WP-20-07

NCASI White Paper

IMPACT. SCIENCE. SOLUTIONS.

AN ANALYSIS OF GWP_{BIO} AND THE EFFECTS OF SCALE

NCASI
WHITE PAPER
JULY 2020

by
Reid Miner, NCASI Emeritus
Cary, NC

and

Dr. Caroline Gaudreault, NCASI
Montreal, QC

For more information about this report, contact:

Caroline Gaudreault
NCASI
Program Manager, Sustainable
Manufacturing and Climate
2000 McGill College Avenue, 6th Floor
Montreal, QC H3A 3H3
(514) 907-3162
cgaudreault@ncasi.org

Kirsten Vice
NCASI
Vice President, Sustainable Manufacturing
and Canadian Operations
2000 McGill College Avenue, 6th Floor
Montreal, QC H3A 3H3
(514) 907-3145
kvice@ncasi.org

For more information about NCASI publications, contact:

Publication Coordinator
NCASI
1513 Walnut Street, Suite 200
Cary, NC 27511
(919) 941-6400
publications@ncasi.org

Cite this report as:

NCASI. 2020. *An analysis of GWP_{bio} and the effect of scale*. White Paper (WP-20-07). Cary, NC: National Council for Air and Stream Improvement, Inc.

About this report:

The GWP_{bio} metric provides a plot-level means for incorporating the biogenic carbon cycle into estimates of the global warming impact of biogenic CO_2 emissions. In this report, we discuss the assertion that plot- and landscape-scale approaches are equivalent (and hence that use of GWP_{bio} can be reconciled with a landscape approach), we test the use of GWP_{bio} under several scenarios and discuss challenges in its application. We find that while the metric provides useful information and can be easily calculated for simple scenarios, it contains several embedded assumptions and conventions that (a) have large impacts on results; and (b) may be inappropriate in several contexts.

About NCASI:

NCASI (National Council for Air and Stream Improvement, Inc.) is a non-profit environmental research organization that seeks to create credible scientific information required to address the environmental information needs of the forest products industry in North America. NCASI conducts surveys, performs field measurements, undertakes scientific research, and sponsors research by universities and others to document the environmental performance of industry facility operations and forest management, and to gain insight into opportunities for further improvement in meeting sustainability goals.

Acknowledgment:

The Alliance for Beverage Cartons and the Environment (ACE) and the Confederation of European Paper Industries (Cepi) graciously provided additional funding to the undertaking of this project.

AN ANALYSIS OF GWP_{BIO} AND THE EFFECTS OF SCALE

SUMMARY

A variety of methods and metrics have been proposed to quantify the impacts of biogenic CO_2 emissions. Most consider biogenic CO_2 in the context of the biogenic carbon cycle, recognizing that this cycle requires that biogenic CO_2 be differentiated from fossil CO_2. One of the metrics receiving attention is GWP_{bio} (Cherubini et al. 2011).

To examine the utility and application of the GWP_{bio} metric, herein we discuss inherent assumptions in the metric and replicate and then expand the calculations in Cherubini et al. (2013). Our findings include:

- GWP_{bio} is a plot-level metric that starts the accounting at harvest. As such, all other things being equal, GWP_{bio} is lower for wood from shorter rotation forests because the GWP_{bio} value is directly related to the time a pulse of biogenic CO_2 remains in the atmosphere, and shorter growing cycles provide faster removal of biogenic CO_2 from the atmosphere.
- Cherubini et al. (2013) used several debatable arguments to justify using a stand-level approach rather than a landscape approach.
  - They argued that landscape-level accounting is flawed to the extent that it may not be possible to attribute landscape-level carbon fluxes to specific harvesting activities. However, careful consideration of the spatial scale of the landscape and careful attribution of indirect impacts of wood demand on carbon fluxes (e.g., market effects) can help reduce, and in some cases eliminate, these effects.
  - They argued that landscape-level accounting attributes sequestration benefits that cannot be directly linked to the studied product. However, the same can be said about applying the plot-level approach they used, which involved modeling regrowth of trees instead of initial growth. Indeed, by including a tree that is replanted to compensate for one that was harvested in the system boundary, carbon fluxes that are not physically linked to the studied product are being attributed to it.
- GWP_{bio} results are relatively insensitive to selection of the model describing gradual loss of CO_2 from the atmosphere because GWP_{bio} is a ratio of radiative forcing from biogenic CO_2 to that from fossil CO_2 and the model is applied to both types of CO_2.
- GWP_{bio} is extremely sensitive to its assumption that accounting should begin at harvest. If accounting was started when a plot begins to grow instead, results would be completely opposite to those obtained when starting accounting at harvest. This suggests the need for care in deciding what start time is appropriate for specific circumstances.
- Cherubini et al. (2013) found that the cumulative 100-year warming effect of a single harvest is the same as the instantaneous effect, at 100 years, of ongoing harvesting over a

landscape. They concluded that this demonstrates that plot- and landscape-level accounting give the same results. The information presented herein, however, demonstrates that this interpretation could be misapplied by policy makers. Specifically, it could result in use of a GWP_{bio} metric that assigns non-zero net emissions to wood harvested on an ongoing basis from sustainably managed forests at a time when the net emissions from this activity are, in fact, equal to zero.

- GWP_{bio} considers only biometric factors, whereas carbon impacts of wood demand are affected by both biometric and economic factors, including landowner responses.
- Despite its apparent ease of application, in several cases use of the GWP_{bio} method requires a significant amount of data to define the length of time a product is stored in the anthroposphere (in use and in landfills) and lacks the flexibility of more general methods such as the dynamic LCA framework proposed by Levasseur et al. (2010).

