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LITERATURE REVIEW TO ASSESS THE USE OF STOCK AND FLOW MODELS COMPARED TO OTHER GHG METHODOLOGIES TO MODEL BIOFUEL GHGS

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Project

Literature Review to Assess the Use of Stock and Flow Models Compared to Other GHG Methodologies to Model Biofuel GHGs
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Executive Summary

Savant Technical Consulting has conducted a review of literature that have used carbon "stock and flow approaches" to evaluate biofuels, bioenergy, and bioproducts. These stock and flow approaches have been compared to attributional and consequential life cycle assessment methods.

We have used the term "stock and flow approaches" to capture the diverse forms of stock and flow models, which can differ materially in terms of complexity, scope, and boundary conditions. Stock and flow approaches aim to track the amount of carbon present in different pools within the ecosphere, and the exchange of carbon between these pools. The key pools include the atmosphere, soil, water, and land. Each of these may be divided into sub-pools that capture different spatial or compositional features, e.g., different ocean or soil depth, or different types of biomass on land. Earth system models (ESMs) represent the most comprehensive type of stock and flow model for carbon. ESMs have massive data requirements, and large uncertainty in model parameters, but represent the gold standard for tracking carbon through all major pools. Simplified stock and flow models have been developed for biofuels, bioenergy, and forest products, which can materially reduce data requirements and computational complexity. These simplified stock and flow models generally exclude certain pools (e.g., soil, or water), and may have narrower system boundaries (e.g., a regional forest or agricultural area, rather than the whole Earth). These simplifications lead to an issue with carbon "leakage" across the system boundaries. Such leakage (or "missing carbon") must be quantified in order to properly interpret results from a simplified stock and flow model.

Stock and flow and LCA models both have an important role in the analysis of biofuel and bioenergy systems. They address different, yet important questions. Stock and flow models capture temporal changes that a conventional (attributional) LCA method cannot. Stock and flow models also have the potential to track the absolute amount of CO_2 in the atmosphere, with the potential to link this information to climate impacts (temperature, precipitation, etc.). In contrast, an LCA approach provides information regarding the expected steady state or long-term emissions intensity of a bioproduct relative to a fossil-derived counterpart, but does not provide information regarding temporal impacts on atmospheric CO_2, which may be important if land use changes. Because stock and flow approaches are not fundamentally product-based, we note that stock and flow approaches also use (and need) LCA to account for emissions due to feedstock production and process operations, and also to properly account for co-products that may move across a system boundary ("leakage"). Thus, a stock and flow approach cannot replace LCA, but, if the model is well developed, and based upon robust data, it can augment the knowledge gained from conventional LCA approaches. Stock and flow models are better suited than LCA to look at long-term predictions of the climate effects of biofuels and bioenergy use as LCA is limited to only following flows, and stock and flows models carry the analysis through to quantify changes in sinks, which are important for climate change mitigation and modelling. Studies of forest carbon have been using this combined approach for more than a decade. Limited-scope stock and flow models have also

already been combined with LCA in the form of modeling greenhouse gas emissions due to land use change (LUC).

Approaches to stock and flow modelling have not been standardized, nor is there consistency in the assumptions employed regarding system boundaries or treatment of co-products or other forms of leakage. There can be massive geospatial heterogeneity in data availability or quality. These issues can have a serious impact on conclusions from a stock and flow modelling effort. Consequently, an important next step, from a research perspective, would be to address these issues, and move from a set of "user-specific" assumptions and structures to a consistent framework that uses the same structure, assumptions, and methods. A subsequent step would be to improve upon the availability and quantity of data, which are needed to support effective use of stock and flow models. The most significant data gaps are in the realm of soil carbon and biomass carbon (forest, agriculture, grassland). Integrating more robust data and sophisticated stock and flow modeling techniques could also improve the quality of the LUC modeling currently included in biofuels regulations. Collectively, these steps will put stock and flow models in a better position to answer important questions about atmospheric CO_2, and the merits of various biofuels, bioproducts, and bioenergy sources.

The stakeholders currently advancing the state of the science most drastically for stock and flow models are working on Earth System Model-scale frameworks, as part of large-scale modeling efforts to assess the potential effects of climate change, e.g., the Intergovernmental Panel on Climate Change (IPCC). Dozens of such models are currently being used and modified, as can be seen from the summary in the IPCC 5th Assessment Report (AR5)[1]. Related efforts, such as National Greenhouse Gas Inventories (NGGIs), being undertaken by countries signatory to the Kyoto Protocol/United Nations Framework Convention on Climate Change (UNFCCC), are pushing the envelope in terms of data collection, as are climate researchers working in parallel to investigate global carbon pools. Since NGGIs are national, and access for measurements is not uniform globally, the resulting data are typically non-homogenous in terms of scale and quality, with the exception of some satellite data.

Unlike ESMs, simplified stock and flow models are primarily being developed and used for specific applications, such as in forestry research. These models tend to be ad hoc, developed by relatively small teams of researchers using simplifications intended to answer a specific question, and such simplified models are rarely applied more broadly. These have some usefulness in the interim, but their results must be interpreted with caution. As stock and flow model development progresses, the simplified models continually being developed by researchers are likely to serve in progressing discussion of how to simplify more complex models in a meaningful way.

Given that the greatest advancements are being made at the ESM level, it is more likely that a consistent framework will result from ESM development efforts than from simplified models; however, given significant data limitations to closing the global carbon balance, a high-quality, consistent modeling framework is unlikely in the near future.

Table of Contents

Executive Summary 2

Table of Contents 5

Table of Figures 6

Table of Tables 6

1 Introduction 7

2 Traditional Attributional and Consequential LCA Methods 9

- **2.1 LCA for Biofuels** 9
- **2.2 Land Use Change (LUC) Modelling** 10
- **2.3 Scenario Modeling Concepts** 13
- **2.4 Additionality and Carbon Debt** 13
- **2.5 Crediting of Biogenic carbon** 14
- **2.6 Timing of Flows and Dynamic LCA** 17

3 Stock and Flow Models 18

- **3.1 Introduction to Types of Stock and Flow Models** 19
- **3.2 Simple Stock and Flow Systems and Proposed Stock and Flow Frameworks** 20
- **3.3 Earth System Models (ESMs)** 25
  - 3.3.1 Summary of ESM Literature Review 28
  - 3.3.2 Calculating, Measuring and Estimating Carbon Stocks for use in Stock and Flow Models 31
    - 3.3.2.1 Forest Carbon 31
    - 3.3.2.2 Soil Carbon 32
- **3.4 Climate Models and Integrated Assessment Models (IAMs)** 34
  - 3.4.1 Climate Models 34
    - 3.4.1.1 Application of a Stock and Flow Model with a Simple Climate Model 35
  - 3.4.2 Integrated Assessment Models (IAMs) 36
    - 3.4.2.1 Bioenergy Specific Carbon Balance and Application of an Integrated Assessment Model 37
- **3.5 Proposed Frameworks for Application of Stock and Flow Models to Crop-Based Biofuels** 38
- **3.6 Leakage** 41

4 Comparison of Methods: LCA versus Stock and Flow 42

- **4.1 Time** 42
- **4.2 Product Focus versus Reservoir Focus** 42
- **4.3 Land Use Change and Carbon Debt** 43
- **4.4 Climate Feedbacks** 43
- **4.5 Policy Considerations** 44

4.6 Data Requirements, Data Gaps, Model and Data Uncertainty ... 45

5 Conclusions ... 48

6 References ... 51

Appendix A ... 56

Table of Figures

Figure 1: Schematic of Land Use Change (LUC) Models ... 12

Figure 2: Schematic Comparison of Corn Use for Feed versus for Ethanol Production ... 16

Figure 3: Framework for a Carbon Stock and Flow Model, from Ajani et al. (2013)[29] ... 23

Figure 4: Illustration of Physical Processes, Pools, and Exchanges Incorporated into an Earth System Model, from Luo et al. (2015)[31] ... 26

Figure 5: Framework for an Earth systems model (ESM). Note that individual ESMs may include more or fewer modules, pools and sub-models than shown here ... 27

Figure 6: Attributes of Climate Models ... 35

Figure 7: Relationship between IAMs, ESMs and AOGCMs ... 36

Table of Tables

Table 1: Important classes of model related to stock and flow modeling ... 19

Table 2: ESM-Related and TEM Models Compared in Luo et al.[33] and Huntzinger et al.[35] ... 30

Table 3: Comparison of Soil Carbon Models, from McGuire et al. (2016)[52] ... 33

1 Introduction

Modeling is useful for understanding and planning for future events, especially when outcomes rely on future technology development. Modelling also assists in the evaluation of strategies and policies to mitigate the CO_2 emissions driving climate change. Such analyses can compare options to reduce fossil fuel use, identify the most effective use of feedstocks and land resources, and evaluate short-term versus long-term impacts on atmospheric CO_2 and, ultimately, climate. Analysts will need to use multiple (and different) models that help to answer different questions.

This report investigates and compares the models and methods developed and used to inform policy related to the adoption of biofuels in the US. In particular, a goal of this report is to compare stock and flow models with the existing approaches of life cycle assessment and other alternatives, including an assessment of strengths and weaknesses.

A crucial debate centers on the value and validity of various modeling approaches, and the extent that that they can provide representative, accurate and actionable information for policy makers. Currently, life cycle assessment (LCA) models dominate the policy sphere.

Energy LCA methods fall into two distinctive classes, attributional and consequential. The two major US biofuels policy initiatives use attributional LCA (aLCA) to determine either a fuel pathway's carbon intensity (CA Low Carbon Fuel Standard[2]) or the qualification of a fuel under the standard (US Renewable Fuels Standard (RFS2)[3]). Both policies combine the life cycle inventory (LCI) with some aspects of a consequential model to add a land use change component to the analysis.

The use of LCA for biofuels policy design has many proponents, as well as many critics. Even with the limitations of conventional aLCA (see section 2), application of LCA models with consistent assumptions and reasonably robust data can provide insights into underlying processes and encourage improvements. For example, these insights may lead to improved energy efficiency for a biofuel production process, improvements in agricultural practices, or use of agricultural or process inputs that lower energy intensity or emissions. Some critics have proposed replacing LCA with the use of carbon stock and flow-based models, to directly assess changes in atmospheric CO_2.

In their most rigorous format, carbon stock and flow models would track carbon in various pools, including the atmosphere, soil, land (biomass), and water. These models may be either static (like aLCA), or dynamic, accounting for changes in carbon stocks over time. With a sufficient degree of sophistication and data quality, along with appropriate system boundaries, it is theoretically possible to have a complete mass balance on carbon, in its various forms and in various locations within the Earth's biosphere. Earth system models (ESMs), described in section 3.3, currently represent the most comprehensive stock and flow models for carbon on Earth. Conceptually, it is possible to expand upon these stock and flow models and ESMs to link climate with the carbon cycle, and/or economic impacts associated with changes in atmospheric CO_2. Some researchers have applied simple climate models (SCM) as an approach to conduct rapid scenario analyses, although the simplifications incorporated into these SCMs can materially impact the accuracy of the results, and thus, their utility.

Stock and flow models have the potential to assess the impact on carbon stocks when a biofuel or bioenergy source is added to the system. Flows of CO_2 into the atmosphere due to combustion of the fuel/energy source can be tracked, along with CO_2 removal from the atmosphere due to photosynthesis. Further distribution of carbon into the soil and water can also be followed. However, as will be further discussed in section 3.2, selection of appropriate system boundaries remains an issue in stock and flow models, particularly in terms of co-products and agricultural residues. In the context of this report, stock and flow models have been published for harvested wood products, wood pellets, and biofuels, although these models also contain elements of LCA. These will be discussed in more detail in section 3.2.

2 Attributional and Consequential LCA Methods

Life cycle assessment (LCA) is a tool that is used to look at the resource use and waste/emissions created as a result of a given production process, including all inputs, outputs and product life cycle stages. LCA began as a tool to evaluate total process energy use, and has evolved into a widely used method for holistically investigating the impacts of various products. The International Organisation for Standardisation has published guidelines for LCA (e.g., ISO 14040:2006[4] and ISO 14044:2006[5]).

When used to examine the physical flows for a specific production process, LCA is referred to as attributional LCA, or aLCA. While uncertainty exists in conducting aLCAs based on the input data used and some methodological questions (e.g., co-product treatment), the usefulness of aLCAs in comparing process options for a given product is widely recognized. Assessment of changes in physical flows resulting from market-mediated impacts of using a product is typically referred to as "consequential LCA" or cLCA[6]. The idea is compelling; a policy to promote a renewable fuel or energy source may have indirect consequences that may offset some or even all of the emissions reduction found using an attributional LCA approach. Many studies have focused on including the greenhouse gas (GHG) emissions created due to market-mediated land use change induced by use of different types of biomass for fuel production (LUC).

cLCA methods are used by various bodies and researchers to estimate production impacts. cLCAs typically encompass a higher degree of uncertainty than aLCAs, chiefly due to inherent uncertainty in modelling the future of the global economy[7]. This technique tends to be data and computationally intensive and lacks some critical transparency needed to critique the modeling effort.

cLCAs avoid dealing with co-product allocation by expanding the system boundaries to include demand for those products[6]. Another difference between attributional and consequential LCA is that aLCA is designed to look at production of an "average" unit of product, whereas cLCA is designed to calculate the effects of “marginal” systems that are brought online to satisfy incremental demand, i.e., the "next" unit of product to be produced. Both aLCA and cLCA can produce useful insights about emissions impacts, but recognizing the limitations of these analyses is key for proper use.

2.1 LCA for Biofuels

LCA is frequently used to compare different pathways for producing a biofuel, and also for comparison of the biofuel with the fossil fuel that it displaces. Typically, these assessments focus on comparing the lifecycle GHG emissions from production and use of the different fuels.

In recent years, the aLCA methodology has been adapted in an attempt to investigate the impacts of various policy decisions associated with the use of biofuels. Choosing the counterfactual, i.e., comparing the world with and without the use of the alternative fuel, is key to assessment of a policy impact. In spite of limitations in the methodologies, the results have the potential to be informative for developing policy instruments. Nonetheless, it is important to understand that a lower aLCA-calculated emissions value for the biofuel (compared to the incumbent) does not necessarily mean that adopting the alternative will reduce atmospheric CO_2 levels. Contributing to the confusion is the common practice of saying that using the alternative "reduces emissions". A more rigorous statement might be that, under the assumptions and limitations of the study, the emissions factor for "X" is lower than that for "Y". This is consistent with the fact that aLCA compares fuel pathways using an agreed upon method that has recognized flaws, along with underlying assumptions and uncertainty in the data that may lead to differences in results, even for the same fuel pathway.

An aLCA calculation typically assumes zero emissions associated with biogenic carbon, and does not include temporal effects; the premise is that the emissions are constant throughout the life of the operating facility. Reap et al.[8,9] discussed the "unresolved problems" with LCA, many of which remain unresolved today. The unresolved problems with LCA discussed by Reap et al. are primarily methodological problems (e.g., allocation methods, functional unit definition, representation of uncertainty, etc.), the majority of which cannot be solved by the introduction of stock and flow methods due to the fact that stock and flow modeling is not process-linked. Some of the problems, such as trade-offs between types of impact (e.g., water use versus social impacts), are not applicable, as only GHG emission-related impacts are being considered here. Reap et al. discuss the weakness of LCA in dealing with temporal impacts, something that stock and flow modeling could help to address. Other issues discussed by Reap et al., such as the time horizon over which impacts are considered and the methods used for discounting future impacts, are applicable to both LCA and stock and flow-based analyses, and continue to be the subject of ongoing, intense debate about treatment of all types of environmental and social impacts. The use of aLCA is thus subject to much debate, with some defending its use, and others criticizing its ability to provide meaningful results. In reality, aLCA is useful but not definitive. It provides some insights, but its structure and format mean that it cannot address all questions. Additional methods are needed to fully explore the utility of an alternative fuel.

2.2 Land Use Change (LUC) Modelling

cLCA has been adopted as part of a number of biofuels regulations to account for the indirect effects of biofuels use. Typically, this has encompassed combining results from an aLCA with results of a partial cLCA designed to estimate GHG emissions due to LUC caused by a change in feedstock allocation for biofuels use as a result of the regulations. Values for LUC have been included in the EPA's Renewable Fuel Standard (RFS2)[3] and the California Air Resources Board Low Carbon Fuel Standard (LCFS)[2]. [a]

The LUC/cLCA component of these regulations is based on adapted versions of either partial or general economic models that predict how much economic pressure there will be to change land use as a result of increased demand for biofuels use in the policy region, and where those land use changes will take place. These predictions are then applied to a land use model that includes data on carbon stocks based on "agro-economic zone" (AEZ) and land use. A minimum of two model runs are required: one for a "business as usual" (BAU) case (the "counterfactual"), in which a given biofuels policy is not implemented, and one in which the biofuels policy is in place (the "shock" to the system). This is discussed further in section 2.3. Changes in land use between these two scenarios are then converted to changes in stored carbon using emissions factors, and net carbon releases are calculated. Figure 1 presents a simplified schematic showing how LUC models are typically structured. One key item to note is that, in order to integrate LUC modelling results with aLCA results, which are typically calculated on an annual basis, the results from LUC modelling are amortized (usually linearly) over a given number of years (30 years in RFS2 and LCFS). This gives consistent emissions throughout the modelled policy period, but ignores the time-based element of land use conversion, which may result in an emissions "pulse" at the time of conversion. If such a pulse does occur, there may be a "carbon debt" to be eliminated over a period of years or decades as the biofuel/bioproduct is used in place of its petroleum-derived counterpart (see section 2.3).

The integration of LUC/cLCA findings with aLCA data for estimating emissions from biofuels is an attempt to integrate stock-and-flow model principles with LCA concepts. Use of finite resources such as arable land on a global scale is more obviously aligned with stock and flow concepts than with traditional aLCA, which is entirely flows-based and therefore inherently assumes a steady-state condition.

