{[eq. 39]}$$

$$1\ Kg\ burnt\ litter\ biomass\ = 0.00007\ Kg\ N_2O * {}^{\%\ litter\ burnt}\!/_{100} \quad \text{[eq. 40]}$$

Where *litter biomass* is derived in the IBM from eq. 15.1, in the case of deciduous species and eq. 15.2 for evergreen species. *litter biomass* is derived in the ABM from eq. 25 for litter or eq. 24 for the unproductive year. From the combustion, CO_2, N_2O and CH_4 are produced. Values of those gases are transformed into CO_2eq using equations eq. 1 to 3. The $\%\,litter\ burnt$ is the percentage of residues that go to the burnt set (see section "Model definition").

Litter left on the ground

When the leaves are left on the ground, they either decompose or become part of the soil organic carbon pool (Schulze and Freibauer, 2005). The litter that decomposes is carbon neutral. To calculate the remaining soil organic carbon we used the decay function eq. 23. In the IBM, the decomposition value for litter *k*=0.83 (Wu et al., 2012). In the ABM, the decomposition value *k* =0.776 (Amougou et al., 2012).

The equation to estimate CO_2 from litter is:

$$CO_2\,litter_i = Remaining\ mass_{litter_i} * CF_{leaves} * {}^{\%\,litter\ left}/_{100} * \frac{44}{12} * (-1) \quad \text{[eq. 41]}$$

Where $Remaining\ mass_{litter_i}$ is the mass after using eq. 15 for calculating litter biomass followed by eq. 22 for calculating litter decomposition in the IBM sub-model and eq. 25 for litter biomass followed by eq. 23 for litter decomposition in the ABM sub-model. CF_{leaves} is the carbon fraction in the leaves, a specific value (Tables 1, 2). The $\%\,litter\ left$ is the proportion of litter left on the ground (see section "Model definition").

Discarded fruits left on the ground

Some produce which does not meet quality standards may be left on the ground instead of harvested. If this is the case, it either decomposes or becomes part of the soil organic carbon pool. The part that decomposes is carbon neutral. To calculate the remaining soil organic carbon we used the decay function eq. 30. The fruit decomposition value *k*=0.83 (Wu et al., 2012).

The equation to estimate CO_2 from those fruits is:

$$CO_2\,fruits = Remaining\ mass_{discarded\ fruit} * CF_{fruit} * {}^{\%\,fruit\ dis}\!/_{100} * \frac{44}{12} * (-1) \quad \text{[eq. 42]}$$

The biomass of discarded fruits is calculated using eq. 20. CF_{fruit} is the carbon fraction in the fruits, a specific value (Table 1). The $\%\,fruit\ disc$ is the percentage of discarded fruits, a model input.

Fruit pulp left on the ground

If the pulp of de-pulped fruits is spread out on the farm, it either decomposes or becomes part of the soil organic carbon pool. The part that decomposes is carbon neutral. To calculate the remaining soil organic carbon we used the decay function eq. 23.The fruit decomposition value *k*=0.83.

The equation to estimate CO_2 from those fruits is:

$$CO_2\,fruits = Remaining\ mass_{pult} * CF_{fruit} * {}^{\%\,pulp}\!/_{100} * \frac{44}{12} * (-1) \quad \text{[eq. 43]}$$

The biomass of discarded fruits is calculated using eq. 21. CF_{fruit} is the carbon fraction in the fruits, a specific value (Table 1). The $\%\,pulp$ is the percentage of pulp that is spread out, a model input.

Composting residues from leaves, wood chips, discarded fruits and pulp

If the residues are composted within the farm, to be used either in the farm or in a different area, the model accounts for the GHGs. If the residues are removed for composting elsewhere, then they are considered GHG neutral. Although plant residues accumulate biomass, GHGs are emitted during composting. Those GHGs result from fuel used in combustion and from the degradation of the feedstock biomass (Boldrin et al., 2009; Brown et al. 2008). GHGs from the fuel from combustion and the degradation depend on the type of technology used in composting (Brown et al. 2008). The equation to estimate CO_2 from composting is:

$$CO_2eq\ compost = CO_{2eq}\ Biomass_{compost} + CO_{2eq}\ Compost_{process} + CO_{2eq}\ Compost_{energy} \quad \text{[eq. 44]}$$

The $CO_2\ Biomass_{compost}$ can be calculated:

$$CO_2\ Biomass_{compost} = (biomass_{residue} * CF_{residue} * \frac{44}{12} * \left(1 - {}^{\%C_{degraded}}\!/_{100}\right) \quad \text{[eq. 45]}$$

Where $\%C_{degraded}$ is the percentage of carbon that degrades during the process of decomposition. The model uses the values of $\%C_{degraded}$=60 for open systems and $\%C_{degraded}$ =55 for enclosed systems (Boldrin et al., 2009).