Forest carbon is affected by a series of complex biometric and economic factors. This white paper, and many other studies, demonstrate that plot-level assessments are not able to properly account for these factors. Landscape-level accounting allows them to be addressed. In applying landscape-level accounting, however, a balance must be found between utility and comprehensiveness. Addressing market forces introduces complexity and uncertainty, but research shows that focusing on plot-level biometrics while ignoring larger-scale landowner responses to market forces can produce misleading forest carbon accounting results.

KEYWORDS

biomass carbon accounting, GWP_{bio}, stand-level vs. landscape-level accounting

TABLE OF CONTENTS

1.0 INTRODUCTION 1

2.0 BACKGROUND 2

3.0 A REVIEW OF CHERUBINI ET AL. (2013) 6

3.1 The Supply Area (Landscape) Approach to Calculating Net Emissions of Biogenic Carbon 6

3.2 Attribution of Emissions in Supply Area and Landscape Calculations 7

3.3 Double Counting 8

3.4 Starting Plot-Level Carbon Accounting at Harvest Rather than at Beginning of Tree Growth 8

3.5 Market Impacts 9

4.0 APPLICATIONS OF GWP_{BIO} TO DIFFERENT CONTEXTS 10

4.1 Rotation Length 10

4.2 Atmospheric Decay Models 12

4.3 Accounting Start Point 13

4.4 Accounting for Repeated Harvest Over A Given Supply Area 15

5.0 ADDITIONAL CONSIDERATIONS 19

5.1 Apparent Ease of Application 20

5.2 Encouragement of Land Conversion to Shorter Rotations 21

6.0 CONCLUSIONS 20

REFERENCES 22

LIST OF TABLES

Table 1. GWP_{bio} for Three Different Rotation Periods in the Norway Spruce Forests Case Study 12

Table 2. 100-Year GWP_{bio} Estimates using Different Atmospheric CO_2 Models 13

LIST OF FIGURES

Figure 1. Annual Warming from a 1 kg Emission of CO_2 2

Figure 2. Cumulative Warming from a 1 kg Emission of CO_2 3

Figure 3. Comparison of Instantaneous Impacts of 1 kg of CO_2 and 1 kg of CH_4 Released 4

Figure 4. Comparison of Cumulative Impacts of 1 kg CO_2 and 1 kg CH_4 Released 4

Figure 5. Amount of CO_2 in the Atmosphere from a Pulse Emission of Fossil Fuel CO_2 and CO_2 from Bioenergy Harvested from Norway Spruce Forests on Three Different Rotations 11

Figure 6. Atmospheric CO_2 Models from Bern et al. (used in IPCC's FAR) and Joos et al. (used in Cherubini et al. 2013) 12

Figure 7. Effect of Moving the Starting Point for Calculating GWP_{bio} on a 40-Year Rotation Norway Spruce Harvest on the Quantity of CO_2 in Atmosphere Per Unit of CO_2 Emitted at Combustion 14

Figure 8. Carbon Stocks on the Assessment Area for the Norway Spruce Example 16

Figure 9. Comparing Single Plot and Expanding Supply Area Calculations for the Cherubini et al. (2013) 100-Year Rotation Norway Spruce Forest 17

Figure 10. Annual Carbon Emissions from a Fuel Based on Ongoing Sustainable Forest Management on a 25-Year Rotation Compared to Ongoing Emissions of the Same Annual Amount of Fossil Fuel Carbon 18

AN ANALYSIS OF GWP_{BIO} AND THE EFFECTS OF SCALE

1.0 INTRODUCTION

A variety of methods and metrics have been proposed to quantify the impacts of biogenic carbon dioxide (CO_2) emissions. Most consider biogenic CO_2 in the context of the biogenic carbon cycle, recognizing that this cycle requires that biogenic CO_2 be differentiated from fossil CO_2, and typically consider the timing of emissions and/or removals (Head 2019).

Most commonly, the methods involve a metric that quantifies the cumulative radiative forcing (or avoided radiative forcing) associated with greenhouse gas (GHG) emissions or stored carbon over time. The methods vary primarily in how the cumulative forcing impact is quantified. They can also vary with regards to whether they rely on approximations or fully elaborated models of radiative forcing over time, as well as on model selection. In this paper, we highlight the basic concepts upon which these methods rely, summarize several of the proposed methods and metrics, and examine one of the methods, the Cherubini et al. (2011) GWP_{bio} metric, in detail.

GWP_{bio} was used by Quantis (2019) as an example to test the feasibility of considering timing of emissions in bio-based products. Quantis described it as particularly relevant *"when comparing systems that have significant differences in either […] the biomass regrowth rate [or] the time carbon is stored in products before being re-emitted".* However, questions have been raised about the areal and temporal scales for applying GWP_{bio}. Cherubini et al. (2013) published a paper attempting to reconcile application of GWP_{bio} at the stand and landscape levels. Cintas et al. (2017) examined the findings of Cherubini et al. (2013) and concluded that the GWP_{bio} approach, as applied in that paper, had several limitations. NCASI undertook the study described herein to assess the Cherubini et al. (2013) paper, expanding on the Cintas et al. (2017) analysis. Specifically, the NCASI study:

1. Reviewed the paper by Cherubini et al. (2013);
2. Tested the application of the GWP_{bio} metric to different rotation lengths (using examples applicable to US and European contexts);
3. Examined the effect of using IPCC's Bern et al. CO_2 degradation model (IPCC 2007, p. 213)[1] in place of the Joos et al. (2013) model used in Cherubini et al. (2013);
4. Examined the effect of beginning the accounting at the point where growth begins instead of at harvest;
5. Examined the basis for the Cherubini et al. conclusions regarding the effect of extending the accounting to the supply area (sometimes referred to as landscape-level accounting); and
6. Identified other potential challenges in applying the GWP_{bio} metric.