The methods, policy scenarios, and models used for development of LUC values for biofuels are issues of ongoing debate in the scientific community, and estimates of magnitude vary widely. For example, in the soybean biodiesel pathway, published estimates of mean LUC values developed using similar economic modeling techniques vary by more than 400%[10,11]. Both the economic modelling component and the carbon accounting portion of LUC models are subject to high levels of uncertainty; a detailed look at the uncertainty in model components and attempts to quantify the uncertainty is given in Plevin et al. (2015)[12]. Major sources of model uncertainty include: identifying land use and consequent carbon

[a] Although, historically, researchers and policy makers have discussed direct and indirect land use change, in fact, partial and computable general equilibrium models can only measure induced land use change, which captures both direct and indirect effects, and cannot be disaggregated.

storage from satellite data, resolution of satellite data, key economic modelling parameters such as crop yield-price elasticity, location of predicted land use change, and treatment of co-products.

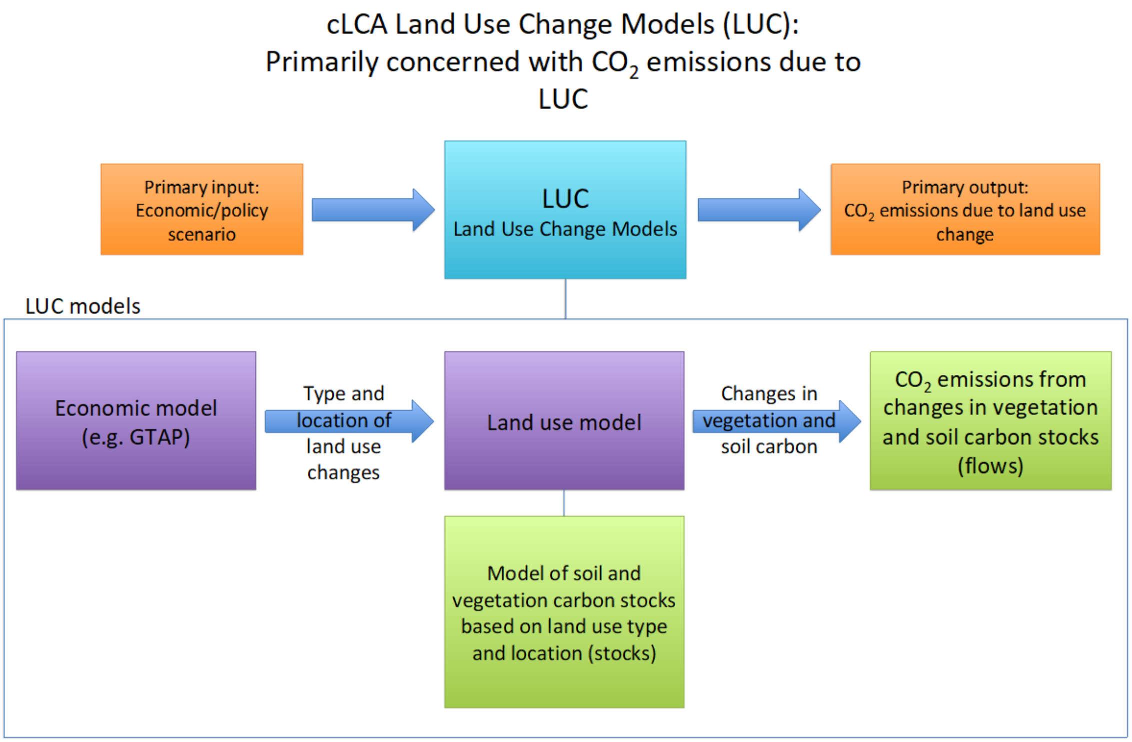

Figure 1: Schematic of Land Use Change (LUC) Models

Other key LUC issues that are debated include the appropriate size and timing of the biofuels “shock”, land management practices such as double-cropping that may impact land use, and land classification, which affects carbon release and/or sequestration as a consequence of land use change. These land use questions are directly related to issues surrounding modelling of soil carbon, forest carbon, etc. that are described in more detail in section 3.3.2 of this report.

While carbon emissions due to LUC are analogous to at least one facet of a stock and flow model, LUC calculations do not consider carbon allocation across all pools, including water and atmosphere, nor the uptake of atmospheric CO_2 into biomass. LUC models thus fail to capture this feedback within the carbon cycle, which has the potential to attenuate or amplify net impacts on atmospheric CO_2.

2.3 Scenario Modeling Concepts

Publications describing the potential merits of biofuels and bioenergy systems frequently rely on scenarios to assess outcomes under various hypothetical situations. Such comparisons are referred to as "scenario modeling" or "scenario analysis". Scenario modeling can include projected outcomes under some future scenario, when process performance has been optimized, or comparisons between several alternative processes, or differences between facilities located in different geographies. Scenario analysis highlights the fact that these models are designed for comparisons, under a consistent set of assumptions.

When using scenario analysis to compare policy, process or product options, e.g., adoption of a given biofuels policy or non-adoption of the policy, two "scenarios" are studied: the case where changes proceed as expected in the absence of the policy, process or product change, typically referred to as the "business as usual" (BAU), baseline or "counterfactual" case, and the case where the policy, process or product change is implemented. The two scenarios are used to isolate the effects of the change: the differences between the modeled future under the counterfactual scenario and the modeled policy, process or product change scenario at some point in the future are compared, and differences between the scenarios are attributed to the change. Selection of the counterfactual case can be difficult, and is key to the results of the modeling. Such comparisons are important whether using LCA, simple stock and flow models, or other more complex models of the carbon cycle or climate. Modeling policy impacts on climate effects, in particular, requires consideration of a number of steps: economics and demand changes, the influence of such changes on carbon flows, the resulting changes in carbon stocks and atmospheric GHGs, and ultimately the effects on climate. Even the first component of this chain, i.e., economic modeling of the counterfactual case (predicting the intricacies of the global future economy) is highly subject to model parameters and assumptions.

2.4 Additionality and Carbon Debt

The concept of additionality is related to the concept of biogenic carbon crediting for biofuels. Some researchers have criticized biofuels by stating that they are unable to "reduce atmospheric CO_2 concentrations" unless the crops grown for biofuel feedstocks could fix carbon at a higher rate than the land used for growing the feedstock in the absence of biofuels production (e.g., Searchinger et al., 2010[13]). The net rate at which carbon is fixed by biomass per unit of time (the rate of fixation minus the rate of plant respiration) is referred to as net primary production (NPP), and normally expressed in units of $g\ C\ m^{-2}\ yr^{-1}$. These groups attest that only increases in NPP can be credited against the emissions from biofuels combustion, because that is the only "additional" contribution biofuels have to removing CO_2 from the atmosphere. Increasing NPP could be accomplished in several ways, such as by yield increases on current plantations, or by using biomass that would otherwise have decayed and had its carbon released back into the atmosphere in a relatively short time period (e.g., residues, heavily insectinfested biomass, etc.)[14]. These groups suggest that using biofuels will not reduce CO_2 concentrations in the atmosphere, since the CO_2 fixed by the crops will be returned to the atmosphere upon combustion. However, if biofuels displace fuels that emit CO_2 at even higher rates, they may reduce the rate of atmospheric CO_2 increase. This difference in CO_2 emissions between the biofuel and the displaced fossil fuel is referred to as a reduction in carbon intensity.

Carbon debt is a concept attributed to Fargione et al. (2008)[15] and widely discussed in the realm of biofuels. The idea is that the LUC emissions created by conversion of a given plot of land to biofuel production must be "worked off" by the emissions avoided by displacing a more carbon-intensive fuel with a biofuel. The time required for the avoided GHG emissions to match the initial LUC emissions is referred to as the "payback period". For forest biomass, some studies have shown that estimated payback times for similar scenarios can vary by up to 200 years[16].

2.5 Crediting of Biogenic carbon

There has been some controversy regarding the automatic crediting of biogenic carbon in LCA analysis of biofuels to counterbalance CO_2 emissions upon combustion. As discussed in section 2.4, a number of groups have suggested that, because tailpipe CO_2 emissions from biofuel combustion are equivalent to those from fossil fuel combustion in terms of increasing atmospheric concentrations and the land used for biofuel feedstock production would be absorbing CO_2 from the atmosphere regardless of end use, that the uptake of carbon from growing biofuel feedstock should not be credited. There are several counterarguments to this approach. The underlying premise behind such a statement is that the crop would be grown irrespective of the presence of biofuels in the market. However, removing bioenergy or biofuels from the market materially impacts demand for these agricultural (or forestry) commodities, and the typical economic response would be to reduce production, rather than grow the crops at a financial loss. Consequently, the true counterfactual is carbon uptake from some (undetermined) lower amount of crop production, versus the carbon uptake from the atmosphere when the additional crop is grown and available for bioenergy use. It is also important to consider how LUC is included in the analysis of biogenic carbon. Consider a plot of land used to grow corn for ethanol production that would otherwise used for feed production. The carbon fixed by the growing corn is not sequestered long-term, but rather, respired by livestock or converted either to methane, a potent greenhouse gas, or to animal flesh that is ultimately consumed by humans and respired as CO_2 in a relatively short timeframe (2-3 years). Using the corn for ethanol production will therefore not increase short-term release of carbon from the given plot of land, but will yield transportation energy instead of food/feed energy. Decreasing the amount of corn available for feed will likely increase the price/demand for feed and may induce conversion of land from farming other crops to corn farming or conversion of another type of land to agricultural use elsewhere. An increase in the cost of animal feed may also lead to other indirect effects, such as an increase in beef prices, leading to lower demand and consequent reduction in demand for pastureland. The GHG emissions caused by these indirect effects are accounted for as LUC. Removing the credit for biogenic carbon therefore effectively "double-charges" biofuels for carbon emissions. As discussed by Wiloso et al. (2016)[17] and Haberl et al. (2012)[18], keeping the credit for biogenic carbon does not assume carbon neutrality, but rather accounts for emissions changes as part of LUC. Wiloso et al. consider the case of a plot of forest harvested for wood to be burned as a biofuel. The emissions can either be accounted for as part of LUC, if the plot will be converted to a different type of land use, or as emissions from combusting the biomass if the forest will be regrown as plantation forest.

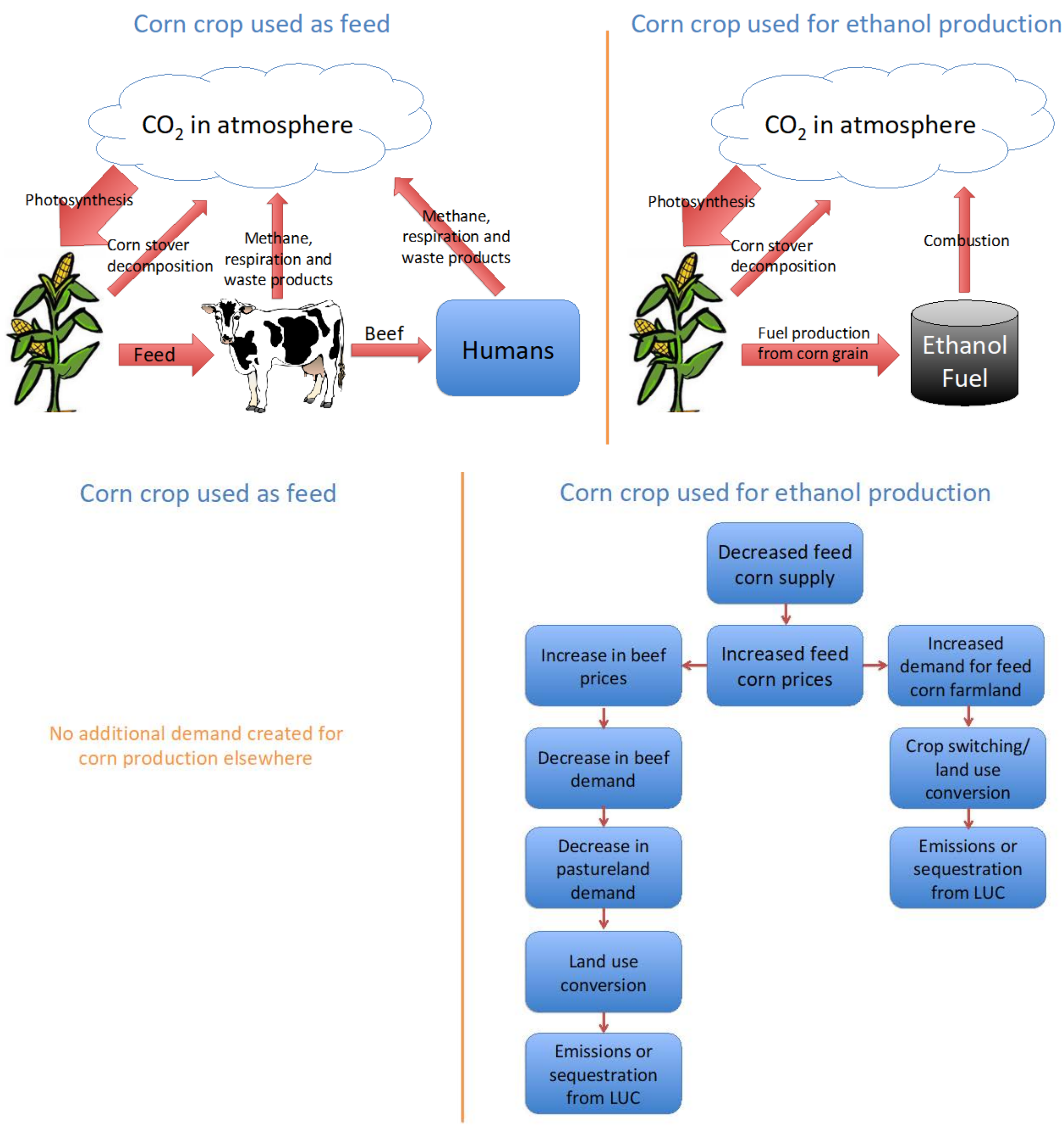

Figure 2: Schematic Comparison of Corn Use for Feed versus for Ethanol Production

2.6 Timing of Flows and Dynamic LCA

Time-sensitive flows are often handled on an ad hoc basis in LCA[7], and they are treated in different ways by different LCA standards[19]. The timeline of an aLCA is aligned with the lifetime of the product. For crop-based biofuels, this period is approximately one year, and new biofuels crops are produced annually. Flows, whether credits or debits, that are "one-time" occurrences associated with the production process are typically "annualized" (as in the case of LUC) over a chosen time horizon (e.g., 30 years for LUC), and also normalized to the assumed volume of production. One-time flows include items such as GHG emissions associated with production plant construction. For GHG emissions, however, the timing of emissions matters in terms of the impact on radiative forcing (RF). RF is a measure of the potential impact of a GHG on the energy balance of the Earth, and hence on global warming. The RF of emissions is usually reported in terms of the 100-year Global Warming Potential (GWP) of a given gas, which is a measure of the integrated RF of a gas over a time horizon and the 100-year GWP value for CO_2 is set to 1. Emissions of different GHGs can therefore be expressed as "kg CO_2 equivalent" emissions. Calculating a GWP depends on the climate, the physical characteristics of the gas and the longevity of the gas in the atmosphere, as well as the time horizon used. Using the 100-year GWP for a gas means that GHG emissions at different times are not compared on a consistent basis, e.g., the 100-year GWP value for a GHG emission at year 1 represents RF from year 1 through year 101, whereas for an emission at year 25 it represents RF from year 25 through 125.

Some groups have tried to assess the temporal limitations of traditional aLCA and the inconsistencies in RF comparison of flows for biofuels and biomass harvest through use of "dynamic LCA"[20,21]. For example, Levasseur et al. (2010)[20] used dynamic LCA to investigate GHG emissions from biofuels by looking at flows incurred during time "steps" and applying the mathematical RF equation used to calculate GWPs for each GHG in each time step, integrating the RF from the time of emission to the end of the time horizon. These flows were then summed to develop a CO_2-equivalent emissions value for the given time horizon. Levasseur et al. (2010) found that, using dynamic LCA, the substitution of gasoline with corn ethanol was less favourable than using traditional LCA by up to around 18%, depending on the time horizon used. When a discount rate was applied, they found a smaller difference between traditional and dynamic LCA results. While this technique addresses some of the time limitations of LCA, Levasseur et al. used the current atmospheric concentration of CO_2 to set up the GWP equations rather than predicted future concentrations. The IPCC GWP relationships are developed based on climate models; improving the estimates requires modelling of future atmospheric concentrations. Such models are typically more complicated than LCA models and are based on stock and flow principles (as discussed further in section 3.4).

3 Stock and Flow Models

The premise behind stock and flow models is to account for the movement of carbon between different reservoirs (or pools). Stock and flow models are applied for two fundamentally different purposes: (1) carbon stock and flow accounting and (2) climate forecasting. These two purposes require significantly different modeling techniques, and also have different concerns in terms of data requirements, data gaps and sources of uncertainty and error.

Stock and flow models and concepts are widely used for GHG emissions accounting. National Greenhouse Gas Inventories (NGGIs) and carbon credits for trading under the UNFCCC are based on stock and flow methodologies. As pointed out by a number of groups (e.g., DeCicco et al.[22]), the certainty of data is asymmetric between different sources, and many of the sources accounted for in an NGGI are relatively certain, such as tailpipe and facilities emissions. Other sources, such as N_2O emissions and soil carbon stocks, are less certain and typically require some type of modeling to determine, even on an annual basis for NGGI purposes[23]. However, estimating annual emissions is still relatively certain when compared with forecasting methods. More difficulty is encountered when attempting to estimate carbon stocks in various reservoirs, because, e.g., atmospheric CO_2 concentration measurements fluctuate, are location-dependent, are affected by climate changes and are non-linearly related to stock changes (see, e.g., Cannell (2003)[24]). However, as with the UNFCCC carbon credit system, changes to stocks can be tracked if flows are measured; tracking stocks via flows, however, requires mass closure, and accounting for all "pools" where carbon may be present.