To estimate the $CO_{2eq}\ Compost_{process}$, the model uses the mean value of the range of compost emission factors presented in Boldrin et al. (2009) and the values to calculate CO_2eq from CH_4 and N_2O from eq. 1-3. The compost emissions factor vary between open and enclosed technology:

$$CO_2eq\ (CO_2)open = biomass_{residue} * (1 + WC_{residue}) * 0.25 \quad \text{[eq. 46]}$$

$$CO_2eq\ (CO_2)enclosed = biomass_{residue} * (1 + WC_{residue}) * 0.3 \quad \text{[eq. 47]}$$

$$CO_2eq\,(CH_4)open = biomass_{residue} * (1 + WC_{residue}) * 0.0035 * 34 \quad \text{[eq. 48]}$$

$$CO_2eq\,(CH_4)enclosed = biomass_{residue} * (1 + WC_{residue}) * 0.0009 * 34 \quad \text{[eq. 49]}$$

$$CO_2eq\,(N_2O)open = biomass_{residue} * (1 + WC_{residue}) * 0.001 * 298 \quad \text{[eq. 50]}$$

$$CO_2eq\,(N_2O)enclosed = biomass_{residue} * (1 + WC_{residue}) * 0.00659 * 298 \quad \text{[eq. 51]}$$

Where $WC_{residue}$ is the fraction of water in the introduced residue. It was necessary to consider the water since the emission factors were based on feedstock wet weight.

To estimate the $CO_{2eq}\,Compost_{energy}$, the model used the diesel intake consumption factor presented in Boldrin et al., (2009), which is approximately 3 litres per kg of wet residue for both open and enclosed technology. The emission factor for combustion of diesel is 2.7 kg CO_2eq/litre (Fruergaard et al. 2009). Therefore:

$$CO_{2eq}\,Compost_{energy} = biomass_{residue} * (1 + WC_{residue}) * 8.1 \quad \text{[eq. 52]}$$

Model parametrization

The generic model needs empirical data for parametrization to be functional and applicable for different crops, different varieties, and different geographic regions. The required empirical data for parameterization are biomass quantity of the different plant parts at different age. The most accurate method to obtain plant biomass values is by destructive sampling (see Chave *et al* 2015), but if these are not available, local allometric equations to estimate biomass as a function of plant size can be used, for example the ratio of height to biomass in Miscanthus (Kalinina et al 2017).

Empirical values of biomass of the different plant parts at different ages are then fitted to a power law equation. We used the nonlinear least-squares estimates for parameter estimation, using the R build in function “nls” (R code in Supplementary information S1). The generic model needs empirical data not only to work for most crops, but also to improve the current estimates presented in Table 1 and 2, and to account for varietal and geographical differences. The data used for parametrize the crops is in Supplementary information S2.

The power law is frequently used for biomass estimation of woody plants (Stephenson et al, 2014). This function is asymptotic for small alpha values, as in the present case (Table 2). In addition, tree biomass in the model is highly related to the management practices which reduce biomass (i.e. pruning), and therefore unlimited growth.

Case studies: Biomass and GHGs in four main crops: apple, coffee, *Miscanthus*, and sugarcane

The perennial-GHG model presented in section 2 is used here to estimate GHGs in four perennial systems: apple, coffee, *Miscanthus* and sugarcane. We selected these crops to have a variety of temperate, tropical, food and bioenergy examples. In each case, we calculated GHGs in a standard 1 ha production area. We used the Myhre et al. (2013) GWP over a 100-year time horizon. We then used the Cool Farm Tool (Hillier et al. 2011) to calculate GHGs due to agrochemicals, fertilizers and energy consumed during crop management for those example using representative management practices. Our aim here is to illustrate the model application using typical management practices (Table 4), and also to examine the importance of the biomass pool in the context of total GHG emissions from crop production. We used specified values at crop maturity. In every case, further transportation of the crop was excluded from this analysis, consistent with our farm gate boundary.