NCASI's analysis addressed only the calculation of emissions of, and global warming potentials (GWPs) for, biogenic CO_2. Studies addressing different questions, such as the net impacts of displacing fossil fuel with wood-based fuel, involve considerations not addressed here.

[1] Model developed by Bern et al., as used in IPCC's Fourth Assessment Report, Physical Science Basis, pg. 213, footnote a

2.0 BACKGROUND

Two important parameters determining the warming impacts of a GHG are its radiative forcing, which can be thought of as a GHG's potency, and its lifetime in the atmosphere. The warming potential of a GHG is often expressed in terms of its cumulative radiative forcing over a specified period, often 100 years. Figures 1 and 2, developed using DynCO_2 (Levasseur 2013), show annual and cumulative radiative forcing, respectively, of an emission of 1 kg of CO_2 over 100 years. After 100 years, the instantaneous (essentially, annual) impact is about 42% of what it was in year 1. This is due to the slow removal of the emission from the atmosphere by oceans and terrestrial sinks. The cumulative radiative forcing over 100 years is 9.17 x 10^{-14} watts per square meter.

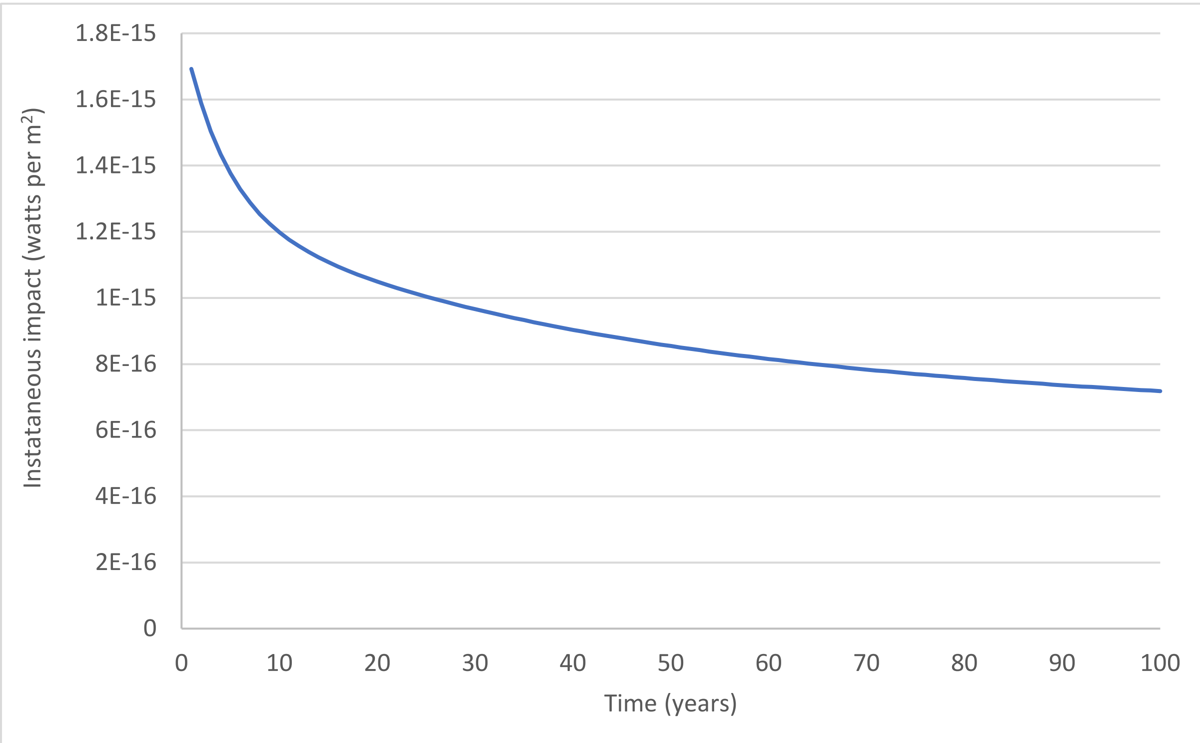