Stock and flow-based models are also used for forecasting changes in carbon stocks and resulting climate change. Forecasting-type models run the gamut from simple climate models (SCMs) that can be used for relatively rapid scenario analysis, to sophisticated models of biogeochemical cycles linked with physical circulation models and economic forecasting software (Earth system models (ESMs) coupled with Atmospheric-Oceanic General Circulation Models (AOGCMs) and linked to Integrated Assessment Models (IAMs)). The varying levels of model complexity have associated strengths and weaknesses.

In the subsections that follow, we provide an introduction to types of stock and flow models (section 3.1), followed by a description of simple stock and flow models (section 3.2), a review of Earth system Models (section 3.3), then followed by a review of climate models and integrated assessment models, focusing on their combination with models of the carbon cycle (section 3.4). We conclude section 3 with a discussion of frameworks for application of stock and flow models to biofuels and bioproducts (section 3.5), along with a discussion of issues associated with leakage.

3.1 Introduction to Types of Stock and Flow Models

Due to the complexity of modeling a global carbon system and associated climate effects, a large number of models have been developed to predict and capture carbon stocks and flows and their resulting effects on climate. Table 1 presents a summary of a number of important model classes related to stock and flow modelling that will be discussed, and how they are defined in this report.

Table 1: Important classes of model related to stock and flow modeling

Model Class Name	Description	Type of model
Carbon stock and flow models	General term for any model that tracks the movement of carbon between different reservoirs/pools. Earth system models and many simple carbon accounting systems and frameworks fall under this umbrella, and the level of sophistication varies widely - from relatively simple forest carbon stock inventories to modelling the global carbon cycle (GCC).	Stock and flow
Earth system models (ESMs)	ESMs represent the most comprehensive and complex class of stock and flow models. ESMs model the GCC, including flows between the atmosphere, ocean, land, ice and biosphere, to track changes in carbon stocks. ESMs typically track other important geochemical cycles including nitrogen and phosphorous. ESMs are generally coupled with climate models to account for feedback between carbon stocks and climate conditions (e.g., temperature, precipitation). These coupled models are often referred to as ESMs in the literature; however, in this report we separate ESMs and climate models.	Stock and flow
Greenhouse gas inventories and national greenhouse gas inventories (NGGIs)	While not technically stock and flow models, GGIs use stock and flow principles and models to track the carbon sinks/reservoirs (stocks) and the flows of carbon between these reservoirs. Flows based on both natural and anthropogenic activities, including both emissions and sequestration. GGIs are widely used for emissions tracking: projects seeking carbon credits under the Kyoto Protocol's Clean Development Mechanism use GGIs to create baseline projections, and annual country-level NGGIs are required from countries party to the United Nations Framework Convention on Climate Change.	Stock and flow accounting
Climate models	Climate models are not stock and flow models. Climate models attempt to simulate interactions between various aspects of the physical environment that may include the atmosphere, oceans, land surface and ice, and predict how climate, e.g., temperature and precipitation in various regions, will change as a result of these interactions. Climate models are primarily concerned with physical flows, geochemistry and energy transfer. Climate models are often linked with ESMs to look at the effects of carbon stock changes on the climate, and to account for climate feedbacks that influence the carbon and other cycles. Climate models take reservoir CO_2 stocks and predict the resulting change in climate.	Climate
Atmospheric-oceanic general circulation models (AOGCMs)	AOGCMs constitute the most sophisticated class of climate model, linking the physics and chemistry of the atmosphere and oceans.	Climate
Coupled climate-carbon models	Coupled climate-carbon models are stock and flow models that also predict climate. Coupled climate-carbon models typically combine ESMs and AOGCMs. Confusingly, these models are sometimes referred to as ESMs, because ESMs are rarely used without being linked to a climate model.	Stock and flow Climate
Integrated assessment models (IAMs)	IAMs are not strictly stock and flow models, but do contain stock and flow models. IAMs introduce a policy/economic/social modelling component that predicts changes in carbon flows/land use. These predicted changes can be used as inputs into a coupled climate-carbon model to ultimately predict the effect of policy/economic changes on climate, or the effect of changes in climate on economic or social outcomes	Economic Stock and flow Climate
Simple climate models (SCMs)	SCMs are simplified versions of coupled climate-carbon models or IAMs used for relatively rapid scenario analysis due to their much lower demand for computing resources.	Economic (sometimes) Stock and flow Climate

3.2 Simple Stock and Flow Systems and Proposed Stock and Flow Frameworks

In stock and flow models for simple systems, such as applications to wood products, the goal is to track carbon stocks and flows, including carbon stored in forest pools (soils, aboveground/belowground biomass, dead biomass), carbon sequestered in such products, and the eventual release of carbon stored in products during the end-of-life stage. The basis behind a model for wood products (which can include lumber, plywood, furniture, or paper) is that carbon is ultimately removed from the atmosphere and into forest pools, then subsequently into products, until these products reach the end of their useful life. In addition to storing biogenic carbon, wood products can also displace more carbon-intensive alternative materials (e.g., timber use in construction sector, displacing steel/concrete). The evaluation of forest products uses a combination of approaches: stock and flow models are used to evaluate carbon stored in forest pools and products; LCA (typically aLCA) is used to evaluate the GHG emissions associated with using wood products in place of alternative materials. Wood products used, e.g., to build homes and other structures, have a long lifespan, whereas paper has a comparatively shorter lifespan. However, the latter is readily amenable to recycling, which extends the period of carbon sequestration (albeit, rigorously, at an additional carbon cost for energy used in the recycling process). At the end of the product's life, the fate of biogenic carbon depends on the waste treatment route undertaken: material degradation can result in the release of carbon to the atmosphere in the form of methane or CO_2/CO, depending upon whether the process is anaerobic or aerobic; combustion will release most carbon as CO_2 but energy recovery can avoid fossil fuel use; if disposed in landfill, a portion of biogenic carbon can remained sequestered over long timescales (>100 years) depending on landfill conditions.

Implications for forest carbon have been modelled using both allometric and ecosystem process model approaches. Hartl et al. (2017)[25] assert that forest sector carbon balances must be comprehensive, and include forest carbon stocks, the product carbon pool, and avoided emissions associated with product use (following LCA concepts). From this perspective, forest harvest represents a transfer of carbon from one pool to another; however, bioenergy represents a biogenic carbon emission source as constituent carbon is released during combustion. Mass balance closure of carbon flows is possible with this approach, with carbon removals at harvest accounted for within the forest carbon model component. Other studies similarly evaluate the net carbon implications of forest management for HWP manufacture in Lithuania[26] and the US[27].

As mentioned above, human behavioral factors such as recycling, means for disposal, and consumption rates may also be considered in a stock and flow model for wood products. However, such simple stock and flow models are rarely linked to atmospheric CO_2 or climate. Rather, they account for local policies or behaviors that affect carbon sequestration, without directly accounting for changes in atmospheric

CO_2, or the dynamic effects of carbon exchange with the atmosphere on vegetation uptake rates. These simple models account for time in the context of stored carbon, but typically assume a static atmospheric CO_2 concentration and climate.

There have been some attempts to apply simple stock and flow concepts to biofuels and bioenergy (outside of land use change modeling, which also represents a narrow application of stock and flow models to these systems). The majority of bioenergy stock and flow-based studies have been focused on energy from forest biomass, where the slow regrowth of the harvested material makes consideration of stock changes extremely important. Forest biomass studies typically combine stock and flow modeling with LCA concepts, as described above. Such studies investigate either how use of forest products for bioenergy and HWP affects carbon stocks, or the amount of time required to pay off the "carbon debt" created by removing the sequestered carbon in the biomass, given that using biomass for energy typically displaces fossil fuel use and will ultimately be replaced by growth of new biomass (see, e.g., Perez-Garcia et al. (2006)[28], McKechnie et al. (2011)[29], Timmons et al. (2016)[30]; Sterman et al. (2017)[31]).

More sophisticated investigations of carbon stocks and flows require a very large increase in model complexity (and data). For instance, even relatively simple models of vegetation growth require atmospheric CO_2 concentrations, which have a very complicated relationship to carbon stock releases that includes, e.g., partitioning into ocean reservoirs. Stock and flow models are typically used to investigate the effect of changes in stocks and flows on atmospheric CO_2 concentrations, which can be used in an AOGCM to model the resulting effect on climate change. When considering the use of stock and flow models for biofuels and bioenergy, it is important to recognize several key differences relative to the simple wood products example illustrated above:

1) Using biomass for energy (whether for power generation or production of liquid fuels) means that product lifespan and recycling is no longer a factor – these products are produced for consumption within a short period – weeks or months.
2) Once consumed, the carbon sequestered in these products is returned to the atmosphere, primarily as CO_2.
3) The overall carbon cycle is much more important for these systems. The carbon cycle includes global CO_2 levels, and atmospheric exchange of CO_2 between the atmosphere, vegetation, soil, and water.
4) The link to the global carbon cycle means that the analysis cannot be confined to local effects, or policies. For example, while one might analyze local carbon uptake by biomass feedstocks used for fuels, the CO_2 is distributed globally, and thus, impacts biomass grown outside the region in which a bioenergy/biofuels plant is located. A key example of this is bioenergy plants, particularly in Europe and SE Asia, that rely extensively on wood pellets imported from the US southeast, or from British Columbia. In these cases, the carbon uptake by biomass is far removed from the facility in which the biomass is used. This is related to the issue of "leakage",

in which changes in carbon stocks take place outside the system boundaries, analogous to the impact of induced land use change that is often added to aLCA calculations.

5) Forest product studies do not attempt to attribute carbon stock/flow impacts to a single product type. Application of this approach to bioenergy – with an explicit goal of isolating the impact of bioenergy production from other forestry and/or agricultural products – would require additional considerations, including the definition of a counterfactual scenario for comparison (see section 2.3). The selection of a counterfactual can be a deterministic factor in results, and its selection is subjective.
6) However, forest carbon methods (and UNFCCC forest carbon accounting framework) do look at the forestry sector as a whole and attempt to isolate contemporary anthropogenic impacts on carbon stocks/flows by comparing forest carbon stocks with a baseline that incorporates natural disturbances and, in some cases, business-as-usual forest carbon trends (to factor out past management activities). This also helps to make sure changes in forest carbon credited to projects/countries are additional (see section 2.4).

Rigorous application of a stock and flow model to analyze the impact of biofuels or bioenergy on climate must take into account the carbon cycle, the water cycle, the nitrogen cycle, and the phosphorus cycle. Collectively, these all play a role in fostering or limiting biomass growth. The analysis would need to be global, and would need to take into account other contributions – either as credits or debits to the physical/accounting system for carbon and energy. For example, fossil energy used to produce feedstocks or energy products, or for transportation, would need to be considered. Similarly, co-products of various types may reduce (or add to) net energy and emissions. These analyses are typically included in aLCA, but a consistent framework to account for these effects in stock and flow models needs to be developed. Ultimately, comprehensive modelling of other systems is needed to analyze the counterfactual case, or to account for the use of fossil energy or displacement of existing products by a biofuels/bioenergy system. Modelling of fossil energy systems, their emissions, and climate impacts is needed in order to rigorously analyze the impact of bioenergy and biofuel systems. Similar modelling is required to account for energy or emissions associated with co-products, and the existing products that may be displaced.

Ajani et al. (2013)[32] presented a carbon accounting stock and flow framework for climate mitigation, on the premise that it can complement and improve on the current flow-based inventory under UNFCCC and the Kyoto Protocol (flow-based National greenhouse gas inventories, NGGI). They build upon the German Advisory Council on Global Change (WBGU) proposed framework using total stock carbon in the atmosphere. They suggest a “land unit” method to track and estimate land carbon stocks (The System of Environmental-Economic Accounting or SEEA Central Framework). The SEEA Framework has been used by the Australian Bureau of Statistics. They also use the Global Carbon Project data, which compiles flows of the global carbon cycle with geographical and temporal variations. The authors validate the global estimates with aggregated national estimates. See Figure 3, below, for a diagram of the framework. We note that this method is set up to track carbon stocks and flows in an accounting sense, but not to attribute changes to a specific product, such as a biofuel.

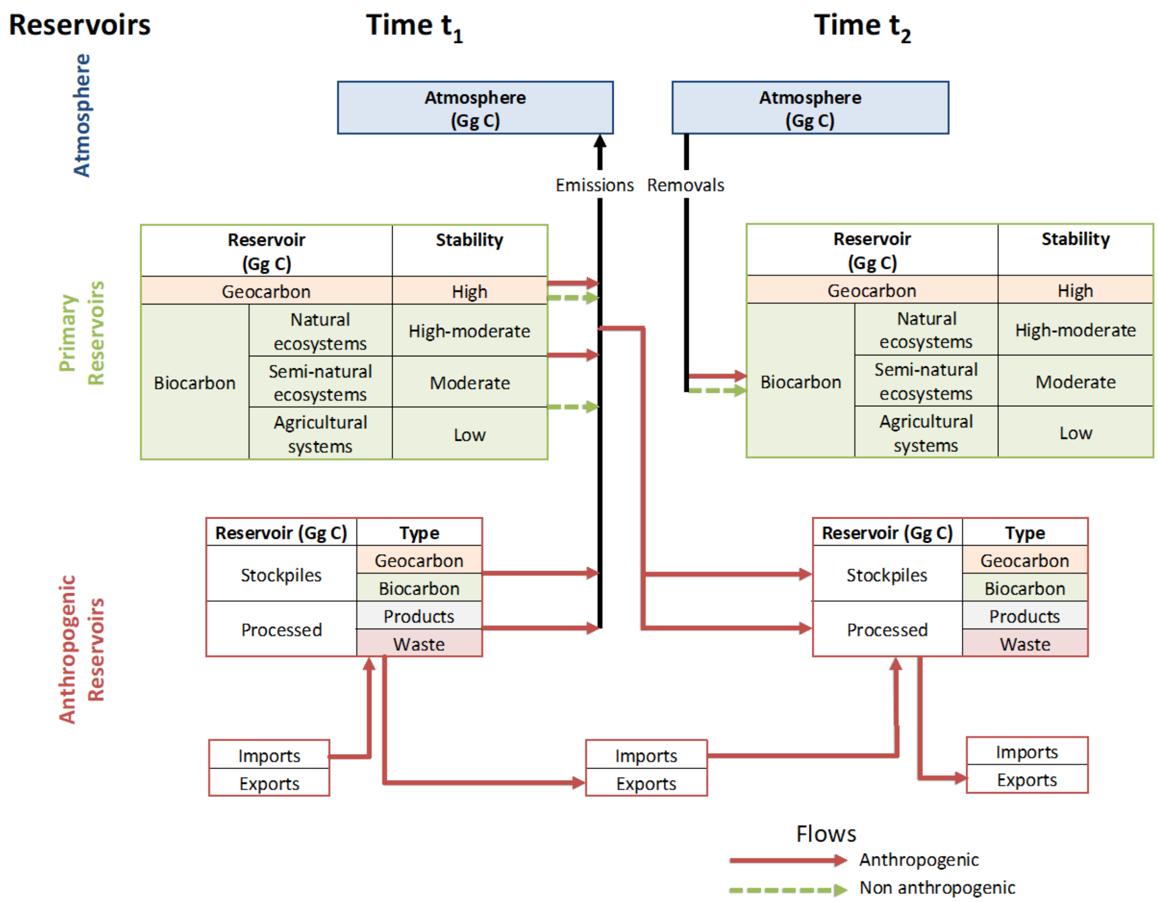

Figure 3: Framework for a Carbon Stock and Flow Model, after Ajani et al. (2013)[32]

The framework proposed by Ajani et al. adopts the following principles and methods:

- "*Carbon stocks, carbon stock changes, emissions and removals [should] be estimated for each reservoir for defined time intervals. Emissions are disaggregated from removals.*"
- *"Within a network of land units covering a region, each land unit [should] be separately identified and tagged with information on land use history; ecosystem type and condition; carbon stocks (current and at determined baselines); annual emissions and removal," etc.*
- "Geocarbon", i.e., extremely stable fossil carbon deposits that are extremely unsusceptible to disturbance in the absence of anthropogenic activity, and biocarbon, which is exposed and

susceptible to climate changes, fire, and development, are treated as distinct reservoirs. Types of biocarbon with different inherent stabilities are also distinguished: carbon stored on agricultural land, for instance, tends to be shorter-lived and less stable than carbon stored in old growth forest. Emissions from biocarbon reservoirs should not be considered equivalent to combusting highly stable fossil carbon resources.

- Biocarbon stocks are limited by "carrying capacity" for each type of ecosystem. Knowing the carrying capacity is key for understanding the interplay of demand for food, fiber and fuel with a finite land asset.

Ajani et al. touch on several important points regarding the use of stock and flow models:

- *"Distinguishing direct human-induced changes from indirect changes and natural variability presents similar issues for both stock[-based] and flow[-based] inventories…". Also, "biocarbon stocks vary temporally and spatially to such an extent that statistically reliable estimation is difficult".*
- Stock-and-flow models, unlike solely flow-based models such as LCA, allow distinction between types of stocks. Combustion of fossil carbon resources results in "permanent" contributions to atmospheric CO_2 concentrations, whereas combustion of biocarbon stocks does not, and stock-and-flow models can make the distinction between flows from these different reservoirs, while flow-based models typically cannot or do not.
- *"Carbon stock accounts that incorporate carbon carrying capacity [the maximum amount of carbon potentially stored in an ecosystem under prevailing environmental conditions and without anthropogenic disruption, although including natural disturbances such as fires] provide information that is highly relevant to policy related to the demand for food, fiber and fuel from a finite land asset. Policy issues include: (i) estimating the carbon footprint of converting natural ecosystems to agricultural land; (ii) prioritising land for restoration of biocarbon stocks through reforestation, revegetation, restoration or improved land management; (ii) the tradeoffs between managing land to favor carbon stocks or food or fiber production; and (iv) assessing the density and longevity of the carbon stored under different agricultural land uses and the contribution to climate mitigation".*
- *"Solving the climate change problem is fundamentally about accepting that there are natural limits; and here, comprehensive carbon stock and flow accounts will provide relevant information to assist policy makers, etc."*

Their framework method presents a way to account for carbon, but, as Ajani et al. point out, rigorous implementation may be difficult, because of the volume of data required for each "land unit", which might be hard to come by. Much of the reservoir and stock data are already collected in NGGI evaluations, as these are published with varying frequency for different countries, and typically less often than annually; refined time-based data for stocks in reservoirs are more difficult to compile.