<TABLE 4>

<FIGURE 2>

The negative GHG emissions derived from the plant biomass exceed the positive GHG emissions from the supply of nutrients and agrochemicals, resulting in negative overall emissions (Fig 2). In coffee and sugarcane the total emissions are positive due to the litter and final cut burning. For the perennial grasses, sugarcane and *Miscanthus*, most of the negative GHGs are due to root biomass accumulation followed by litter left on the ground. The amount of litter is larger but it mainly decomposes in the following years (Schulze and Freibauer, 2005) while the root biomass persists for longer. In the top-fruit crops, apple and coffee, most of the negative GHGs are due to root biomass accumulation. Litter and residues left on the ground also contribute to sink carbon in the top-fruit crops, but to a lesser extent. Litter is less abundant and decomposes faster than for the bioenergy crops. For sugar cane especially, emissions are substantial during the crop lifecycle, mainly as a result of residue burning. If burning is avoided in sugarcane and coffee, these crops would have had large negative values, in spite of the fact that these crops require more nutrient supply than the others. This illustrates that alternative practices may significantly impact GHG emissions. A large source of negative GHGs could have been obtained from sugarcane, coffee and apple with different management. Nevertheless, in every case, the results show that leaving the roots and the removed leaves on the ground contributes to fixing atmospheric carbon, providing noticeable negative GHGs. Interestingly; the C input in the soil at the end of crop cycle was 8-10 tonnes for all crops. It is important to mention that the root and litter biomass input in the soil is not equivalent to the carbon sink in the soil. The quantity of carbon that stays in the soil depends not only on the input, put also on the former land use and soil properties (Dixon et al., 1996; Don et al., 2011). Evaluating such soil processes is beyond the scope of this study and it requires the use of process based models of soil biochemistry.

<FIGURE 3 >

The annual contribution of each plant residue and fertilizer can be seen in Fig 3 for the case of apple and *Miscanthus*. In apple, plant biomass and residue carbon accumulation increase exponentially with time (Fig 3, left). Most of the negative GHGs are due to biomass accumulation in the woody part of the tree. But those potential negative emissions become neutral when the trees are removed. Chips and litter also contribute to the fixation of some atmospheric carbon, but a large proportion of their biomass may decompose in the future. However, GHGs from chips have a longer life and contain more carbon and stable compounds than litter, contributing to longer term carbon storage. That characteristic produces a carbon accumulation curve with a marked decreasing slope. The GHG emissions due to fertilizers applied every 2 years are fairly constant through the life of the crop. Our model estimates a total negative value of -360 $MgCha^{-1}$, stored after 20 years, similar to the range value of -230 to -475 $MgCha^{-1}$ after 20 years measured by Wu et al. (2012). The root biomass and the aerial woody biomass measured in that study were 22.93 Mg ha^{-1} and 125 Mg ha^{-1}, respectively, while the root and aerial woody biomass predicted in our model were 25.4 Mg ha^{-1} and 105 respectively.

In *Miscanthus*, the first year growth material left on the ground - including both the leaves and the stalk - is almost totally decomposed in 8 years (Fig 3, right). Plant residues left on the ground from other years also contribute to the carbon pool, but we expect that they decompose in about 8 years, as the residues of the first year did. Hence, they may not have a very long term impact in terms of carbon, but still they have a slight contribution to negative GHGs in the long term. This rapid biomass loss causes a decrease in the cumulative litter curve (Fig 3, right). The annual biomass litter production of 5-7.6 Mg ha^{-1} $year^{-1}$ derived from our model is the same annual value of 5-7.5 Mg ha^{-1} measured form field in Robertson et al. (2016). The annual soil organic carbon inputs from the roots was 2.12 Mg ha^{-1} year^{-1}, similar to the value of 2-3 Mg ha^{-1} year^{-1} showed in Dondini et al. (2009), Zatta et al. (2012), and Zimmerman et al. (2013). Once again, our model provided similar values to those measured in the field, confirming the suitability of the model for both perennial bioenergy and food crops.

Discussion

Quantifying CO_2 capture by plants and biomass accumulation and changes in soil carbon, are key in evaluating the impacts of perennial crops in life cycle assessment. We have presented the Perennial-GHG, a working model that can be used to assess the contribution of biomass to GHGs in perennial crops. It is applicable both to food and bioenergy crops, and we have already parameterised it for several crops (Tables 1, 2). We used the model to calculate GHGs in four perennial systems as an illustration. In every case, the carbon stored in plants due to biomass accumulation and derived plant residues more than offsets the contribution of agrochemicals and nutrients (Fig. 2). This finding is timely, and highlights the importance of taking into consideration crop biomass of perennial plants as contributors to climate change mitigation. This model will help to reduce the uncertainty that exists in quantifying the benefits of perennial crops. In addition, the model supports the FAO's drive toward "perennialisation" or increase of perennial crops strategy (Rai et al., 2011), to help to mitigate climate change and increase food and ecosystem security (Glover et al., 2010).

The Perennial-GHG is a theoretical model that needs empirical data to be parametrized. Henceforth, most of the uncertainty and errors are linked with the variability of the empirical data and not with the model definition itself. Therefore, model uncertainty and sensitivity cannot be quantified in this paper because it depends on the existing empirical data. Most of our data sources did not show standard deviation of the empirical measurements, either for the biomass or decomposition values. For that reason, uncertainly was not specified and accounted for in this paper. Adding more empirical data and re-defining the parameters in a more precise way may improve the model and reduce uncertainty. Indeed, the Perennial-GHG model can be parametrized at farm level but this will require within-farm experiments and biomass measurements, which will incur additional costs. Additionally, it is important to bear in mind that GHGs from other overlooked sources, i.e. harvesting operations, machinery emissions, commodity transportation and storage or GHGs derived from plant reproduction, have been excluded in this analyses. To derive the total crop GHG balance, they should also be accounted for. As yield is not estimated in the model, for theoretical or research purposes crop-production models can be used to estimate yield, which can be then used as an input in the presented model. Examples of such models are the Miscanfor model for *Miscanthus* (Hastings et al. 2009) or the Yield-SAFE model for tree crops (van der Werf et al. 2007).