Figure 1. Annual Warming from a 1 kg Emission of CO_2

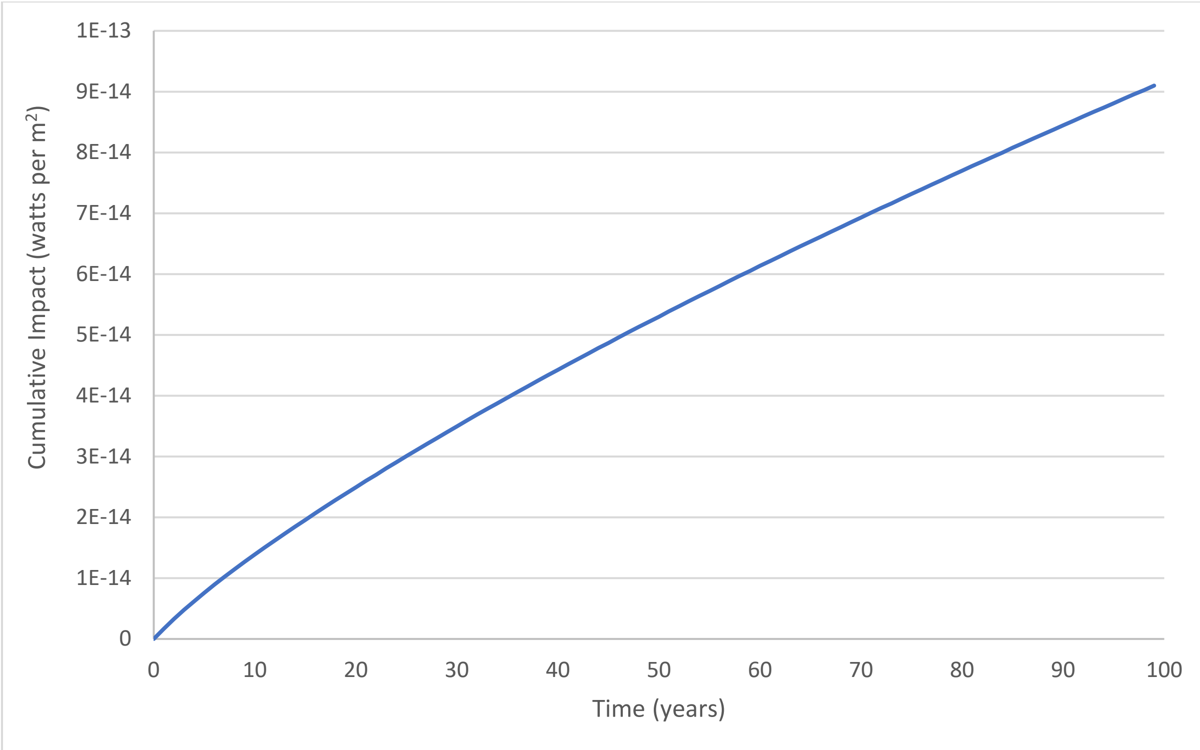

Figure 2. Cumulative Warming from a 1 kg Emission of CO_2

Other GHGs can be compared to CO_2 by comparing the cumulative radiative forcing they produce to that produced by CO_2. The impacts of CO_2 and methane (CH_4) are compared in Figures 3 and 4. The figures demonstrate that CH_4 is a far more potent GHG but dissipates from the atmosphere far more quickly than CO_2. The ratio of cumulative radiative forcing for any gas compared to CO_2 is its GWP. At 100 years, the cumulative radiative forcing of methane is 30 times that of CO_2; therefore methane's 100-year GWP is 30 (IPCC 2013).

This same concept can be applied to forest-derived biogenic CO_2. Biogenic CO_2 from forest biomass has the same "potency" as all other CO_2 emissions to the atmosphere (e.g., fossil CO_2), but its residence time in the atmosphere is affected by its removal from the atmosphere by growing trees. By adjusting the residence time of biogenic CO_2 in the atmosphere to reflect this, we can calculate an adjusted cumulative radiative forcing. This allows us to compare the cumulative radiative forcing of biogenic CO_2 from forest biomass to fossil CO_2.