3.3 Earth System Models (ESMs)

Earth system models (ESMs) aim to map the carbon cycle, using carbon pools and exchanges/fluxes between carbon pools (Figure 4). The primary carbon pools include the atmosphere, soil, water, and vegetation. Some researchers subdivide these major pools into sub-pools that take into account different types (or depths) of soil, and different types of vegetation. The pools (and sub-pools) might also be broken down on a regional or geospatial basis, analogous to the agro-economic zones (AEZs) that are used in some models of induced LUC.

Generally speaking, an ESM integrates other models that individually aim to represent (i) carbon exchange between the atmosphere and biomass via photosynthesis and respiration, (ii) decomposition of litter (dead biomass) to produce soil carbon (or methane), (iii) uptake and release of CO_2/C from water bodies, etc. There are many ESMs available (see IPCC AR5 Chapter 9, pg. 747[1]), which vary in their use of sub-models, embedded assumptions, and geospatial resolution.

Earth system models are intended to be global, and ultimately must aggregate data from various regions, which may have substantial heterogeneity in physical attributes, or even if physical attributes are similar, may have heterogeneity with respect to the rates of exchange (flux coefficients and kinetics parameters) between pools.

Fluxes between pools are dictated by gradients, but are also affected by temperature, presence or availability of water, nutrients such as nitrogen, phosphorous and potassium (NPK), and other physical attributes that may facilitate binding or release of carbon, NPK, or water. These attributes affect the size and capacity of the various pools (and sub-pools), and the rate of exchange of carbon between these pools. Accurately representing all of these features requires a massive amount of data; as it currently stands, major simplifications are employed, either in terms of geospatial characteristics or kinetics/flux parameters.

Earth system models may be employed in static or dynamic mode. In the latter case, systems of differential equations are created to track carbon within each pool/sub-pool, and also account for carbon exchanges between pools. In order to estimate key parameters, the dynamic ESMs are often solved using historical data, assuming "equilibrium", and thus setting the derivatives equal to zero (we note that, rigorously, setting the derivatives equal to zero implies steady state, which is not necessarily the same as equilibrium). Separate sets of experiments may be conducted to estimate parameters for sub-processes (e.g., effect of temperature on litter decomposition rates or photosynthesis rates, or release of carbon from different types of soil). These independent parameters, combined with "equilibrium" or steady state model parameters from the ESMs, are then used in the ESM to predict temporal changes in response to a "disturbance" from the current steady state or equilibrium conditions.

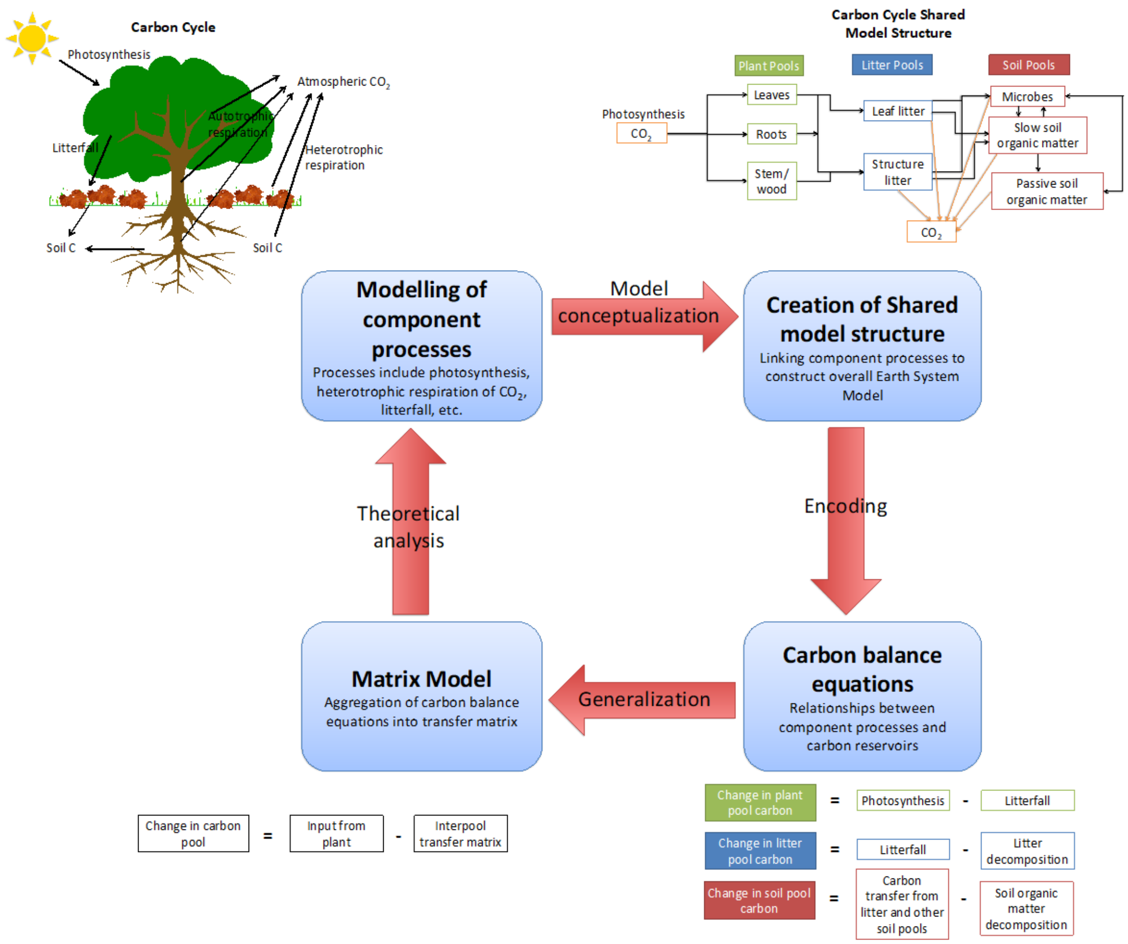

Figure 4: Illustration of Physical Processes, Pools, and Exchanges Incorporated into an Earth System Model, after Luo et al. (2015)[33]

ESMs differ from climate models in that ESMs may track carbon distribution, but may not include models/relationships that link atmospheric CO_2 to temperatures or other climate parameters. ESMs may evaluate changes to carbon accumulation in different pools, or rates of carbon exchange between pools, in response to a gradual or pulse increase in atmospheric CO_2. In this way, they can estimate whether an increase in atmospheric CO_2 may be attenuated by uptake into carbon sinks, or if pools for carbon sequestration may reach capacity, thus potentially exacerbating already high atmospheric CO_2 levels.

ESMs are also commonly used to quantify land use and land cover change (LULCC) emissions and feedbacks between LULCC and climate. However, quantification of sources and sinks of carbon from LULCC is uncertain[34]. Differences in historical LULCC emissions were considerable when comparing reconstructed versus dynamically computed land covers, and this difference was larger than the effects of forest regrowth, shifting cultivation or climate feedbacks.

Comparing the land carbon cycle model component of an ESM with field observations can involve three types of tests. First, a process, such as the response of organic matter decomposition by soil microbes to changes in temperature and soil moisture, can be measured at an individual site. Second, satellite data can be used to study larger spatial scales than can be measured directly. For example, leaf area predicted in the model can be compared with satellite-observed values to see how well the model simulates the annual cycle of growth. Third, the model can be compared to longer-term compilations of data to see how it performs on decadal time scales and over large spatial scales. Since satellite data are limited to the last few decades, these compilations often mix satellite data with in situ measurements and economic data (such as reports of lumber harvested from a nation's forests). The model's prediction of how much deforestation as well as reforestation has changed the carbon taken up by land over the past few decades can be compared to independent estimates based on atmospheric concentrations of carbon dioxide, carbon isotopes, and land-cover-change datasets.

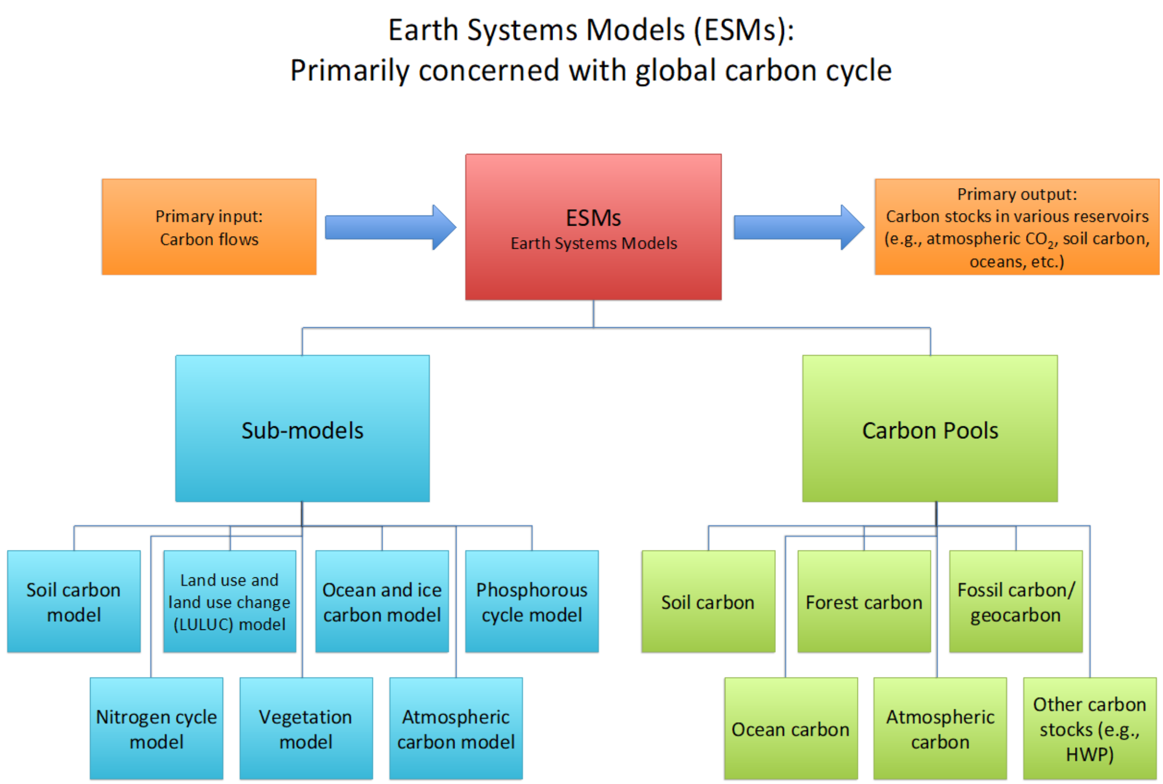

Figure 5: Framework for an Earth systems model (ESM). Note that individual ESMs may include more or fewer modules, pools and sub-models than shown here.

3.3.1 Summary of ESM Literature Review

Most recent literature regarding ESMs reviewed considered different aspects of ESMs and their application to tracking carbon between different pools, including the atmosphere, land, soil, and water. Some models used only some of the pools. The exchange of carbon between pools is represented by “sub-models” for vegetation, soil carbon, etc., with kinetics/exchange constants. Some papers compare different ESMs to assess differences in performance and outcomes. Feedback between climate, CO_2, and the different pools can also be explored.

As discussed below, authors have noted significant uncertainty due to underlying data, model structures, model assumptions, and parameters. These variations predict materially different outcomes in terms of atmospheric carbon, or in the event that changes in atmospheric carbon are used as the basis for modelling, materially different changes in C accumulation in the different pools.

Publications related to ESMs that include comparisons of multiple models and assess their utility and limitations are excellent starting points for understanding the importance of ESM modeling approaches. We briefly summarize these below; more detailed synopses of other publications that develop or use ESMs are provided in Appendix A.

Luo et al.[33] compared 11 ESMs from CMIP5 (the Coupled Model Intercomparison Project) and concluded that none could accurately predict patterns of soil carbon or global primary production, with initial values of carbon pool sizes varying by 250% to 600%. Luo et al. also noted the importance of linking the carbon cycle models with models of N and P cycling, which materially impact temporal accumulation of carbon into leaves and other biomass. Luo et al. also note that the impacts of disturbances such as fires are not well understood nor described in most models. The main conclusion is that these ESMs (and underlying models and data) are inadequate for predicting the dynamics of the C cycle and climate.

Huntzinger et al. (2017)[35] compared an ensemble of 12 models of the global C cycle, with dramatically different representations of land-atmosphere C dynamics. We note that this comparison focused on the terrestrial ecosystem sub-models; while many of these are related to or form part of the models evaluated in Luo et al. (and Anav et al.[36], and Aparicio et al.[37], both discussed below), the models in Huntzinger et al. are different. See Table 2 for details. The terrestrial ecosystem models also vary dramatically in terms of the magnitude of impact of CO_2 fertilization and historical land cover on cumulative land C uptake. This leads to a difference of up to 200 Pg C in estimated land C accumulation. Including N coupling reduced terrestrial C uptake by about one third, indicating the importance of N as a constraint on CO_2 fertilization. Major geospatial differences, especially in the tropics and at the poles, create challenges. Models predict dramatically different drivers of cumulative C uptake; CO_2 fertilization may be a minor or major driver of vegetated land area. Model tuning may compensate for uncertainties and gaps by altering parameters that represent CO_2-climate sensitivity. **Models consistent with global constraints may end up with the right answer (from historical data) for the wrong reason, which implies limited usefulness to predict future climate, temperature, atmospheric CO_2, and C pools**. The authors state that “improvements in terrestrial C cycle (and thus climate) predictability require that the models not only produce the right end points…but also the correct pathways to those endpoints.”

Additional comparisons of ESMs were conducted by Anav et al. (2013)[36] and Aparicio et al. (2015)[37]. Anav et al. compared 18 ESMs (also from the Coupled Model Intercomparison Project (CMIP) and ranked them based on their ability to simulate the land and ocean carbon cycles for our present climate. The authors found that the models correctly reproduce the main climatic variables that control spatial and temporal characteristics of the carbon cycle, but they do not reproduce some specific aspects of the land carbon cycle, and in particular, overestimate photosynthesis and leaf area index. Furthermore, the results were sensitive to reference data and regional variations. Aparicio et al. compared 12 Earth systems models (also from CMIP) used to project trends in vegetation productivity and carbon storage; they also noted major uncertainty in their long-term predictions. Hajima et al. (2014) noted large differences in the degree/strength of concentration-carbon feedback and thus, ESMs predicted materially different changes to terrestrial C, depending upon the assumed rate of CO_2 increase. Over a 140-year period, the ESMs projected gross primary production (GPP) and NPP values that vary by up to an order of magnitude, and land carbon accumulation varying by up to a factor of six. In all eight ESMs studied, elevated atmospheric CO_2 led to a continuous increase in land and soil carbon, in essence, a CO_2 fertilization effect that increased net primary productivity, producing more biomass. While these trends were common among all ESMs, the sensitivity of each model to elevated CO_2 varied greatly.

Table 2: ESM-Related and TEM Models Compared in Luo et al.[33] and Huntzinger et al.[35]

Model Name	Model Description	Review Paper	Type of Model	Model Comparison Project
CCSM4	US Community Climate System Model	Luo et al.[33]	Climate-coupled model (ESM + AOGCM)	CMIP5*
NorESM1	Norwegian Earth System Model			
BCC-CSM1.1	Beijing Climate Center Model			
HadGEM2	UK Met Office Climate Model			
IPSL-CM5	French Institut Pierre Simon Laplace Model			
GFDL-ESM2	US Geophysical Fluid Dynamics Laboratory Model			
CanESM2	Canadian Earth System Model			
INM-CM4	Russian Institute for Numerical Mathematics Model			
MIROC-ESM	Japan Earth System Model			
MPI-ESM-LR	Germany Max Plank Institue Model			
GISS-E2	US Goddard Institute for Space Studies Model			
CLM4	Community Land Model Version 4	Huntzinger et al.[35]	Terrestrial Ecosystem/Biosphere Model (Sub-model forming part of an ESM)	MsTMIP**
CLM4VIC	Community Land Model Version 4, Variable Infiltration Capacity			
DLEM	Dynamic Land Ecosystem Model			
GTEC	Global Terrestrial Ecosystem Carbon Model			
ISAM	Integrated Science Assessment Model			
LPJ-wsl	Based on Lund/Potsdam/Jena-managed Land (LPJmL) model			
ORCHIDEE-LSCE	Organizing Carbon and Hydrology in Dynamic Ecosystems			
SIB3	Simple Biosphere Model Version 3			
SIBCASA	Simple Biosphere Model combined with biochemistry approach from Carnegie-Ames-Stanford Approach			
TEM6	Terrestrial Ecosystem Model Version 6			
VEGAS2.1	Vegetation Global Atmosphere and Soil			
VISIT	Vegetation Integrative Simulator for Trace Gases			

* CMIP5 = Coupled Model Intercomparison Project Phase 5 (https://cmip.llnl.gov/cmip5/). A summary of model features and results is provided in the IPCC Fifth Assessment Report[1].

** MsTMIP = Multi-Scale Synthesis and Terrestrial Model Intercomparison Project (https://nacp.ornl.gov/MsTMIP.shtml). Results of version 1 of the project are available at https://doi.org/10.3334/ORNLDAAC/1225.

3.3.2 Calculating, Measuring and Estimating Carbon Stocks for use in Stock and Flow Models

Earth system models aim to represent the accumulation of carbon in soil, forests, and other biomass. Important factors include growth rates of vegetation, production and decomposition of litter, and the accumulation of carbon in the soil due to roots and litter decomposition. In this section, we discuss models, data, and analyses pertaining to these physical systems.

3.3.2.1 Forest Carbon

Numerous studies evaluated forest carbon stocks and the implications of forest and land management on carbon accumulation in soil and biomass pools. Carbon stocks may be estimated with (i) allometric modelling (based on forest stand characteristics such as species composition, stand age, soil/climate characteristics, height, diameter at breast height, etc.); (ii) ecosystem process models; (iii) field inventory plot measurements; and (iv) remote sensing. Several studies note the potential role of forests for sequestering atmospheric carbon. However, Mackey et al. (2013)[38] caution that: 1) the potential to increase carbon stocks is far less than potential emissions from fossil fuels; and 2) permanence of storage on timescales of 10,000 years is highly uncertain.