The presented Perennial-GHG model could be improved in several ways in the future which we could not consider here due to the lack of empirical data. First, geographic or climate differences among and within crops have not been considered in the proposed model, despite acknowledgement that climate can affect both plant growth and residue decomposition (Basso et al., 2017). Regarding plant growth, we used published empirical data to parametrize the model from the current area of distribution of the considered crop (reproduced in Supplementary information S2). We aim to model crops inside their potential distribution area, and hence discard unlikely production scenarios. Disregarding the effect of climate on decomposition rate is a more important consideration. Nonetheless, for wood decomposition, the effect of climate is a secondary factor (Bradford et al., 2014), and litter has a short decomposition period regardless of location (Schulze and Freibauer, 2005). In any case, the Perennial-GHG model allows different regional decomposition parameters, although we did not explore those in this study. In a similar way, the Perennial-GHG model has a combustion parameter for woody residues (eq. 31 to 33) and the IPCC model for combustion parameters for agricultural residues (eq. 36 to 38), which is used for litter and bioenergy crop burning. Those parameters could be refined in the future, if more empirical data is acquired. Similarly, GHG emissions from composting can be refined in the future as the model considers only main basic technologies (Boldrin et al., 2009). The effect of lack or excess of fertilizer and water was included as a parameter in the IBM model but it was not parameterized due to the lack of robust empirical data (see section 2.1.1 for more details). Different mortality ratios among climates are already considered in the model: in the IBM mortality is a model input; in the ABM mortality is a directly reflected in the yield, a model input. Seasonal variations in terms of plant growth and residue production also exist. However, it was not necessary to include them in the IBM model since the model evaluates annual and not seasonal biomass, residues and GHGs. For the AMB, the biomass ratios change among seasons (Amougou et al., 2012). This is currently considered by requiring as input the harvest period in the model (Table 2). Besides, no varietal differences within crops have yet been considered. We pooled the data of different varieties for each crop, due to the lack of robust data of different varieties. Once again, the present model allows future inclusion of different parameters for different varieties. Once robust data exist, that information can and should be incorporated into the model.

The Perennial-GHG presented in this paper estimates the plant carbon output during the crop cycle, since the plant is established in the ground until it is harvested, and not beyond. It is important to bear in mind that the model does not estimate the persistence of carbon after it leaves the farm gate (see details in the model definition section). At the final harvest, some litter and roots are still in the ground in organic forms and over time will decompose, releasing a fraction of the stored C. Litter and fine roots have, in general, a short life span, thus the C released will occur in the following years. On the other hand, woody roots are quite stable and will decompose slowly (Guo et al., 2006; Withington et al., 2006). The carbon finally stored will depend on the soil and environmental conditions (Dondini et al., 2009) and subsequent land use. The stability of the carbon in the system is highly dependent on the existing carbon in the system, and on the land use after the perennial cultivation. The capacity to store carbon, and it's persistence in the soil, depends on the soil C concentration before the plantation, and on the climate (Powlson et al., 2013). The model also calculates the nitrogen accumulated in the different organs in the plant. This is not required for estimating GHGs, but it gives information about the nitrogen cycle that may be useful for other purposes, such as in studies of nutrient balance. A soil organic carbon model is currently being implemented alongside this biomass model. Both together are required to estimate GHGs and carbon balance from perennial crops. These models will be incorporated in to the Cool Farm Tool (Hillier et al., 2011).

Data and software availability: The R code for the main model including all the modules is provided in S1 and the figshare archive doi <*to be added*>. The database of empirical values used to parametrize the model is provided in S2 and figshare archive doi <*to be added*>. The required model inputs to run the Perennial-GHG model are provided in S3.

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SUPPLEMENTARY INFORMATION

S1. R code for the Perennial-GHG model

S2. Data used to parametrize the crops

S3. Input data required to run the Perennial-GHG model. Details of the inputs values used in the case studies

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TABLES

Table 1: Crop specific parameters for the individual based model (IBM), eq 11 to eq. 21. The carbon (C) and nitrogen (N) values are at harvesting time. Those tables will be interactive and updated in the future if more data are available. New versions will have new doi. The references of the source data are in S2.