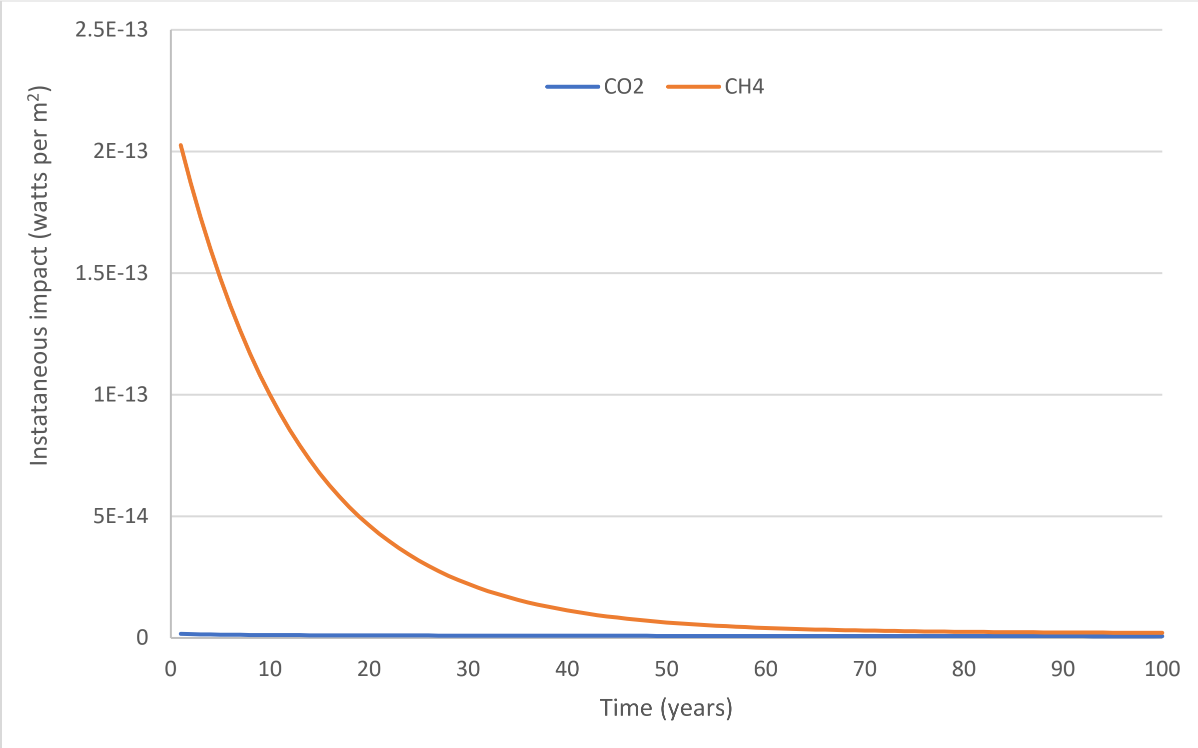

Figure 3. Comparison of Instantaneous Impacts of 1 kg of CO_2 and 1 kg of CH_4 Released

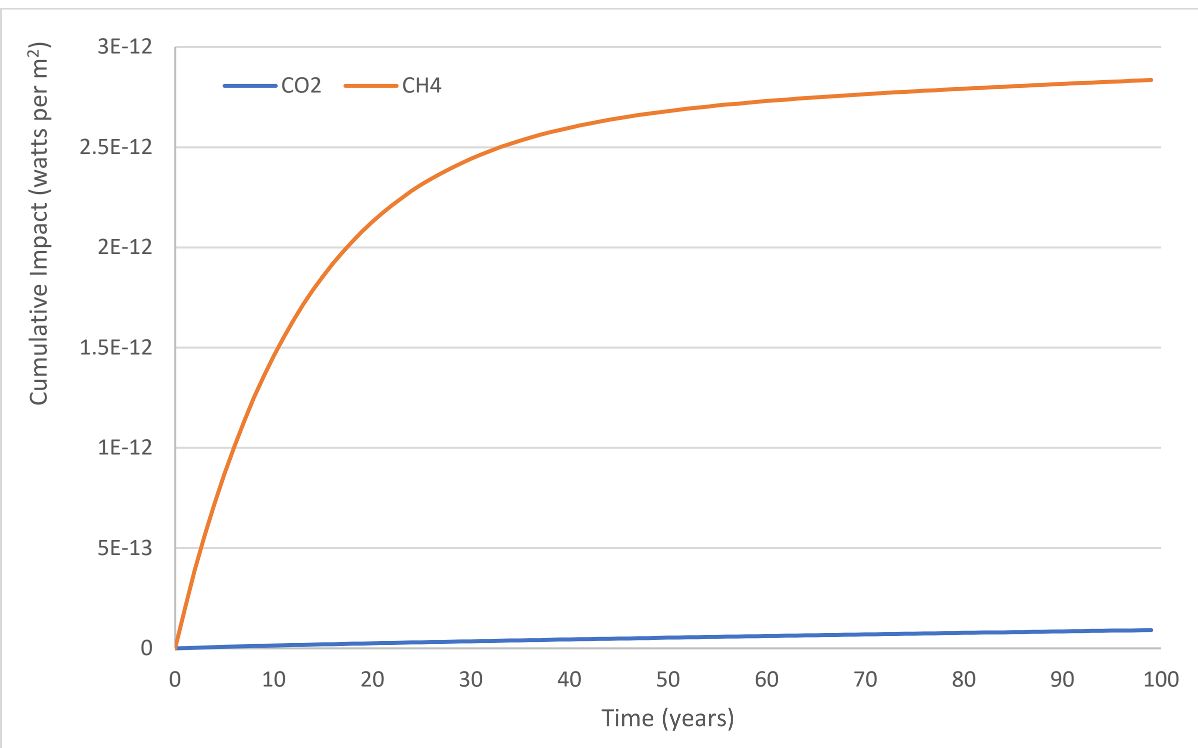

Figure 4. Comparison of Cumulative Impacts of 1 kg CO_2 and 1 kg CH_4 Released

The concepts described have been applied in various methods to quantify the impact of biogenic CO_2 emissions, delayed CO_2 emissions, and carbon storage. Conceptually, all methods that use these concepts are very similar in that they rely on estimates of absolute or relative cumulative radiative forcing attributable to an action of interest. Where the objective of a study is to compare the radiative forcing impact of different scenarios, comparing the scenarios in terms of cumulative CO_2 in the atmosphere provides the same result as comparing cumulative radiative forcing because the radiative forcing per unit of CO_2 is the same for both. For this reason, many studies that compare the cumulative radiative forcing of different scenarios, including many of those cited herein, use cumulative CO_2 in the atmosphere (sometimes called the tonne-year approach) as a proxy for cumulative radiative forcing.

The Dynamic LCA approach (Levasseur et al. 2010, 2013) is perhaps the most general framework based on these concepts. It involves quantifying GHG emissions and removals of CO_2 from the atmosphere as a function of time and assessing their cumulative radiative forcing impacts over time, as reflected by cumulative CO_2 in the atmosphere. Calculating cumulative CO_2 in the atmosphere requires knowing the residence time distribution of CO_2 therein. This is normally expressed in the form of a multi-factor polynomial equation derived to fit the output of far more complex climate models. One of these polynomial equations is the Bern et al. model used by IPCC (IPCC 2007, p. 213)[2], but other equations can be used. Once the residence time distribution in the atmosphere is known, the tonne-year proxy for cumulative radiative forcing can be calculated.

The generic Dynamic LCA approach does not specify temporal or spatial boundaries but can be used within a framework that specifies them. The resulting metric is a measure of cumulative radiative forcing over a specified time.