Studies of forest bioenergy have considered either stand-level or landscape-level spatial perspectives. Stand-level assessments consider a single plot of land which is harvested (or otherwise subject to disturbance) at a single point in time, tracking the immediate removal of carbon from forest and transfer of a portion of the carbon to product pools, followed by the accumulation of carbon in subsequent biomass growth over time. In contrast, a landscape-level perspective simultaneously considers a patchwork of stands, some of which may be harvested at a particular point in time and others that will be undisturbed. Carbon flows associated with forest management occur at different points in time, thereby making the temporal scope of the analysis important. Growing forests accumulate carbon over the course of decades or longer; as such there may be a significant delay before significant carbon sequestration from afforestation, or replenishment of carbon following deforestation. These temporal effects are key to the analysis of a stock and flow (or Earth system) model, but are not normally captured in conventional LCA. Timmons et al. state that the removal of old-growth forest biomass creates an opportunity for new and fast sequestration as old-growth carbon uptake asymptotically reaches zero [30]. We note that this is contrary to the assumption of Sterman et al., in their assessment of wood pellet displacement of coal[31]. In practice, the validity of this assumption may depend upon the location, and age and type of forest.

Ecosystem process models are used to estimate the flow of carbon between soil, living biomass, dead biomass, and atmosphere via respiration. These models thus provide key data for Earth system models. Empirically-informed ecosystem process models base estimates of biomass productivity on the biomass increment and replacement of biomass turnover[39] or with direct measurement of carbon flux from field trials and eddy flux observation sites[40]. These models have been employed to estimate how, for example, changes in climate may impact the uptake of carbon in forests[41], how forest management may impact forest carbon stocks[42], and how spatial variability influences carbon stocks[43].

Baker et al. (2010)[44] note the data limitations that prevent accurate assessment of forest carbon stocks in carbon accounting schemes, and highlight scientific uncertainty associated with statistical and modelling approaches. Uncertainty in forest carbon stock data is a significant issue; Andersson et al. (2009)[45] note uncertainty estimates on the order of 25% to 60% in assessing changes in national carbon stocks. Bustamante et al. (2016)[46] also note significant uncertainty, identifying a >50% uncertainty in estimating carbon stocks of mature forests[47].

These uncertainties materially affect calculations in ESMs and simplified stock and flow models, and may result in different predictions of forest carbon, soil carbon, and atmospheric CO_2.

3.3.2.2 Soil Carbon

An array of models have been reported in the literature as tools to quantify the effects of vegetation, agricultural activities, climate, land use and land cover change on soil organic carbon (SOC), in an effort to understand the movement of carbon in the terrestrial system. These models are based upon field data and sampling from discrete geographical regions; when combined, they have the potential to provide a comprehensive analysis of impacts on a global scale, in an ESM. However, the modeling approaches have varied, and *many could not get good agreement between simulation results and field measurements*. Poeplau et al. (2017)[48] tried to fit field data in a model to study the effect of warming on SOC, and observed that it is challenging to match model results with the measured SOC pools.

The discrepancy between simulation and actual data has been attributed to measurement errors, data resolution, disparity between the microclimate at the experimental site and the climate data used in the model, the effect of pathogens and diseases on plant growth, different model structures and assumptions (such as inclusion/exclusion of key biogeochemical and biophysical pathways for soil carbon, and uncertainties in input data [48–55]. Table 3 below, illustrates some of the differences in structure and assumptions between models of soil carbon.

Table 3: Comparison of Soil Carbon Models, from McGuire et al. (2016)[52]

Table 2. Comparison of Conceptual Representation of Soil Carbon Dynamics Among Models[a]

Model	General Depth	Soil C Storage Explicitly Treated with Depth	Moss Horizon C Considered	Litter Horizon C Considered	Organic Horizon C Considered	BIO C-CH_4 Losses Considered	Disturbance Losses Considered	Lateral Losses Considered	Time Step of Flux Estimates
CLM4.5	4.0 m	Yes	No	Yes	Yes	Yes	Fire	Land use	30 min
CoLM	3.4 m	No	No	Yes	No	No	Fire	No	1 h
ISBA	1.0 m	No	No	Yes	No	No	No	No	30 min to 1 day
JULES	Unspecified	No	No	No	No	No	No	No	30 min
LPJ-GUESS	Unspecified	No	No	Yes	No	Yes	Fire	No	1 month
MIROC-ESM	Unspecified	No	No	No	No	No	No[b]	No	1 day
ORCHa and ORCHb	2 (ORCHa) or 47 m (ORCHb)	Yes	No	Yes	No	No	No	Land use	30 min to 1 day
UVic	3.35 m	Yes	No	No	Yes	No	No	Land use	1 h
UW-VIC	1 to 3 m	No	No	Yes	No	Yes	No	No	3 h
JSBACH	Unspecified	No	No	Yes	No	No	No	No	30 min
TEM6	Variable to ~3 m	Yes	No	No	No	Yes	Yes	Yes (DOC export)	1 month
SiBCASA	3.0 m	Yes	No	Yes	Yes	Yes	No	No	30 min

[a]All models consider soil carbon losses from heterotrophic respiration.
[b]MIROC-ESM does consider fire and land use implicitly but does not report the associated fluxes.

Rafique et al. (2017)[55] compared the performance of the Community Land Model version 4 (CLM4), the CLM model with Carnegie-Ames-Stanford Approach (CLM-CASA), and CSIRO's Atmosphere Biosphere Land Exchange (CABLE) model in global carbon cycle simulations. The authors report that CSIRO's Atmosphere Biosphere Land Exchange (CABLE) model provides results that are closer to the referenced carbon storage and residence time for plant and soil pools. A significant difference in these models is the number of carbon pools; nine in CABLE, 12 in CLM-CASA and 26 in CLM4. In addition, differences in the net primary productivity (NPP) allocation resulted in a longer bulk residence time for soil carbon pools and more carbon storage in roots in CABLE, while CLM4 and CLM-CASA predict that more carbon is stored in pools of woody biomass.

There are many limitations in the existing models and work is needed to improve the models and their underlying data. A noted limitation of SOC models is the inability to capture SOC distribution as a function of soil depth. SOC data and models from agricultural activities are also being developed. In agriculture, the role of carbon and nitrogen are difficult to decouple and are important metrics in determining land fertility and crop growths. Doetterl et al. (2015)[56] note that there is uncertainty about the direction and magnitude of soil carbon responses to climate change, and that climatic and biotic factors and their effects on SOC dynamics are still "poorly represented in current Earth system Models". ESMs predict that SOC will be a major contributor to future climate change, but large uncertainties exist in understanding of interactions of climate and geochemical factors and their control of SOC storage and turnover. The authors state, "These uncertainties are explained partly by ESMs poorly representing the current (observed) global SOC distribution and partly by inadequate parameterization of the temperature sensitivity of SOC, microbial carbon use efficiency, and mineral surface sorption of organic matter". Specifically, they recommend that a better understanding of the geochemistry of soils formed under natural conditions at a global scale could improve understanding of the global terrestrial SOC cycle, and improve results obtained from ESMs.

Information on grasslands (grazing, etc.) and management effects on soil carbon stocks was examined by Conant et al. (2017)[57]. The authors calculated that grassland soil carbon stocks are about 343 Pg C (in the top 1 m), nearly 50% more than is stored in forests worldwide[58], highlighting the importance of grasslands in the global carbon cycle.

3.4 Climate Models and Integrated Assessment Models (IAMs)

3.4.1 Climate Models

Climate models are available with different levels of complexity. Much of the initial scenario-based modeling work to assess changes in climate relied on simple climate models (SCMs), partly due to limitations in computational power available at the time. Such models may have lower geographic resolution, may exclude certain factors known to influence climate, or may exclude feedback or other phenomena.

Advances in computational power and knowledge have led to the development of more sophisticated models, and/or models with greater spatial resolution. Some models focus only on atmospheric phenomena, in so-called atmospheric general circulation models (AGCMs). These models track cloud cover, convection, albedo, and oceanic circulation and temperatures. Oceanic phenomena may be covered in more detail in an Oceanic General Circulation Model (OGCM), which aims to represent horizontal and vertical heterogeneity in ocean conditions, including CO_2 gradients and temperatures. These models may be united under the umbrella of an Ocean-Atmospheric General Circulation Model (AOGCM) (see Figure 6). Ultimately, these climate models (in any form – SCM, AGCM, OGCM, or AOGCM) may be combined with (or within) an Earth systems Model and/or a Socioeconomic model to model other outcomes, such as the extent to which future climate scenarios may impact terrestrial carbon stocks and the rate of uptake into plant matter and soils (the primary issue for this report), or financial consequences of elevated CO_2 concentrations.

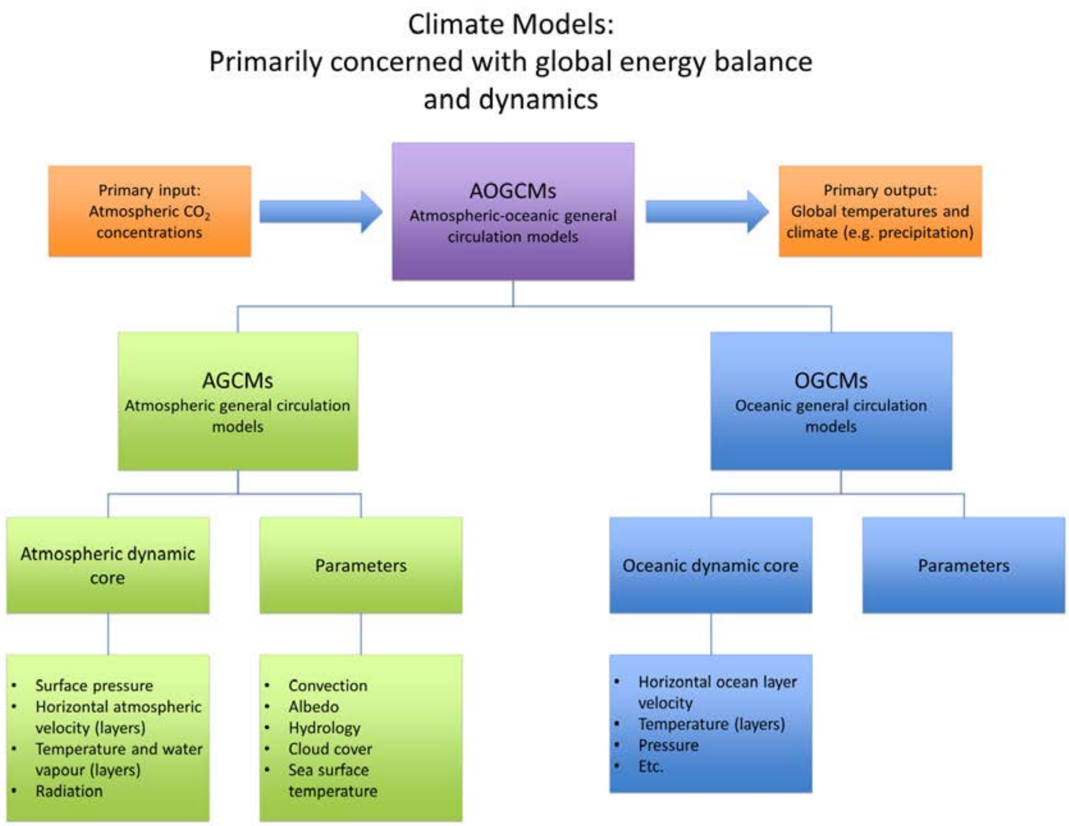

Figure 6: Attributes of Climate Models

3.4.1.1 Application of a Stock and Flow Model with a Simple Climate Model

Sterman et al.[31] developed a model for dynamic bioenergy life cycle analysis that tracks carbon stocks and fluxes among the atmosphere, biomass, and soils. This stock and flow model is combined with a simple climate model (C-ROADS), and was used to evaluate the substitution of wood for coal in power generation. The authors present a number of scenarios based upon different sources of biomass, regrowth cycles, and types of biomass. They ultimately conclude that wood pellets lead to a near-term increase in atmospheric CO_2, even though long-term, CO_2 concentrations would decrease[31]. We note that this conclusion may be affected by the authors' underlying assumptions regarding the type/source of biomass, and limitations of the simple climate model.

3.4.2 Integrated Assessment Models (IAMs)

An Integrated Assessment Model (IAM) combines an ecosystem model (e.g., ESM) with models for socioeconomic drivers of land use and climate-economy relationships. The economic aspects are covered in socio-economic pathways (SSPs) that represent alternative economic decisions related to climate mitigation strategies, and a "damage function" that attempts to predict the consequences of climate change under different scenarios. The relationship between an IAM, ESM, and AOGCM is illustrated in Figure 7.

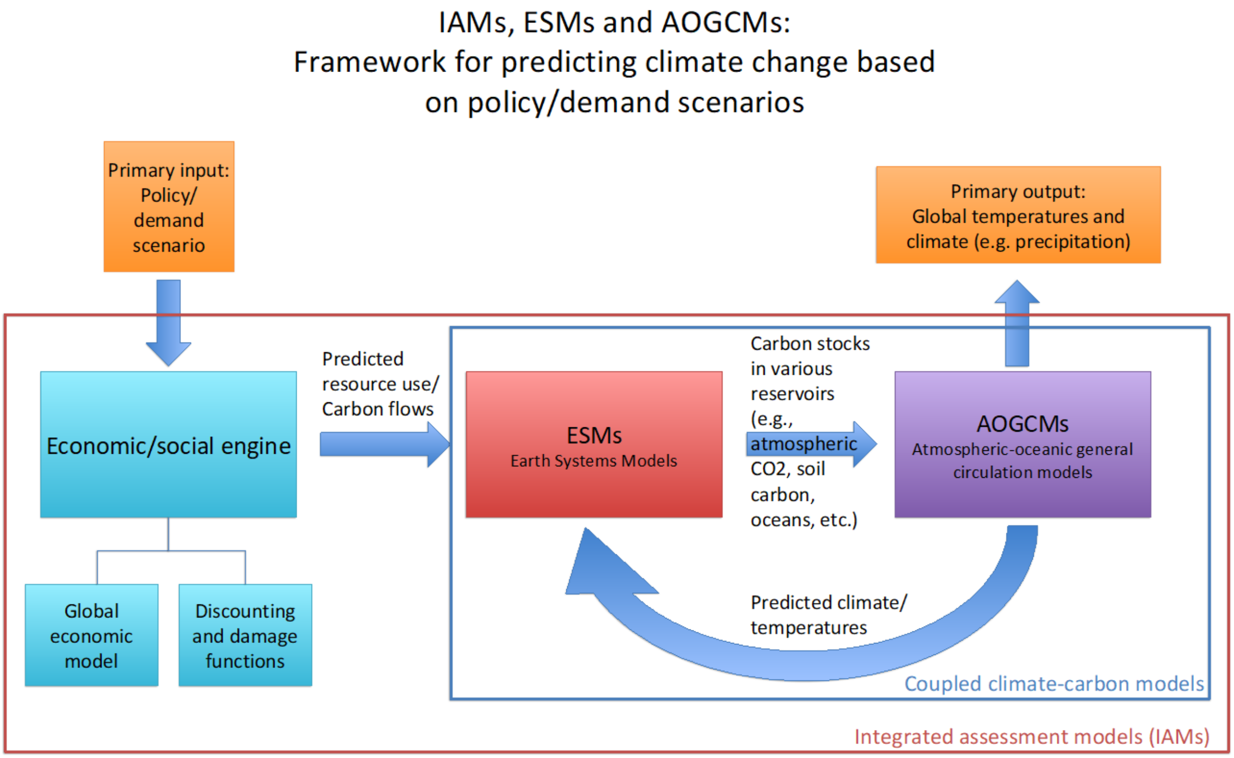

Figure 7: Relationship between IAMs, ESMs and AOGCMs. We note that this terminology is not always consistent in the literature: some literature refers to climate-coupled models as ESMs, since many ESMs integrate some components of AOGCMs, and in recent years some models that began as AOGCMs have also started to integrate ESM components.

Although IAMs have been developed and proposed as a means to develop policies related to climate change and CO_2 emissions mitigation, there remains considerable debate regarding their usefulness. IAM-based analyses of Nordhaus (2008, 2015)[59,60] and Stern (2007)[61] arrive at substantially different conclusions regarding abatement and the appropriate price on carbon. These differences arise from different assumptions regarding the discount rate, and different arbitrary assumptions regarding the GDP damage function, the form and parameters of which are inherently unknowable. Pindyck (2015)[62] thus concludes that there is no scientific or economic basis for any of the IAMs, rendering them essentially useless for climate policy analysis. According to Pindyck, "environmental economists should be ashamed to claim that IAMs can forecast climate change and its impact, or to tell us what the social cost of carbon is."

Pindyck's commentary regarding IAMs serves as a stark reminder about the objectives, roles, and deficiencies of any modelling exercise. Stock and Flow models, LCA models, Integrated Assessment Models, and Climate-Coupled models all fundamentally aim to account for the distribution, exchange and accumulation of carbon in the atmosphere. They all have a potential role to inform climate policy, but may each be addressing different questions, or have different underlying objectives. An IAM adds socioeconomic factors onto an ESM, thus translating data on carbon into financial or social costs (e.g., impacts on GDP, or health, or migration, or biodiversity). A climate-coupled model would build upon an ESM to translate (or integrate) data on atmospheric carbon accumulation into models of climate that predict changes in temperature, precipitation, etc. In each case, there is an important feedback loop to consider, but may be difficult to capture in a model. For example, a reduction in GDP typically means less consumption, which reduces demand for goods and energy, thus attenuating (at least partially) any increase in emissions. Similarly, in a climate-coupled model, changes in temperature and precipitation can positively or negatively impact growth of biomass, and subsequently, soil carbon, both of which affect atmospheric CO_2.