Crop	α_1 AGB	β_1 AGB	α_2 AGBwoody	β_2 AGBwoody	α_3 BGB	β_3 BGB	α_4 Leaves	β_4 Leaves	Wood dry biomass	C wood	N wood	C leaf	N leaf	Fruit dry biomass	Pulp/seed	C fruit	N fruit
Apple	0.683	1.760	0.267	2.025	0.460	1.345	0.699	0.417	0.8	0.47	0.015	0.47	0.25	0.14	--	0.47	0.0038
Citrus	0.395	2.120	0.125	2.376	0.040	2.525	1.297	0.535	0.82	0.47	0.015	0.47	0.02	0.1	--	0.47	0.0095
Cocoa	1.250	1.344	1.135	1.307	0.589	1.113	0.165	1.073	0.8	0.47	0.020	0.47	--	--	--	--	--
Coffee	3.999	0.568	3.334	0.703	0.228	1.589	0.223	0.940	0.8	0.47	0.400	0.47	0.47	0.15	0.4	0.47	1.6
Tea	1.526	0.557	1.215	0.599	0.213	0.580	0.592	0.135	0.8	0.47	0.0041	0.69	0.03	--	0	0.69	0.028
Willow	--	--	0.158	1.611	0.158	1.611	--	--	0.8	0.49	0.275	0.5	0.015	--	--	--	--
Poplar	3.389	1.605	7.223	1.257	0.781	0.745	2.426	-0.182	0.8	0.49	0.238	0.5	0.317	--	--	--	--

Table 2: Crop specific parameters for the area based model (ABM), eq 22 to eq. 28. The carbon (C) and nitrogen (N) values are at harvesting time (maturity). Those tables will be interactive and updated in the future if more data are available. New versions will have new doi. The references of the source data are in S2.

Crop	Stalk:AGB	AGB:roots	BGB:AGB	Stalk water content	Root senescence ratio	C stalk	N stalk	C leaf	N leaf	C root	N root
Miscanthus	0.8	0.85	0.73	0.5	0.17	0.5	0.0016	0.457	0.0045	0.41	0.015
Sugarcane	0.826		0.32	0.71	0.17	0.443	0.012	0.4525	0.014	0.405	0.00395
Switchgrass	1	0.8	0.62	0.2	--	0.44	0.003	0.462	0.01	0.44	0.03

Table 3: list of variables used in the Perennial-GHG model

VARIABLE	MEANING	UNITS
CO_2eq	CO_2 equivalent	kg
Biomass	Plant biomass, dry weight	kg
AGB	Above ground biomass, dry weight	kg
BGB	Below ground biomass, dry weight	kg
$Field\ CO_{2eq}$	CO_2 equivalent emissions in the farm	kg
N	Number of trees in a plantation or orchard	--
S	Number of species in the cultivated area	--
N_s	Number of trees per ha of each species S	--
$Ind\ CO_{2eq}$	Individual (per plant) values of biomass	--
$Years$	Number of years of the crop cycle = last year of the crop cycle	--
$year$	Each single year of the crop cycle	--
$SPrun$	The year in which pruning starts.	--
age	Age of the plant above ground part	year
age_{root}	Plant root age,	year
AGBW	AGB of the woody parts	kg
$actAGBW_{year}$	AGB of the woody parts after pruning	kg
α_1 , β_1 , α_2 , β_2, α_3 , β_3	Specific parameters for the IBM	--
Rw_{AGB}	Parameter to account for water and nutrient limitation	--
Rf_{AGB}	Parameter to account for nutrient limitation	--
l	Average lifespan of the leaves	year
$SProd$	The year in which production starts	--
$rsen$	Root senescence ratio	--
CF_{organ}	Carbon fraction in the organ	one unit
$mass$	Remaining mass in the decomposition model	kg
k	Decay constant in the decomposition model	--
t	Time in the decomposition model	year

Table 4: Farm and crop parameters used in the case examples.

Crop	Production tonnes per ha*	Lifespan years	N trees per ha	Residue Management*						Fertilizers kg per ha*			Agrochemicals		Energy consumed annually
				First years discarded	Litter	Pruning	Discarded fruits	Fruit pulp	Trees end cycle	Nitrogen	Potassium	Phosphorus	Pesticides	Herbicides	
Apple	200 wet	20	800	--	100% left on the ground	chipped, 20% left on the ground and 80% removed	left on the ground	--	cut and removed	67 annually	70 every two years	90 every two years	Annually applied	--	2000 MJ
Coffee	2.5 wet	20	1500	--	100% left on the ground	chipped, 20% left on the ground and 80% removed	20% left on the ground and 80% composted. Compost taken away	100% composted. Compost taken away	cut and burnt	300 annually	50 annually	25 annually	Annually applied	--	1000 MJ
Miscanthus	25-40 (20% hum)	15	--	100% left on the ground	100% left on the ground	--	--	--	--	--	--	--	--	Applied Year 1	1050 MJ
Sugarcane	70-120	6	--	100% left on the ground	80% burnt and 20% left on the ground	--	--	--	--	70 annually	60 annually	90 annually	Annually applied	Applied Year 1	1500 MJ

*production, residues and fertilizers vary among years. The values presented in this table are values are at crop maturity.