Moura Costa and Wilson (2000) use the same concepts to assess the benefits of storing biogenic carbon. They calculate that the 100-year cumulative radiative forcing from a pulse emission of CO_2 could be offset by storing an equivalent amount of biogenic carbon for 55 years – a period they call an "equivalence time". They also calculate that over 100 years the storage of one tonne of biogenic CO_2 for a year is equivalent to preventing the emission of 0.0182 tonnes of CO_2, which they named the "equivalence factor".

Fearnside et al. (2000) used a similar approach to characterize the impacts of different land use change and forestry management scenarios. To calculate the benefits of temporary storage of biogenic carbon, they used the relative difference between the cumulative radiative forcing for a scenario where biogenic CO_2 is released at time zero and a scenario where the same curve is shifted into the future by an amount equal to the storage time. For instance, for a 50-year storage period, they found that the cumulative radiative forcing for a pulse emission of CO_2 over 50 years is only 60% of the cumulative radiative forcing over 100 years, indicating that storing biogenic carbon for 50 years reduces its impact by 60% compared to not storing the carbon. The authors used a similar approach to crediting additional carbon storage (e.g., afforestation). Their approach used the same concepts as those used by Moura Costa and Wilson (2000) but a different metric. Moura Costa and Wilson (2000) calculated the amount of storage, from time zero, required to offset an equivalent emission at time zero. Fearnside et al. (2000) calculated the reduction in radiative forcing associated with delaying an emission for a storage period compared to releasing the equivalent emission at time zero.

[2] Curve developed by Bern et al., as used in IPCC's Fourth Assessment Report, Physical Science Basis, pg. 213, footnote a

To simplify calculations, some approaches simplify the polynomial equations used to calculate cumulative radiative forcing. The *Specification for the assessment of the life cycle greenhouse gas emissions of goods and services*, PAS 2050:2008 (BSI 2008), for example, divided the forcing curve into two parts (at 25 years), using a separate mathematical approximation for each part. PAS 2050 also specifies temporal and process boundaries to use in deriving a final metric (i.e., CO_2 equivalents over a 100-year period following formation of the product), where delayed emissions and carbon storage are included in a way that reflects their radiative forcing over the 100 years.

All these methods use estimates of absolute or relative cumulative radiative forcing over time. They differ only in the specific metric used to express this impact and the model used to estimate the radiative forcing impact of an emission of CO_2 over time.

Cherubini et al. (2013) used the same concepts to develop the GWP_{bio} metric representing the ratio of cumulative radiative forcing, over a 100-year period, of biogenic CO_2 to the cumulative radiative forcing from fossil fuel CO_2 over the same period. As noted, the ratio of cumulative radiative forcing of a GHG to that of fossil fuel CO_2 is its GWP, so the metric calculated by Cherubini et al. (2013) is a GWP for biogenic CO_2, which they refer to as GWP_{bio}. The approach presented in Cherubini et al. (2013) also specifies spatial and temporal boundaries for assessing biogenic CO_2 emissions. In this review, we examine the Cherubini et al. approach in detail.

3.0 A REVIEW OF CHERUBINI ET AL. (2013)

In their paper titled "Bioenergy from forestry and changes in atmospheric CO_2: Reconciling single stand and landscape level approaches", Cherubini et al. (2013) applied the GWP_{bio} approach to a Norway spruce forest on a 100-year rotation. Details on this forest are contained in several background papers referred to in Cherubini et al. (2013).

Five important observations emerge from NCASI's review of Cherubini et al. (2013). They involve (a) overly-narrow conclusions regarding use of the supply area (landscape-level) approach for calculating net emissions of biogenic carbon; (b) inconsistencies in attribution; (c) erroneous conclusions regarding double counting; (d) an inappropriate assumption that forest carbon accounting should always start at the time of harvest; and (e) the absence of consideration of market impacts in addition to biophysical impacts modeled in the approach. Many of these observations were also made by Cintas et al. (2017).

3.1 The Supply Area (Landscape) Approach to Calculating Net Emissions of Biogenic Carbon

Cherubini et al. (2013) critiqued the commonly used landscape or supply area approach to calculating net emissions of biogenic CO_2. In that approach, system boundaries for the analysis are static and encompass all forest used to supply wood for a product on an ongoing basis. Cintas et al. (2017) uses the term "constant spatial boundaries" to describe such conditions. Only a fraction of that forest is harvested in any given year, while the remaining forest continues to grow, removing carbon from the atmosphere. Across the supply area, if removals of carbon from the atmosphere equal carbon removed from the forest in harvested wood plus carbon lost from the forest via decomposition and fire, the carbon in the harvested wood is considered "neutral" by many parties because there is zero net carbon loss from the forest. This condition is reliant on maintenance of stable carbon stocks across the supply area.

Cherubini et al. (2013) criticized this approach for several reasons. For instance, they stated that the supply area approach "*would imply that biogenic CO_2 emissions from bioenergy sources of same substrates (thus approximately similar NEP profiles) could have different climate impacts depending on which region the emissions occur (while the geographical coordinates of a GHG emission do not influence the resulting impact on global climate)*." For example, biogenic emission impacts from using a 100-year old Norway spruce tree (as modeled in Cherubini et al. 2013) should, according to the authors, be the same anywhere on earth as long as growth rates are the same.