3.4.2.1 Bioenergy Specific Carbon Balance and Application of an Integrated Assessment Model

Engstrom et al. (2017)[63] explored the implications of changes in bioenergy demand on terrestrial biosphere carbon balance, including changes in consumption and crop yields for global and national cropland area. They used an integrated assessment modelling (IAM) framework, combining three previously published models (a climate–economy model, a socio-economic land use model and an ecosystem model). They also use the LPJ-GUESS dynamic vegetation model and the PLUM land use model. The economic piece of the model is through shared socio-economic pathways (SSPs) that represent alternative economic decisions related to climate mitigation strategies. The results are focused on climate mitigation strategies, but some of the secondary results are related to the carbon cycle:

- *"The fate of the future net biospheric sink for carbon is highly uncertain. Biospheric models project divergent trajectories in net carbon balance", depending on the increase in atmospheric CO_2, the climate patterns and trends projected by different GCMs in response to CO_2, the ecosystem* *response simulated by different biosphere models, and the inclusion/exclusion of feedbacks between the biosphere and atmosphere.*

- *"Our results suggest that the indirect impacts of climate mitigation strategies on global cropland are small in comparison to impacts due to the spread of bioenergy production and other sources of uncertainties, such as model structure and uncertainties in parameterisations."*
- Uncertainties arise in: (i) model structure, which can lead to a wide range of results, (ii) cropland land change, which has large uncertainty ranges, (iii) future fate of the net biospheric sink for carbon, (iv) different interpretations of scenarios, and (v) translations of qualitative to quantitative information. A better systematic sensitivity of the climate-economy model and the land use model is needed, along with better estimates for the impact of cropland change on the terrestrial carbon balance (from GCMs).

3.5 Proposed Frameworks for Application of Stock and Flow Models to Crop-Based Biofuels

DeCicco and co-workers, in various publications and presentations, have discussed the application of stock and flow models to biofuels. In particular, they have focused upon the analysis of a single biofuel facility, or impacts of a US-wide biofuels strategy. Their premise is that it is important to consider temporal effects, and that replacement of fossil carbon with biogenic carbon is not sufficient to reduce the flow of carbon into the atmosphere. DeCicco and coworkers also state that biomass energy is not inherently carbon neutral. These assumptions/statements are explored in more detail below.

DeCicco (CRC LCA Workshop, October 2017)[64] examines the case of a 56 MMGPY corn ethanol plant, and DeCicco et al. (2016)[65] aim to evaluate the impact of the growth of the US biofuel industry from 2005 – 2013. Their 2016 publication uses USDA crop data to estimate carbon uptake by crops, and data from the EPA and EIA to estimate tailpipe emissions associated with ethanol use. DeCicco et al. use what they refer to as an Annual Basis Carbon (ABC) analysis, which treats carbon flows on a spatial and temporal basis. They state that the ABC method reflects the stock-and-flow nature of the carbon cycle, accounting for both GHGs discharged into the atmosphere (inflows) and CO_2 removed from the atmosphere by uptake into crops (outflows). The authors then aim to assess the assumption of carbon neutrality for biogenic carbon, a common assumption in biofuels LCA. The authors calculate a gap of 83 Tg C between the incremental increase in C in tailpipe emissions and the incremental uptake of C in US crops. While the premise behind the approach is reasonable, i.e., tracking stocks and flows, the analysis is limited by the geographical restrictions imposed in their calculations, the fact that they did not account for all realistic outflows of carbon from the atmosphere (i.e., all major biomass sources), and the fact that "leakage" across the system boundary (e.g., by co-products, or by agricultural production elsewhere) is not taken into account (see further discussion below from De Kleine et al.[66]). This affects their results and conclusions regarding biogenic carbon. For example, DeCicco et al. (2016) only accounted for the increased carbon in the grain portion of the crops, because that is the crop component used to make biofuels. However, the CO_2 emitted from the production facility or tailpipe can be taken up and absorbed throughout the plant (including stalks and leaves), and stored in its root carbon. Any increase in carbon storage in these components of the crop also would need to be accounted for when assessing the question regarding biogenic carbon. To evaluate co-product dried distillers grains and solubles (DDGS), the major co-product of corn ethanol production, both the product displacement aspects (as is currently done in LCA assessments of corn ethanol by considering avoided soy cultivation), but also the "avoided" net ecosystem production (NEP) to produce the displaced animal feed would need to be considered. Furthermore, the highly simplified stock and flow model (or ABC method) used by DeCicco does not account for other important carbon pools that are included in most analyses of the carbon cycle. Finally, DeCicco implicitly assumes a static counterfactual – i.e., without ethanol, US agriculture should be exactly the same in 2013 as in 2005. This assumption is debatable – it is quite likely that agricultural production would differ if demand for corn for biofuel production were dramatically reduced.

DeCicco's presentation at the CRC LCA meeting (October, 2017)[64] discusses predictions of GHG emissions at a facility level. He presented an analysis of a 56 MMGPY ethanol facility, claiming that if "biogenic CO_2 emissions are neutralized during biofuel production and use, then a gain in NEP must be verified on the cropland from which feedstocks are sourced". In this analysis, DeCicco estimated the total cropland serving the ethanol facility, and calculated the incremental carbon in the corn and soy harvested. DeCicco then calculates GHG emissions for farm and biorefinery operations, and CO_2 emissions from biofuel use in the vehicle. These calculations lead to an estimate of net carbon flow, and net GHG exchange to the atmosphere, in year zero and year one. DeCicco then concludes that the difference in net GHG emissions is positive, on the basis that the GHG exchange to the atmosphere is greater in year one (with the biofuels plant) compared to year zero (before the biofuels plant was operational). However, there is no indication that the analysis includes increased biomass uptake into the non-grain portion of the plant, or into the soil. Furthermore, there is no discussion regarding the treatment of co-products such as DDGS (e.g., by accounting for its carbon content and likely export outside the system boundary). DeCicco (2017) again concluded that "field data show that the observed gain in carbon offset falls well short of full offset of biogenic CO_2 emissions". Unfortunately, DeCicco did not acknowledge the significance of the underlying assumptions regarding the system boundary and co-products. By default, DeCicco assumes that the additional biogenic carbon only ends up in the grain portion of the plant, when it is likely to be distributed throughout the plant, including stalks, leaves, and roots. This is, at best, a highly simplified stock and flow model that does not track the essential aspects of the carbon cycle, nor account for leakage across the system boundaries. This is a risk of simplified stock and flow models – if the model is restricted geographically, and/or does not include all relevant pools for carbon (air, water, soil, and plant matter), then there is missing carbon that can affect interpretation of study results.

De Kleine et al. submitted a commentary to the DeCicco (2016)[65] publication on the use of stock and flow models for US biofuels[66]. They challenged DeCicco on three grounds: (i) assessment of biogenic carbon by offsetting biofuel carbon combustion emissions with additional NEP; (ii) the use of national level agricultural production statistics to measure changes in NEP, and (iii) the use of agricultural NEP as a measure of biofuel global warming impacts.

De Kleine et al. specifically challenge DeCicco's conclusions regarding biogenic carbon. They cite the United Nations Framework Convention on Climate Change (UNFCCC, 2006), which states "amounts of biomass used as fuel are included in the national energy consumption but the corresponding CO_2 emissions are not included in the national total as it is assumed that the biomass is produced in a sustainable manner. If the biomass is harvested at an unsustainable rate, net CO_2 emissions are accounted for as a loss of biomass stocks in the Land Use, Land-Use Change and Forestry Sector". This statement is consistent with the definition of net ecosystem production, used by both De Kleine et al. and by DeCicco. De Kleine et al. also note that this is consistent with the physical reality wherein the biogenic carbon in the fuel was recently absorbed from the atmosphere, and is cycling back to the atmosphere.

De Kleine et al. state that it is important to include both cropland and non-cropland ecosystems in the analysis, whereas DeCicco only used cropland (and in some cases, only a part of the available cropland). De Kleine et al. also state that, by the definition of NEP, the analysis also must include non-biological oxidation, which is not included in the analysis by DeCicco. De Kleine et al. also demonstrate that a single year shift in the baseline materially impacts the conclusion of DeCicco et al. regarding biogenic carbon. DeCicco used a baseline of 2005, and concluded that the NEP increase represented only 37% of the total increase in tailpipe emissions, and thus, the argument regarding biogenic emissions is not valid. De Kleine et al., by switching the baseline year to 2006, found that the net increase in NEP now <u>exceeded</u> the incremental tailpipe emissions by 38%. Their conclusion is that the DeCicco approach is not robust as a means to assess the merits of biogenic carbon assumption.

Most significantly, De Kleine et al. present the framework for a proper counterfactual analysis – a case in which there are no biofuels in the system. They calculate the change in carbon flow to the atmosphere in a scenario either with or without biofuels. While their analysis is admittedly simplified (also ignoring other carbon pools), they calculate that U.S. biofuel production in 2013 reduced net carbon flow to the atmosphere by 29 Tg C. While the final result is uncertain, this is the type of analysis that is needed to assess whether or not biofuels lead to a net reduction in CO_2 accumulation in the atmosphere, compared to the case without biofuels.

An additional critique, Mueller (2016)[67], focuses largely on similar issues to those already raised above. Mueller notes several concerns with the DeCicco approach, including: setting of system boundaries and lack of consideration of leakage; challenging causality between ethanol production, corn acres planted, and NEP; and failure to consider co-products of ethanol production. Regarding system boundaries and missing carbon pools, Mueller notes that DeCicco assumes no change in soil carbon stocks, whereas other data and models (e.g., CCLUB-GREET, based on county-level data) indicate an increase in soil carbon when cropland moves to higher corn rotations. Mueller notes that the expected increase in soil carbon (4.2 TgC/yr) would come close to balancing the 5 TgC/yr "gap" found by DeCicco, and thus demonstrates the necessity of complete accounting of carbon stocks/flows.

3.6 Leakage

Leakage occurs when a simplified stock and flow model is used, incorporating narrow system boundaries, or excluding key carbon pools. For example, a system may generate co-products that are exported outside the system boundary. Alternatively, carbon may be absorbed (or released) outside the system boundary, e.g., due to changes in land use and associated soil emissions triggered by change within the system boundaries, or CO_2 fertilization (increased NPP resulting from higher atmospheric CO_2 concentrations) of biomass outside the system boundaries. Leakage leads to a mass balance that is not closed (at least when focusing on material within the system boundary alone); a comprehensive Earth systems model, which includes all carbon pools and fluxes, would conceptually avoid the issue of leakage. Any carbon stock and flow model with a more restricted scope needs to consider the effects of leakage, which, given their dependence on global trade and economics, is extremely challenging. In LCA-based analysis, this issue is addressed via LUC modeling (see section 2.2).

4 Comparison of Methods: LCA versus Stock and Flow

Stock and flow modeling and LCA methods are fundamentally different, and each technique is designed to answer different questions. Here we explore some of the limitations and strengths of each technique, and discuss why both strategies are key to investigating questions of biofuels policy. We also discuss the data gaps and predominant sources of uncertainty that affect both methods. For the purposes of our discussion below, a stock and flow model (in its most rigorous form) is analogous to a comprehensive ESM, accounting for all relevant pools in which carbon stocks may be present, and all relevant exchanges (flows) between these pools. However, given the complexity of ESMs, simplified stock and flow models that exclude certain pools or have a narrower geographic boundary are more likely to be applied.

4.1 Time

One important difference between LCA and stock and flow-based models is their treatment of time. In LCA, time is considered to be the lifecycle of the product; for annually harvested crop-based biofuels, this period is approximately one year. For that reason, policymakers typically amortize LUC emissions to give an annual emissions value that can be combined with the aLCA results for biofuels production. In the US, the chosen amortization period is 30 years. This choice is arbitrary, and given that many types of LUC constitute up-front carbon releases, using amortized emissions from LUC likely underestimates climate-forcing effects to some degree[12]. Stock and flow models, on the other hand, have the potential to capture the time-based aspects of carbon flows/emissions [the accuracy of these predictions depends upon the structure of the stock and flow model, its parameters, and the assumed boundary conditions]. Given that climate impacts are highly sensitive to feedback, this theoretically makes stock and flow models a better tool for comparing long-term climate effects of policy changes.

4.2 Product Focus versus Reservoir Focus

aLCA is a product- and flow-focused technique. Stock and flow modeling, on the other hand, is primarily focused on reservoirs and changes in reservoir stocks. While aLCA is poorly set-up to deal with the timing of flows, its strength is in accounting for the inputs and outputs associated with producing a unit of product. Stock and flow modeling, for example, is unable to predict changes in animal feed production or energy demand associated with an increase in biofuels production, because it is not designed to account for the flows associated with production. LCA, on the other hand, cannot be used as an accounting system to track carbon credits and debits. In order to predict the effect of changes in biofuels production, both types of modeling are required; LCA to estimate the associated resource demands and co-products, and stock and flow modeling to link those changes to carbon stock and resulting climate changes. The inclusion of cLCA/LUC modeling in biofuels policy, as well as the use of

LCA techniques in forest carbon stock and flow modeling, is an acknowledgement of the necessity of both LCA and stock and flow modeling for policy decision-making.

4.3 Land Use Change and Carbon Debt

As discussed in section 2.2, LUC modeling is, fundamentally, a type of predictive stock and flow modeling driven by economic parameters, albeit essentially restricted to emissions from the soil and biomass carbon stocks to the atmosphere. LUC models are intended to predict how much carbon will be absorbed or emitted to the atmosphere, given LUC projected by modelling economic response to a change of supply and demand within the system. The carbon emissions from LUC associated with biofuel production represent either lost opportunities for CO_2 sequestration, or C/CO_2 lost from soil. Depending upon the timing and/or circumstances, this may also lead to a biofuel's "carbon debt". If, for instance, a forest is converted to corn production for bioethanol, or additional forest land is brought into production to produce wood pellets, the land conversion can lead to a short-term (or long-term) release of CO_2 from the soil and biomass carbon pools to the atmosphere. If the CO_2 release occurs over a short period of time (such as the case for peatland conversion), a carbon debt may occur, wherein there is a short-term or medium-term penalty (or debt) from increased CO_2 in the atmosphere, until eventually the cumulative CO_2 released from land use change is offset by lower CO_2 emissions from the ongoing use of a lower carbon intensity fuel or product. The challenge associated with such a carbon debt is that the timing of CO_2 release to the atmosphere may matter a great deal in terms of climate impacts.

4.4 Climate Feedbacks

The carbon cycle is ultimately affected by feedback amongst several key processes and activities. For example, higher atmospheric levels of CO_2 are projected to cause an increase in temperature. However, elevated temperatures and CO_2 concentrations also promote greater biomass growth, removing CO_2 from the atmosphere. Furthermore, decomposition rates for litter (dead biomass) and rates of soil carbon release are also affected by temperature. The water cycle is also affected by temperature and atmospheric CO_2; in turn, the water cycle affects biomass growth, and the release of CO_2 from soil.

Models vary with respect to the extent to which such feedbacks are captured. An ESM without a climate model would miss key feedback mechanisms. Similarly, a simplified stock and flow model that focuses, e.g., on vegetation and atmospheric CO_2 could miss key feedback arising from exchanges with soil and water. Consequently, the structure, scope, and system boundaries of a stock and flow model are vitally important.

4.5 Policy Considerations

Key global biofuel policies that incorporate life cycle assessment estimates of the carbon intensity of biofuels include the US Renewable Fuel Standard 2 (RFS2), Low Carbon Fuel Standards implemented in California, Oregon, and British Columbia (CA-LCFS, OR-LCFS, BC-LCFS), and the European Renewable Energy Directive / Fuel Quality Directive (EU-RED/FQD). Overall, LCA methods used within these policies are based on an aLCA approach. Some policies, notably the RFS2, CA-LCFS, and OR-LCFS, take a partial cLCA approach by include estimates of land use change (LUC), thereby integrating stock-and-flow model principles with LCA concepts. Implementation of LUC models, however, is subject to substantial uncertainty and vigorous debate, with estimates of LUC emissions varying by more than 400% between different modelling techniques arising from uncertainty and resolution of carbon stock data, economic model parameters, predicting location of land use change, and treatment of co-products.

To date, no policy has attempted to implement a comprehensive global stock and flow model to assess the carbon intensity of biofuels. As we discuss here and in Section 4.6, there are significant barriers to developing a usable stock and flow model that could provide accurate and predictive insights to improve carbon intensity estimates in biofuel policies relative to current practices or to quantify the overall impact of biofuels policies on atmospheric CO_2 and climate.

LCA models and stock and flow models address different questions with respect to the effectiveness of alternative energy sources to reduce or exacerbate climate change. aLCA does not account for temporal effects, nor climate feedbacks, and is, in essence, used for steady state comparison of the renewable fuel to a petroleum-based fuel. Some consequential/indirect effects, such as land-use change, may be added to aLCA to provide a broader picture of the relative impacts of an alternative energy source versus conventional sources.

Compared to aLCA, which tracks flows of CO_2 equivalents (CO_2eq) for a process, (usually normalized per unit of energy in the fuel, and including some embedded assumptions about the carbon neutrality of biomass and land use effects), an integrated LCA/stock and flow model has the potential to calculate the rate of, or total accumulation or depletion of, carbon/CO_2 in different pools, including the atmosphere, and the consequent time-dependent climate feedback effects not included in aLCA models, even those incorporating LUC. Consequently, stock and flow models, when linked with aLCA, have the potential to address important policy questions, such as, “if we adopt a policy that will result in the use of a specific quantity of renewable fuel, what is the predicted change in the atmospheric stock of carbon, over time?”