FIGURE CAPTIONS

Figure 1: Model structure diagram. The emissions in plane black are positive emissions, GHGs released to the atmosphere. Emissions in grey are neutral emissions, the uptaken CO_2 equals the released CO_2. Emissions in bolt are negative emissions, atmospheric carbon fixed in the system.

Figure 2: CO_{2eq} emission in Mg at the end of the crop cycle per plant organ, residue and agrochemical for (a) an apple orchard, (b) a coffee plantation, (c) a *Miscanthus* field and (d) a sugarcane field. Details of farm management are detailed in Table 4.

Figure 3: Annual CO_{2eq} emissions in Mg at the end of the crop cycle per plant organ, residue and agrochemical in an apple orchard with a life period of 20 years. Details of farm management are detailed in Table 4.

FIGURES:

Figure 1:

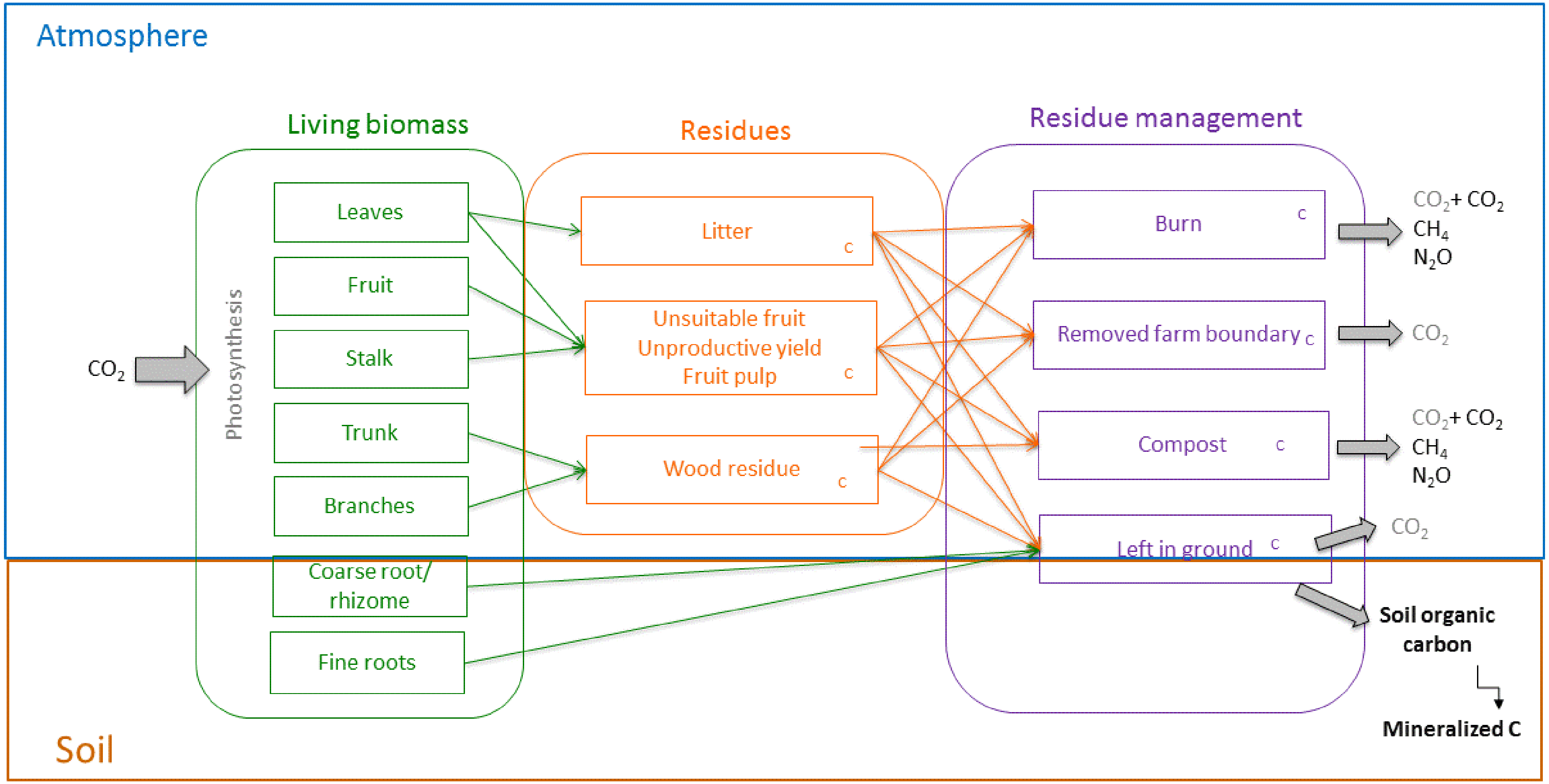


Figure 2:

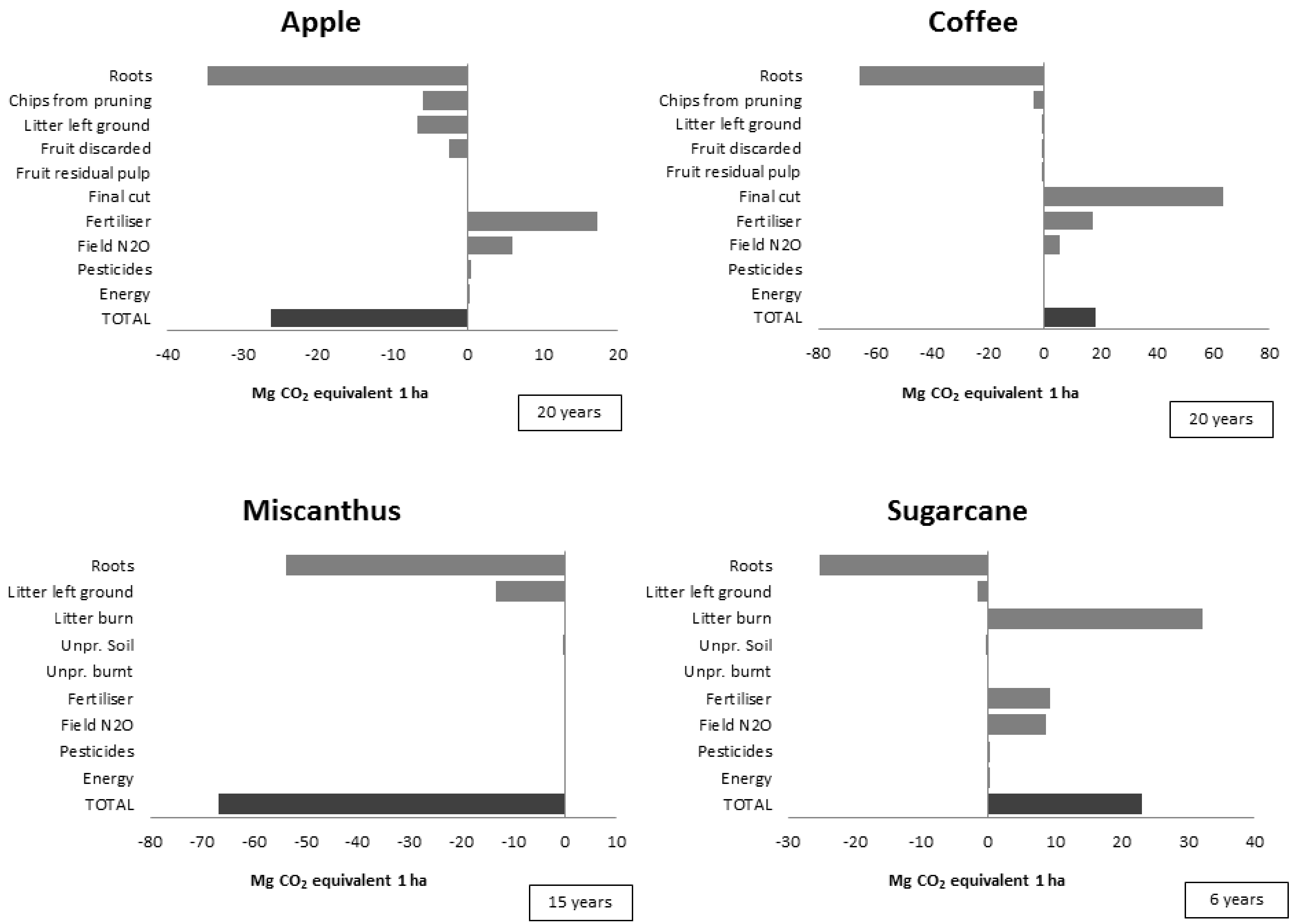
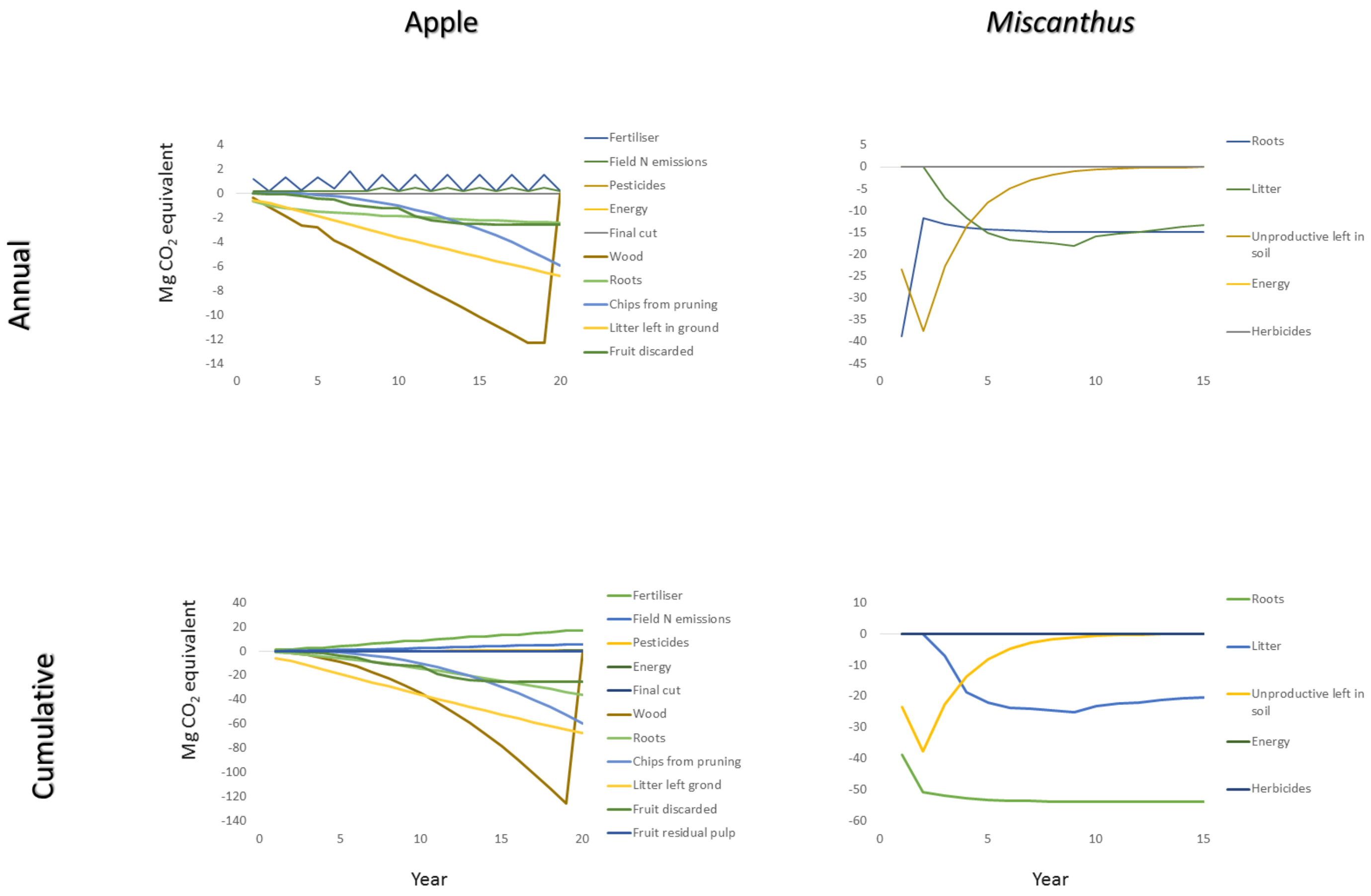