If the landscape is a well-defined supply area[3] [the example used by NCASI in this study is a supply area (landscape) consisting of 100 individual forest stands providing biomass over a 100-year period) and if growth rates and decay rates are unchanged by location (i.e., similar net ecosystem productivity profiles as noted by Cherubini et al.), then the landscape-level analysis would *not* show different climate impacts in different regions. On the other hand, as observed by Cherubini et al., if growth and decay rates for otherwise identical forests vary by region, plot-level accounting will show differing climate impacts while landscape-level accounting may not. It is important to understand the implications of this.

Atmospheric CO_2 levels are affected by net emissions across large spatial scales (not individual plots). It is reasonable, therefore, to ask why the use of wood from one supply area with net-zero carbon flux to the atmosphere should be assigned different emissions than wood from a different area also with net-zero flux just because the growth rates are different. Yet the Cherubini et al. approach will often show different emissions from wood sourced from different forests even when both forests are resulting in zero net emissions from year to year. As shown herein, this means that the Cherubini et al. plot-level approach will show warming impacts from wood produced on an ongoing basis from supply areas under some conditions where there are no net emissions. This aspect of plot-level accounting is important to understand when applying the GWP_{bio} approach at the plot level, as promoted in Cherubini et al. (2013).

3.2 Attribution of Emissions in Supply Area and Landscape Calculations

Cherubini et al. (2013) also criticized the supply area approach because *"it attributes to the bioenergy system sequestration benefits that cannot be directly (and logically) linked with the product of interest; its system boundaries cannot be scientifically justified, as they are not limited to the actively managed stands only but they are arbitrarily expanded to include other stands and get CO_2 sequestration credits; technically speaking, a reduction in CO_2 sequestration corresponds to an emission; one can easily argue that the same principle is valid for fossil CO_2 as well, e.g., in a region with increasing terrestrial carbon stocks, CO_2 emissions from fossil fuel combustion are carbon neutral as long as they are smaller than such an increase."*

There is no question that attribution is a complex issue in supply areas that cannot be narrowly defined. Difficulty in assigning attribution depends on the circumstances. At one extreme might be a planted forest supplying a single user. In this case, attribution is simple. At the other extreme, however, might be an assessment where the supply area is defined at a large geographic or political scale (an entire country, for instance). At large spatial scales, attribution of carbon fluxes to an individual grower or user of wood would be impossible in many cases.

[3] In this paper, "well-defined supply area" describes a supply area where harvesting and management activities to supply wood to a facility can be isolated from other factors affecting forest carbon such as harvesting to supply other facilities and changes in carbon stocks in areas clearly not associated with growing wood for the facility.

For some purposes, it may be important to carefully define the supply area to avoid these complexities. This is not always necessary, however. Some carbon accounting applications are suited to a more comprehensive view of the factors impacting carbon stocks over large spatial scales. In many developed countries, carbon stocks are stable or increasing except in regions heavily affected by wildfire and regions where forest is being converted to non-forest, which is primarily where urban areas are expanding. On a year-to-year basis, wood-producing regions in many countries have net emissions of zero or less (FAO 2015; O'Sullivan et al. 2016; Oswalt et al. 2019). In developed countries, where land is in private hands and is sustainably managed, markets for wood help keep land in forest (e.g., see discussion in Miner et al. 2014). For some purposes, therefore, it can be reasonable to ignore direct attribution (i.e., not try to associate specific stocks and flows of carbon with specific products) and instead recognize that the net effect of wood markets, even over large areas, is to produce wood under conditions where the net flux of carbon from the forest is zero or less.

It is also worth noting that the plot-level approach used by Cherubini et al. (2011) in defining GWP_{bio} values attributes sequestration benefits to harvested wood that cannot be directly linked to that wood. This is caused by including a tree that is planted to replace a tree that was harvested within the system boundary. This system boundary assigns carbon fluxes to harvested wood that are not physically linked to that wood. If one wants to calculate carbon fluxes that are physically linked to harvested wood, the accounting would need to start at planting.

3.3 Double Counting

Cherubini et al. (2013) stated that *"In the [case where managed forest is harvested on a continuing basis], when all the stands have a uniformly distributed age class, it is commonly assumed that a net instantaneous CO_2 flux to the atmosphere is zero at a landscape level, because emissions from the harvested stand are simultaneously offset by the sequestration in the other stands. However, such an attribution of instantaneous yearly sequestration benefits of the stands to the emissions from the harvested stand reveals an accounting problem. The sequestration benefits of the nearby stands sequestering CO_2 are already attributed to the CO_2 originally associated with the harvest event that occurred in that stand in the past. Such a sequestration is needed to ensure the carbon neutrality over the rotation period at a stand level. If the carbon neutrality is taken valid at a landscape level as well, it means that the sequestration benefit is also attributed to offset the yearly emission from the harvested stand, and therefore resulting in a double counting of the sequestration potential of the forest."*

This criticism, however, is based on a flawed understanding of how carbon flows are accounted for in the supply area (landscape-level) approach. In supply area accounting, only one year's worth of "the sequestration benefits of the nearby stands sequestering CO_2 are already attributed to the CO_2 originally associated with the harvest event that occurred in that stand in the past," because net fluxes of carbon in the forest are accounted for only in the period when they actually occur. Therefore, there is no double counting in supply area (landscape-level) accounting.