In stock and flow models, all carbon is (in principle) tracked as it moves from one stock/pool to another, and by considering carbon flows to/from all carbon pools, these models can track changes in the atmospheric stock of CO_2. There is interplay between atmospheric CO_2, temperature, and rainfall that can all impact NPP, and the corresponding changes in transfer of carbon between pools that must be considered. For example, in order to achieve a decrease in atmospheric CO_2, there must be an increase in net primary production (NPP) or some other sequestration process to take the carbon from the atmosphere. However, policies with stated aims of reducing GHG emissions may not plan to reduce atmospheric CO_2, but rather, to reduce the flow of CO_2 to the atmosphere relative to "business as usual". When considering policy development, it is also important to consider the counterfactual case, i.e., continued use of the fossil fuel (see section 2.3). Most renewable energy sources will lead to an increase in atmospheric CO_2 levels: e.g., the production of photovoltaic panels will result in CO_2 emissions to atmosphere due to material and energy inputs. However, if the continued use of fossil fuels leads to an even greater increase in atmospheric CO_2, then the renewable energy source will still contribute to reducing the rate of increase of atmospheric CO_2 stock, and help to prevent concentrations from rising above a certain level.

Previous applications of stock and flow models to harvested wood products have also included LCA calculations or data from LCA models to account for energy inputs for feedstocks or processing, or to account for co-products. Similarly, a question such as, "from a carbon perspective, should we cut down all of the world's forests and replace them with biofuels plantations?" requires both stock and flow modelling and aLCA to answer (see section 3.2).

LCA is appropriate (and useful) when the focus is on a product, whereas stock and flow models are valuable when tracking a specific component, or output. In the case of biofuels, the LCA focuses on the fuel product, whereas the component of interest in the stock and flow model is carbon, or CO_2.

One can debate whether or not an LCA calculation provides the "right" answer (even for a well-defined system, the result will vary). Likewise, it is possible to debate the outcome from a stock and flow model, because the results will depend upon the pools used to track stocks, the accuracy of models (and parameters) used to predict exchanges (flows) between pools, and other factors that can affect the size/capacity of a pool and exchange rates/fluxes. Boundary conditions are important in both types of models, to account for flows of mass, or energy, or specific components across the system boundary and to avoid "leakage". A poorly constructed stock and flow model is unlikely to provide an accurate result, or be useful. Meanwhile, to obtain "accurate" results from a stock and flow model, a comprehensive global model may be required, which has enormous data requirements to address the geospatial heterogeneity in carbon pools and fluxes.

4.6 Data Requirements, Data Gaps, Model and Data Uncertainty

The quality of the results from any modelling effort depends upon the model structure, underlying data, and assumptions. LCA, Stock and Flow models, Earth System models, and climate models each face particular challenges. It is important to recognize the magnitude and sources of uncertainty in any model result, and the degree of certainty needed to support a policy or policy outcome.

LCA is a well-established tool, but even for well-known pathways and established industries, there is uncertainty in the results due to operational and geographical factors, assumptions regarding treatment of co-products, and variations in agricultural or forestry operations. Additional uncertainty arises when consequential effects are added, such as induced land use change. One advantage of aLCA is the fact that it is governed by an ISO standard, which dictates methodology and selection of boundary conditions. An aLCA model, while based upon carbon accounting, has a relatively straightforward system definition, and data requirements are manageable.

By comparison, stock and flow models have been used to a lesser extent, and have not been investigated to the same depth as LCA for application to biofuels systems. Work is needed among the research community to identify common ground regarding model structure and complexity, boundary conditions, and the importance of capturing certain phenomena that contribute to feedback, affecting the distribution of carbon among pools. An extreme benchmark/case would be to adopt the structure of Earth system models, which aim to track carbon around the globe in various key pools. While this goal is laudable, and important, the complexity of ESMs and the lack of sufficient data can affect the model output and seriously affect the conclusions drawn from these data and model results. If we hold stock and flow models to the standard of an ESM, it will be a long time before these models can be employed to monitor the distribution of carbon in the biosphere, and the data requirements will be unmanageable. Acceptable *simplified* structures are needed for stock and flow models, perhaps balancing loss of resolution or precision against computational complexity and data intensity. In such a case, it is important to acknowledge the limitations of a simplified stock and flow model. If the stock and flow model simplification is based upon narrower system boundaries, or a narrower subset of pools for carbon, then it is fundamentally important to understand the magnitude of and consequences of "leakage" across the system boundary. Conclusions derived from use of these simplified models must be "qualified" due to these limitations.

An example of a possible simplification to a stock and flow model may be to lump all biomass into a single type, with a weighted average rate of CO_2 uptake from the atmosphere. Other options include separate pools for woody biomass versus grasses and agricultural crops, or perhaps geographical variations for a single (class of) species, reflecting growth rates in different climate zones, and different initial capacities of these pools. Until work is done to investigate these options, and quantify the resulting uncertainty or loss of resolution that may arise, it is difficult to determine if such simplifications may be acceptable in terms of impact upon model results. It does seem that some of these attributes have already been incorporated into LUC models (e.g., AEZ models of soil carbon), and this may be a useful starting point to evaluate suitability for stock and flow models. We note that, besides LUC models, some other simplified models, such as the C-ROADS SCM used by Sterman (2018)[31], do exist and are being used by researchers in combination with LCA concepts to study bioenergy questions; however, in reviewing the literature, we did not identify any studies that evaluated the implications of using these simplifying assumptions on the study results. We also note that scenario modeling is highly dependent on modeling future economic conditions, for both the "change" case and for the "counterfactual" case; given the inherent uncertainties in economic modeling, SCMs may be a sufficiently good representation of ESMs and climate models for the purposes of evaluating future biofuels use scenarios.

Data gaps associated with the use of stock and flow models depend upon the context and application for the model. Agriculturally based products will have different data requirements than products based upon forest biomass, or municipal solid wastes. Geography will also be important – the extent to which regional temperatures, rainfall, and soil conditions impact results predicting carbon exchange between pools will also depend upon the application and scale of implementation. Furthermore, plant growth is affected by the presence/absence of other nutrients. An important knowledge gap that needs to be addressed is the relationship between the carbon cycle, and cycles for nitrogen, phosphorus, and potassium. These relationships may be affected by geography, soil and climate.

As these stock and flow models are developed (either in simplified or more complex forms), it will be critical to take steps to validate the model predictions. It will be important to recognize that a perfect description will be impossible to achieve; however, it may be possible to obtain an acceptable result, either in terms of magnitude, direction, or trend. Determining what is sufficient or acceptable will also depend upon the application, the context/objective of the modelling effort, and the degree of uncertainty that can be tolerated. It will also be important to validate models based upon their predictive capability, and not just adherence to historical data. A model may correlate data well, but for the wrong reasons, leading to uncertainty (or cross-correlations) in parameter estimates. The ability to *predict temporal trends* provides a higher degree of confidence than parameter estimation of historical data under quasi-steady state conditions.

5 Conclusions

Stock and flow and LCA models both play an important and complementary role in the analysis of biofuel systems. Stock and flow models have the capability of predicting dynamic changes in carbon stocks in various regions of the ecosphere, and in particular, could be valuable for tracking changes in atmospheric CO_2, and corresponding impacts on climate. LCA models are suitable for analysis of products, tracking emissions or energy use for new products compared to an existing product, or comparisons of new processes to make existing products. Stock and flow and LCA models have fundamentally different structures, significant but different sources of uncertainty, and address different, yet important questions.

While there is growing use of stock and flow approaches to track carbon, the models developed and used vary substantially in terms of boundary conditions and carbon pools included. These assumptions can lead to missing carbon, due to materials such as co-products that cross the system boundary, exclusion of key processes that may transform carbon into CO_2 (or vice versa), or exclusion of external carbon pools that are relevant sinks or sources. These forms of "leakage", if not adequately accounted for, can materially impact the results of a stock and flow modelling effort, and conclusions derived therefrom.

Earth system models (ESMs) represent the most comprehensive effort to track carbon stocks and flows, and represent the ultimate stock and flow model for carbon accounting. Accounting for carbon stocks and flows globally eliminates the problem of leakage. ESMs, however, suffer from massive data requirements, can generate contradictory results, have a high degree of uncertainty in both parameters and model results, and have not been adequately validated. Ongoing work to address these issues is needed, and important to complete, before such models can be used to assess the impacts of biofuels and bioenergy on the Earth's carbon cycle and climate.

Simplified stock and flow models have been developed to evaluate issues related to biofuels, bioenergy, and bioproducts, especially within the realm of harvested wood products. In some cases, these simplified stock and flow models have been combined with LCA in an effort to account for co-products, energy flows, and other transfers across the system boundaries. While the simplifications employed by these models render the stock and flow calculations much simpler, and reduce data requirements, they may lead to even greater uncertainty in parameters and results, and a greater need to accurately track leakage. The conclusions from several of these publications are consequently subject to much debate.

An important next step to foster use of stock and flow models would be for key researchers within the space to develop some consensus regarding appropriate system boundaries, use of a consistent set of pools for carbon, models or data sources to account for exchange of carbon between pools, methods to handle co-products, and methods to account for leakage. If a consistent framework can be developed (as has been done for LCA), the interpretation of results from stock and flow models will be improved dramatically.

Another urgent need is to address the geospatial heterogeneity in data available for stock and flow models. Improvements to these data could also improve estimates from current models of induced land use change (ILUC), which rely on a combination of economics models and models of biomass and soil in various agroeconomic zones, and constitute a simplified application of stock and flow modeling. The wide uncertainty in LUC values for various pathways is in large part due to widely varying estimates of carbon emissions from so-called "carbon hot spots". There is similar uncertainty regarding release or sequestration of carbon from forests, depending upon geography and the age and type of trees. Publications have reached dramatically different conclusions regarding the use of forest biomass, even thinnings, for biofuels and bioenergy. The differences in conclusions typically relate to assumptions about biomass growth rates, and thus, the rate of CO_2 removal from the atmosphere. Addressing these uncertainties would improve predictions from a carbon stock and flow model, and also for LCA models wherein ILUC is added to the estimate.

The analysis and recommendations of Ajani et al. are particularly useful and insightful. They note the importance of distinguishing geocarbon from biocarbon, accurate measurement of biocarbon reservoir capacity in a multitude of pools, and the need to develop baseline data for a network of land units that includes land use history, ecosystem information, current and historical carbon stocks, annual emissions, and annual removals. They also note the importance of distinguishing between (and separately accounting for) biocarbon that has short-term versus long-term stability (e.g., agricultural crops versus forests).

Improvements to stock and flow models could help to address ongoing questions about carbon debt, crediting of biogenic carbon, and near-term versus long-term impacts of any transition to biofuels and bioenergy. In-depth development of data and corresponding analysis of carbon stocks and flows has the potential to address important questions such as the trade-offs between use of land for food or fiber production versus managing land to sequester carbon. Similarly, it may be possible to set priorities for land restoration by reforestation or improved land management.

From a policy perspective, there is a critical need to analyze a counterfactual case, irrespective of whether a stock and flow model or LCA model is used. In conventional LCA, it is common to compare the predicted emissions versus a petroleum- or fossil-derived counterpart. Similarly, when developing a stock and flow model to track, say, atmospheric CO_2, it is important to examine a "business as usual" case alongside the analysis of the case that includes the biofuel, bioenergy source, or bioproduct. It is conceivable, even likely, that atmospheric CO_2 levels will continue to rise when biofuels are deployed; the main question is whether or not the increase is attenuated relative to the business as usual case wherein geocarbon continues to be released into the atmosphere at the rates predicted in the absence of increased biofuels use. Selection of a counterfactual, however, is subjective and varying interpretations of "business as usual" have led prior studies to reach very different conclusions about forest biomass use for bioenergy applications. A well-developed stock and flow model also has the potential to account for climate feedbacks on the carbon cycle (and vice versa), whereas aLCA cannot.

Substantial development of stock and flow modelling approaches must be undertaken to achieve a tool capable of tracking and predicting changes in atmospheric CO_2 and corresponding climate impacts. As such, it is not straightforward to prescribe specific action items to progress model development. The key areas for ongoing focus include:

1. **Development of a consistent stock-and-flow framework:** Develop consensus among key researchers regarding setting system boundaries, methods to account for leakage across system boundaries, methods to account co-products, and consistent datasets/model approaches for estimating carbon pools and carbon flows.
2. **Improvement of data collection and verification:** Improve the resolution and reduce uncertainty of data for carbon pools and carbon flows to/from terrestrial carbon pools, through greater data collection and improved correlation between remote monitoring and modeling approaches with actual carbon stocks/flows.
3. **Development of policy-relevant applications of stock-and-flow models:** Establish best practices for stock-and-flow model application, including selecting "business as usual" counterfactuals for policy evaluation. Incorporate temporal effects and climate feedback on carbon cycle (and vice versa), providing greater insights on the overall impact of biofuel policies on carbon stocks/flows and climate.

There is an important role for stock and flow models in the analysis of biofuels and bioenergy; with important advantages due to their potential to predict temporal changes in atmospheric CO_2. However, stock and flow models cannot replace LCA models; neither can LCA replace stock and flow models. Indeed, simplified stock and flow models rely on LCA to track materials and energy that cross system boundaries, and many LCA-based policies include LUC values derived from a simplified stock and flow model. Each type of analysis provides complementary information of value for policy development and evaluation.

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Appendix A

Additional Literature Review Information

Additional Earth System Models (ESMs) Literature Review Information

Smith et al.[68] developed a global terrestrial C model with model data/constraints from 12 datasets of stocks/flows, imposing constraints and probability distributions on key parameters. They claim that terrestrial vegetation accounts for about 60% of the annual flux in atmospheric C. They also note that there are vastly different predictions arising from different models, and the initial assumptions have not been validated, in spite of updates to the original models to add more details or processes. The model is formulated as a set of ODEs, assuming carbon pools in dynamic equilibrium. Six carbon pools are included – leaves, fine roots, structural plant parts, and three pools in the soil, corresponding to metabolic, structural, and recalcitrant fractions. They note that the ability to predict equilibrium data of the terrestrial C cycle does not imply that the model/parameters can represent temporal dynamics. They also note that model constraints based upon historical data may not apply when predicting future scenarios.

Luo et al.[33] examined 11 Earth system models (ESMs). This is based upon the need to accurately predict the dynamics of the terrestrial C cycle, and predict future changes to Earth's climate. However, "none of the 11 Earth system models…could accurately predict patterns of soil carbon across the global land surface". There is a similar issue with models of gross primary production. In spite of collection of more geospatial data and experimentation, there has been essentially no improvement in the predictive capability of the models. Even amongst so-called "equivalent" models, initial values of carbon pool sizes differ by 250 to 600 %.

Luo et al. note the importance of coupling the C cycle models with models of N and P cycling. These processes have a greater impact on temporal aspects, but long term, leaf area index reaches a maximum, minimizing the effect of N and P. This is consistent with the perception that "one of the most widely observed properties of the terrestrial carbon dynamics is that total carbon tends to converge over time to some form of equilibrium". The authors suggest that cyclic patterns of photosynthesis are well-predicted via models of leaf-level responses to light, T, water, and respiration responses to environmental variations are also well described. However, the impact of disturbances (e.g., fires) and mechanisms of inter-annual variability in the C cycle are not well understood. Longer-term disturbances may have a stochastic element and require long-term data to establish frequency and severity. These disturbances may result in a gradual return to the original equilibrium state, or a new equilibrium state may result. The basic conclusion is that these ESMs (and underlying models and data) are inadequate for predicting the dynamics of the C cycle and climate.

Huntzinger et al. (2017)[35] compared an ensemble of 12 models of the global C cycle, with dramatically different representations of land-atmosphere C dynamics. The models also vary dramatically in terms of the magnitude of impact of CO_2 fertilization and historical land cover on cumulative land C uptake. This leads to a difference of up to 200 Pg C in estimated land C accumulation. Including N coupling reduced terrestrial C uptake by about one third, indicating the importance of N as a constraint on CO_2 fertilization. Major geospatial differences, especially in the tropics and at the poles, create challenges. Models predict dramatically different drivers of cumulative C uptake; CO_2 fertilization may be a minor or major driver of vegetated land area. Model tuning may compensate for uncertainties and gaps by altering parameters that represent CO_2-climate sensitivity. The GTEC and TEM6 models predict the same historical land uptake of C, but differ by >200% in their sensitivities, which lead to dramatically different predictions of responses to changes in global (or regional) temperature and atmospheric CO_2. **Models consistent with global constraints may end up with the right answer (from historical data) for the wrong reason, which implies limited usefulness to predict future climate, temperature, atmospheric CO_2, and C pools**. The authors state that "improvements in terrestrial C cycle (and thus climate) predictability require that the models not only produce the right end points…but also the correct pathways to those endpoints" "*We should be very cautious about interpreting the results from a single model, when there is significant breadth in potential responses and dearth of observations that can truly validate which response is correct*."

Additional comparisons of ESMs were conducted by Anav et al. (2013)[36] and Aparicio et al. (2015)[37]. Anav et al. compared 18 Earth system models (from CMIP) and ranked them based on their ability to simulate the land and ocean carbon cycles for our present climate. The authors found that the models correctly reproduce the main climatic variables that control spatial and temporal characteristics of the carbon cycle, but they do not reproduce some specific aspects of the land carbon cycle, and in particular, overestimate photosynthesis and leaf area index. Furthermore, the results were sensitive to reference data and regional variations. Aparicio et al. compared 12 Earth systems models (also from CMIP) used to project trends in vegetation productivity and carbon storage; they also noted major uncertainty in their long-term predictions.

Zhang et al. (2014)[69] noted that most ESMs exclude limitations due to N and P, which is important since these are essential for growth, and may reduce CO_2 uptake in vegetation if levels are insufficient. Per their model, N limitations reduced global C uptake on land by about 40%. If land C uptake is reduced, this leads to CO_2 accumulation in the atmosphere. The effects of N/P limitation represent about 125 to 287 Pg of C, compared to about 55 to 60 Pg C due to land use change. Similarly, Meiyappan et al. (2015)[70] looked at the effect of N limitation on emissions for several different climate scenarios from 1900-2011, and concluded that estimates that ignore N limitation underestimate emissions due to LUC by 34–52 Pg C (20–30%) during the 20th century and 128–187 Pg C (90–150%) during the 21st century.

