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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.

1. 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 a secure food and energy supply is one of the main human challenges (Smith et al., 2010a). 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 and Smith, 2007). Besides, some perennial crops, and in particular perennial grasses like Miscanthus, are more effective at intercepting and utilizing water

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and CO_2 resources (Dohleman and Long, 2009), and some need less or no fertilizer application (Hastings et al., 2009, 2017; Davis 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 (PAS 2050), 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.

1.1. 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