Apple
Roots
Chips from pruning
Litter left ground
Fruit discarded
Fruit residual pulp
Final cut
Fertiliser
Field N2O
Pesticides
Energy
TOTAL
-40 -30 -20 -10 0 10 20
Mg CO_2 equivalent 1 ha
20 years
Coffee
Roots
Chips from pruning
Litter left ground
Fruit discarded
Fruit residual pulp
Final cut
Fertiliser
Field N2O
Pesticides
Energy
TOTAL
-80 -60 -40 -20 0 20 40 60 80
Mg CO_2 equivalent 1 ha
20 years
Miscanthus
Roots
Litter left ground
Litter burn
Unpr. Soil
Unpr. burnt
Fertiliser
Field N2O
Pesticides
Energy
TOTAL
-80 -70 -60 -50 -40 -30 -20 -10 0 10
Mg CO_2 equivalent 1 ha
15 years
Sugarcane
Roots
Litter left ground
Litter burn
Unpr. Soil
Unpr. burnt
Fertiliser
Field N2O
Pesticides
Energy
TOTAL
-30 -20 -10 0 10 20 30 40
Mg CO_2 equivalent 1 ha
6 years

Figure 3:


Apple
Miscanthus
Annual
Cumulative
Mg CO2 equivalent
Fertiliser
Field N emissions
Pesticides
Energy
Final cut
Wood
Roots
Chips from pruning
Litter left in ground
Fruit discarded
Roots
Litter
Unproductive left in soil
Energy
Herbicides
Litter left grond
Fruit residual pulp
Year
Year