Landry et al. (2017)[71] evaluated the impact of recalcitrant pyrogenic carbon in a climate-carbon model. Pyrogenic carbon is produced from incomplete combustion of vegetation or organic carbon during fires. Pyrogenic carbon (also known as black carbon and biochar) decomposes more slowly than regular vegetation, and thus is sometimes (incorrectly) considered a carbon sink. As fires become more frequent, more pyrogenic carbon would be produced. Cycling of pyrogenic carbon is expected to reduce accumulation of CO_2 in the atmosphere due to delayed/slower release from this modified vegetation pool. Only some models contain "fire modules" that estimate burned vegetation area and C emissions. Adding a pyrogenic C module reduces the amount of C emitted as CO_2 to the atmosphere. However, there is great uncertainty in parameters representing production and degradation of pyrogenic C. The size of pyrogenic C pools and fluxes varied by at least 2 orders of magnitude. Pyrogenic carbon cycling is expected to reduce atmospheric CO_2 by 0.3 to 39.7 Pg C (variation mainly due to the amount of pyrogenic C in soil). Major gaps in knowledge regarding decomposition rate, amount of pyrogenic C, and heterogeneity of pyrogenic C pools still have to be addressed.

Hajima et al. (2014)[72] investigated concentration-C and climate-C feedbacks in ESMs. Concentration-C feedback results from increased CO_2 in the atmosphere, and Climate-C represents release of CO_2 to the atmosphere from ecosystem respiration. They suggest that concentration-C feedback is about 4.5 times greater than climate-C feedback. The authors note large uncertainty in C-cycle feedback, especially concentration-C feedback and exchange between atmosphere and land. The degree/strength of concentration-carbon feedback seems to be non-linear, or at least, depends upon the CO_2 concentrations assumed in the different scenarios. ESMs predict materially different changes to terrestrial C, depending upon the assumed rate of CO_2 increase. Over a 140-year period, the ESMs project gross primary production (GPP) and NPP values that vary by up to an order of magnitude, and land carbon accumulation varying by up to a factor of six. Uncertainty in GPP may be due to greater allocation of C to leaf (which means more leaf area), or due to more sensitive modelling of leaf-scale photosynthesis (i.e., photosynthesis rate). Authors state that limited data availability prevents detailed analysis of GPP. They also note the strong correlation between parameters; for example, the change in litter decomposition rate relative to change in soil carbon and the change in soil carbon relative to vegetation carbon are not independent. In all 8 ESMs studied, elevated atmospheric CO_2 led to a continuous increase in land and soil carbon, in essence, a CO_2 fertilization effect that increased net primary productivity, producing more biomass. While these trends were common among all ESMs, the sensitivity of each model to elevated CO_2 varied greatly. Models that predicted a greater change in net primary productivity also predicted a greater change in terrestrial carbon. Similarly, changes in respiration rate were correlated with changes in net primary productivity. Two ESMs included the N-cycle, but results from these models were not materially different from results obtained from ESM models that excluded the N-cycle. The land carbon allocation between vegetation and soil was subject to the largest spread (i.e., uncertainty relative to the mean value). Close behind was uncertainty in the change in GPP relative to changes in atmospheric CO_2, and uncertainty in change of vegetative carbon relative to change in NPP. The parameters that affect global primary production varied by up to a factor of 6, and a factor of 4 difference in parameters representing respiration. Such model-specific differences will impact the response to elevated CO_2, temperature, and temporal effects. Carbon pools with a slow turnover rate (soil and land) were much more sensitive to the rate of CO_2 increase, with more carbon uptake into the soil when the rate of CO_2 increase was lower. More data/evidence from free-air CO_2

enrichment experiments would help improve modelling of the relationship between CO_2 and photosynthesis, leaf area index, and plant productivity.

The literature also includes terrestrial ecosystem models (TEMs), which are narrower in geographic scope than Earth systems models (ESMs) that account for global phenomena. Vegetation/land models coupled with climate are also reported, in which changes in vegetation growth might be estimated in response to climate parameters (temperature, atmospheric CO_2). These vegetation/land models may be incorporated within TEMs and ESMs. Some examples of models include:

- LPJ-GUESS: A dynamic vegetation model, but does not account for the interdependence of some feedbacks and does not project well into the future (see Ahlstrom et al. (2015)[73]).
- Coupled Model Intercomparison Project Phase 5 (CMIP5): Includes a set of Earth system models (ESMs). The models represent the 20th century carbon cycle over the land and ocean. They also contain the main climatic variables that impact the carbon cycle.
- National Center for Atmospheric Research Community Climate System Model version 4 (NCAR CCSM4) – Coupled climate-carbon model that consists of atmosphere, land, ocean, and sea-ice that are connected through exchanges of state information and fluxes. It uses the Community Land Model version 4 (CLM 4). The CLM land component of the model includes carbon-nitrogen biogeochemistry with prognostic carbon and nitrogen in vegetation, litter, and soil organic matter. They also track total ecosystem carbon (TEC), which is the sum of all terrestrial carbon. A limitation of the model is that it does not have representation of high latitude permafrost carbon reservoirs which contain a large quantity of organic carbon matter.
- Carbon Exchanges in Vegetation-Soil-Atmosphere (CEVSA): Models temporal and spatial variations in generated carbon storage and fluxes. These are then related to climate variability and land use and cover, as well as net primary production (NPP), heterotrophic respiration, net ecosystem production (NEP), storage and soil carbon, and vegetation carbon. The CEVSA model cannot account for land use and land cover change from remote sensing data, does not simulate changes in soil physical structures, and the hydrological cycle changes are not connected.
- LM3V-N: A global land model that can resolve C-N interactions using a grid approach.

Terrestrial Ecosystem Models (TEMs)

Li et al. (2017)[74] optimized parameters of a terrestrial ecosystem model (TEM) for 6 forest sites in China. The authors noted uncertainties in results due to model structure, definition of initial conditions, spatial resolution, parameter values, and climate forcing. State of the art C cycle models adequately represent the qualitative behaviour of the terrestrial ecosystem, but are unable to reproduce the observed response of the C cycle to climate variability, either temporally or spatially. They used the ORCHIDEE TEM to estimate parameters related to photosynthesis, respiration and phenology using eddy covariance data from 6 forest sites in China, representing different forest types. They noted that gross primary production (GPP) was underestimated at 5 of the 6 sites when using the “baseline” parameters, but resolved after optimization to better predict water and C fluxes. The effect of temperature on GPP and photosynthesis rate has a material effect on NPP. Sensitivity of soil respiration rate to temperature was also significant. They also note that there is an issue with initial estimates of soil organic carbon (SOC) – the assumption of equilibrium forces the model to predict similar SOC densities across all sites, and overestimate initial SOC. Optimizing parameters leads to a lower initial size of the soil C pool, allowing these regions to act as a sink for future carbon. The SOC density is extrapolated from a network of spatial SOC measurements, but accurate SOC measurements specific to these forest sites are needed. This is also an issue with other forest sites around the world. There is also clearly cross-correlation between parameters, e.g., the sensitivity of respiration rate to temperature depends upon the parameter values quantifying initial soil C. NPP also responds differently to changes in precipitation, depending upon the site. There is large uncertainty in the magnitude and seasonal variations of Leaf Area Index (LAI) between datasets. Authors note the need to improve simulation of (and presumably data for) canopy structure and C allocation to foliage. These observations point to the need for highly site-specific data on soil type, initial soil C, other nutrients, forest type, forest age, location, seasonal variations. ORCHIDEE, like other models, does not seem to accurately represent slow changes to C pools or low rates of C exchange. ORCHIDEE does not account for variations in photosynthetic processes as the forest ages.

Additional Soil Carbon and Forest Carbon Aspect Literature Review Information

Forest Carbon

Forests are an important pool in the carbon cycle, accumulating carbon in above-ground biomass during growth, and transferring carbon to the soil via roots or decomposition of leaves, branches, and other litter. There have been longstanding efforts to quantify the area covered by forests, along with their age and the diverse types of trees that may be present. Most countries have adopted forest management plans to ensure that harvested wood is replenished, and that the harvest and (re-)growth cycles are matched, to avoid long-term deforestation. As concerns regarding climate have mounted, greater attention has been paid to carbon stocks in forests, with more concerted attempts to limit deforestation, and in some cases, promotion of afforestation. Forests thus represent a simple example of the application of stock and flow concepts.

A wide range of literature was reviewed pertaining to forest carbon stocks and flows. These studies have been focused on strategies to increase forest carbon stocks (“forest carbon sequestration”) to evaluate stocks and flows of carbon stored in harvested wood products (“HWP”) such as timber and paper, and, to a lesser extent, to evaluate the implications of forest-based bioenergy production. Accounting for forest carbon stocks is well established, with guidelines developed by IPCC as well as the UNFCCC (i.e., the Kyoto Protocol). Several studies focus on evaluating implications of these accounting rules from the perspective of specific countries in the context of forest carbon sequestration and harvested wood products. These guidelines provide some useful insights for more broadly considering the application of carbon stock and flow models to bioenergy systems within the forestry sector and in other sectors. Some literature is focused on forest carbon stock measurement techniques, including plot-based sampling, remote monitoring, and approaches to incorporate this information in regional-scale models. Uncertainties in assessing carbon stocks are also relevant for non-forestry land management and for the development of carbon stock and flow models in general.

Forest carbon stock and flow assessments

Numerous studies evaluated forest carbon stocks and the implications of forest and land management on carbon accumulation in soil and biomass pools. Estimation of carbon stocks in forests is undertaken with a combination of approaches, including allometric modelling (based on stand characteristics such as species composition, stand age, soil/climate characteristics, height, diameter at breast height, etc.); ecosystem process models; field inventory plot measurements; and remote sensing. Several studies note the potential role of forests for sequestering atmospheric carbon. However, Mackey et al (2013)[38] caution on the potential role of terrestrial carbon stocks in mitigating greenhouse gas emissions, noting that: 1) the potential to increase carbon stocks is far less than potential emissions from fossil fuels; and 2) permanence of storage on timescales of 10,000 years highly uncertain.

Allometric models are based on empirical correlations between forest stand characteristics and/or single tree measurements and carbon stored in biomass pools. Applications of allometric models can be validated with plot sampling to account for the high spatial variability of site characteristics, management practices, and resulting carbon stocks (e.g., Haywood and Stone (2017)[75]). However, frequently these approaches are used without explicit consideration of how variability or uncertainty would impact overall results (e.g., Jasinevicius et al. (2017)[26]).

Studies of forest bioenergy have considered either stand-level or landscape-level spatial perspectives. Stand-level assessments consider a single plot of land which is harvested (or otherwise subject to disturbance) at a single point in time, tracking the immediate removal of carbon from forest and transfer of a portion of the carbon to product pools, followed by the accumulation of carbon in subsequent biomass growth over time. In contrast, a landscape-level perspective simultaneously considers a patchwork of stands, some of which may be harvested at a particular point in time and others that will be undisturbed. Carbon flows associated with forest management occur at different points in time, thereby making the temporal scope of the analysis important. Growing forests accumulate carbon over the course of decades or longer; as such there may be a significant delay before achieving carbon sequestration objectives of actions undertaken to increase forest carbon stocks. Conversely, removal of carbon through harvest for bioenergy or other applications will be compensated by regrowth occurring over similar timescales (although, as noted above, how this is accounted for depends on the spatial scope of the analysis). Timmons et al. state that the removal of old-growth forest biomass creates an opportunity for new and fast sequestration as old-growth carbon uptake asymptotically reaches zero, while also claiming that "as the forest harvest releases carbon to the atmosphere, it also increases the capacity of the forest carbon sink, which has value for future carbon sequestration"[30].

GHG emissions associated with HWP will occur at different points in time: immediate (production impacts/emissions; displacement of alternative products); and medium- to long-term when products reach their end-of-life and are recycled or disposed of.

Ecosystem process models are used to estimate the flow of carbon between soil, living biomass, dead biomass, and atmosphere via respiration. Empirically-informed ecosystem process models base estimates of biomass productivity on the biomass increment and replacement of biomass turnover[39] or with direct measurement of carbon flux from field trials and eddy flux observation sites[40]. These models have been employed to estimate how, for example, changes in climate may impact the uptake of carbon in forests[41], how forest management may impact forest carbon stocks[42], and how spatial variability influences carbon stocks[43].

Remote sensing includes a range of techniques based on the reflection of solar radiation (passive) or transmitted radiation (active), with spatial resolutions ranging from <5m to >250m that are then converted to estimates of important forest characteristics based on location-specific field trial data[45]. Authors have used these correlations to understand how disturbances (including harvest) impact forest carbon stocks[76]. The impact of fires on forest carbon stocks is also an important consideration; similarly, pest infestations can materially impact forest growth and carbon stocks. Some of these disturbances are cyclic, while others are random, creating challenges when aiming to integrate these factors into global earth systems models.

Baker et al. (2010)[44] note the data limitations that prevent accurate assessment of forest carbon stocks to use in national and international carbon accounting schemes and also highlight scientific uncertainty associated with statistical and modelling approaches. The authors recommend increased forest carbon measurement reporting and verification to address these knowledge gaps. Uncertainty in forest carbon stock data is a significant issue that has been raised by several of the evaluated papers. Andersson et al. (2009)[45] note uncertainty estimates on the order of 25% in prior studies, and highlight 60% uncertainty in estimating changes in national carbon stocks. In a study of forests in Panama, Asner et al. (2013)[77] estimated a 10% uncertainty in carbon stocks, corresponding to >20tC/ha. Bustamante et al. (2016)[46] also note significant uncertainty in carbon stock estimates, citing prior studies that quantified a >50% uncertainty in estimating carbon stocks of mature forests[47].

Timmons et al. evaluated forest biomass energy [30], using input data from Forest Inventory Analysis (FIA) in the US Forest Service Forest Vegetation Simulator (FVS). They observed that the FVS simulation has high degree of accuracy for growth periods between 30 to 50 years, but was unreliable for prediction of aboveground live carbon accumulation rate for northeastern US late-successional growth and old-growth forest.

These uncertainties materially affect calculations in ESMs, and may result in different predictions of forest carbon, soil carbon, and atmospheric CO_2.

Soil Carbon

Soil Carbon Model Structure and Model Limitations

There are many limitations in the existing models and some work has been done to improve on current models by building modules to fill simulation gaps such as soil biochemistry, which incorporates the catalytic mineralization of litter and soil carbon kinetics[51], microbial models with increasing levels of complexity to simulate short- to long-term soil carbon dynamics[78], and a detachable carbon cycle model with improved transparency and higher degree of freedom for manipulation when simulating the carbon equilibrium state for each carbon pool[49]. The detachable carbon cycle model is reported to present a significant advantage as it processes remote sensing data that are captured in real-time, but the model is unable to predict future outcomes.

Doetterl et al. (2015)[56] note that while climate is regarded as a key driver of soil organic carbon (and vice versa), there is uncertainty about the direction and magnitude of carbon responses to climate change. According to Doetterl et al., climatic and biotic factors and their effects on SOC dynamics have been studied at various spatial and temporal scales but are still “poorly represented in current Earth system models”. ESMs predict that SOC will be a major contributor to future climate change, but large uncertainties exist in understanding of interactions of climate and geochemical factors and their control of SOC storage and turnover. The authors state, “These uncertainties are explained partly by ESMs poorly representing the current (observed) global SOC distribution and partly by inadequate parameterization of the temperature sensitivity of SOC, microbial carbon use efficiency, and mineral surface sorption of organic matter”. Specifically, they recommend that a better understanding of the geochemistry of soils formed under natural conditions at a global scale could improve understanding of the global terrestrial SOC cycle, and improve results obtained from ESMs.

A noted limitation of SOC models is the inability to capture SOC distribution as a function of soil depth. Jia et al. (2017)[79] assessed spatial distributions of SOC content to the depth of 500 cm, and reported that climate (temperature, precipitation) is the main driver of spatial variability of SOC in the top three layers

(0-40 cm). At depths greater than 200 cm, land use was the critical factor, while topographic features have only a weak role for the entire soil profile.

SOC data and models from agricultural activities are also being developed. Liu et al. (2016)[80] modeled the SOC to assess the impact of crop and pasture management system in eastern Australia using Agricultural Production System Simulator (APSIM). SOC can be enhanced by incorporation of stubble (crop residue), application of N, increased rainfall, and continuous grazed pasture for sites. Meanwhile, continuous cropping under burnt stubble can decrease SOC. Mean annual temperature is identified as a key factor in differentiating net carbon sinks from net carbon sources, and a mean annual temperature of >20°C turns land into a net carbon source.

In agriculture, the role of carbon and nitrogen are difficult to decouple and are important metrics in determining land fertility and crop growths. Zhang et al. (2016)[50] adopted a model approach to quantify greenhouse gas (GHG) emissions and stocks of soil carbon and nitrogen for a 20-year fertilized wheat-maize intercropping study. The SPACSYS model reasonably predicts wheat and maize yield, but is not able to account for soil acidification from long-term chemical application. There is good agreement between measured values and model estimates for carbon dioxide and nitrous oxide emissions. In this work, SPACSYS results have higher R^2 values compared to a similar study done using DAYCENT.

Information on grasslands (grazing, etc.) and management effects on soil carbon stocks was examined by Conant et al. (2017)[57]. The authors calculated that grassland soil carbon stocks are about 343 Pg C (in the top 1 m), nearly 50% more than is stored in forests worldwide[58], highlighting the importance of grasslands in the global carbon cycle. In contrast, based upon data from West and Post (2002)[81], grasslands store approximately 150 Pg C, still sizeable, but less than the amount of carbon stored in forests. As reported in Dlamini et al. (2016)[82], the original global analysis of 115 studies by Conant et al. (2001)[83] estimated much lower SOC gains from the conversion of croplands to grasslands (varying from 3 to 5%) than a meta-analysis of 74 studies by Guo and Gifford (2002)[84] which reported gains of 19%. The more recent study of Conant et al. (2017)[57] surveyed 64 new publications, with most of the publications comparing different fields or farms with different management practices. The majority of studies (68.2%) found increased soil C with management improvements. There were two key exceptions – conversion from native vegetation and grazing management, for which soil C declined in more studies than it increased. The authors also noted that improved grazing management doesn't always lead to increased soil C stocks and that even when it does, responses vary based on climate, soil and vegetation properties.