3.4 Starting Plot-Level Carbon Accounting at Harvest Rather than at Beginning of Tree Growth

Although not examined in Cherubini et al. (2013), a key question in plot-level accounting is when to start accounting of carbon fluxes. Cherubini et al., and many others, begin accounting at the time of harvest. This decision is critically important because the warming impact of CO_2 depends on the time it is in the atmosphere. If the accounting begins with a large emission, the effect of the emission will endure into the future. Even if the emission is completely removed from the atmosphere later by regrowth of a new tree, the warming impact of the first emission will continue. It is important, therefore, to examine this convention.

Herein, results are presented where accounting begins at the beginning of tree growth. Results are completely opposite to what one finds if the accounting begins at harvest. Instead of beginning with a large emission of carbon to the atmosphere, the accounting begins with a gradual, but cumulatively large, removal of carbon from the atmosphere. The cooling effect of this early removal of carbon from the atmosphere persists even after the tree is harvested and the carbon returns to the atmosphere.

There are many things to consider when selecting a starting point for forest carbon accounting at the plot level.

- Carbon removed from the atmosphere during growth is the very same carbon contained in the specific product of interest (i.e., it is directly physically linked to the studied products). Thus, beginning the accounting at the beginning of growth is more consistent with attributional analyses, including most life cycle carbon footprinting exercises.
- When accounting is initiated at the beginning of tree growth, there is reasonable certainty about the timing and magnitude of removals of carbon from the atmosphere because they occurred in the past and are represented in the tree being harvested. If accounting begins at harvest and removals are attributed to the subsequently regenerated tree, one must assume what type of tree this will be, how fast it will grow, when it will be harvested, and so on; assumptions likely to have significant implications for the results. Thus, beginning accounting at the time of harvest involves more uncertainty than beginning the accounting at the point where the tree begins to grow.
- From a policy perspective, it can be important to recognize that initiating accounting at the beginning of tree growth may not differentiate sustainable forest management from deforestation. However, policies developed in this regard can incorporate a requirement compelling consideration of land use change impacts.
- In some situations, physical reality is best represented by accounting that starts at the beginning of tree growth. In particular, situations involving afforestation clearly call for accounting that begins at the time trees start growing. At the other extreme, harvesting of original forest (i.e., forest that has never been harvested) could logically be examined using accounting that begins at harvest. Most situations, however, fall between these two extremes, requiring careful thought as to the appropriate start time for carbon accounting.

3.5 Market Impacts

The Cherubini et al. (2013) analysis considered only biophysical factors such as growth rates, decay rates, emission rates, and carbon stocks. Biophysical modeling is important and yields many important insights into the timing and magnitude of forest carbon fluxes and their impact on the atmosphere. Taken alone, however, it can produce misleading results. Multiple studies have demonstrated that understanding forest carbon fluxes over time requires examining the interaction of biophysical factors with market dynamics (e.g., see Cintas et al. 2017; discussion and references cited in Miner et al. 2014).

Market dynamics are particularly important where land is under private ownership and landowners make decisions about how land is used. The role of market forces varies from place to place.

Nonetheless, there are numerous examples where biophysical modeling of the impacts of increased demand for wood has predicted permanent reductions in forest carbon stocks, while combined biophysical and economic modeling has suggested that forest carbon stocks return to, or even exceed, original levels over time. This is due to the effect of landowners responding to increased demand for wood by keeping land in forest, establishing new forests, and improving management of existing forests used for wood production. Cintas et al. (2017) examined the biometric approach and Norwegian forest used in Cherubini et al. (2013) and concluded that:

> *…the influence of bioenergy incentives on forest carbon balances depends on many factors, including forest structure, forest ownership and forest owners' expectations about market development for bioenergy and other wood products, which need to be accounted for. Assessments should therefore not consider forest fuels in isolation but investigate how forest management as a whole is affected by bioenergy incentives and how this in turn affects forest carbon balances and forest product output. The real landscape scenarios presented in this paper exemplify such an approach, which provide complementary insights by combining biophysical and socio-economic data to consider market effects in parallel sectors with several alternative scenarios for critical factors.*

This finding is not unique to Nordic forests. Galik and Abt (2012) examined the effects of spatial scale on estimated GHG impacts of forest bioenergy in the southeastern US and found that "those assessment scales that do not include possible market effects attributable to increased biomass demand, including changes in forest area, forest management intensity, and traditional industry production, generally produce less favorable GHG balances than those that do."

Ultimately, results of biophysical modeling should be interpreted in the context of how market dynamics impact decisions affecting forest carbon. Ignoring this interaction can lead to policies with unintended consequences.

4.0 APPLICATIONS OF GWP_{BIO} TO DIFFERENT CONTEXTS

4.1 Rotation Length

We used the Norway spruce forest modeled by Cherubini et al. (2013) as the basis for examining the effects of shortening harvest rotation on GWP_{bio}. For convenience, we assumed that all forest residue decomposes in one rotation, which is the assumption applied by Cherubini et al. when modeling a 100-year rotation.

Pulse emissions of biogenic CO_2 from combustion of wood fuel harvested from the Norway spruce forest on rotations of 25, 40, and 100 years were compared to a pulse emission of fossil CO_2. Results are shown in Figure 5. In interpreting the figure, it is important to remember that results have been normalized to one unit of combustion CO_2 from each system. Actual amounts of CO_2 emitted are not the same for each case.

At shorter rotations, there is modestly more CO_2 in the atmosphere (per unit emitted at combustion) shortly after harvest because residues are mathematically forced to decompose within one rotation in the calculations. Although there are fewer residues for the shorter rotation forests, their more rapid decomposition increases early emissions.

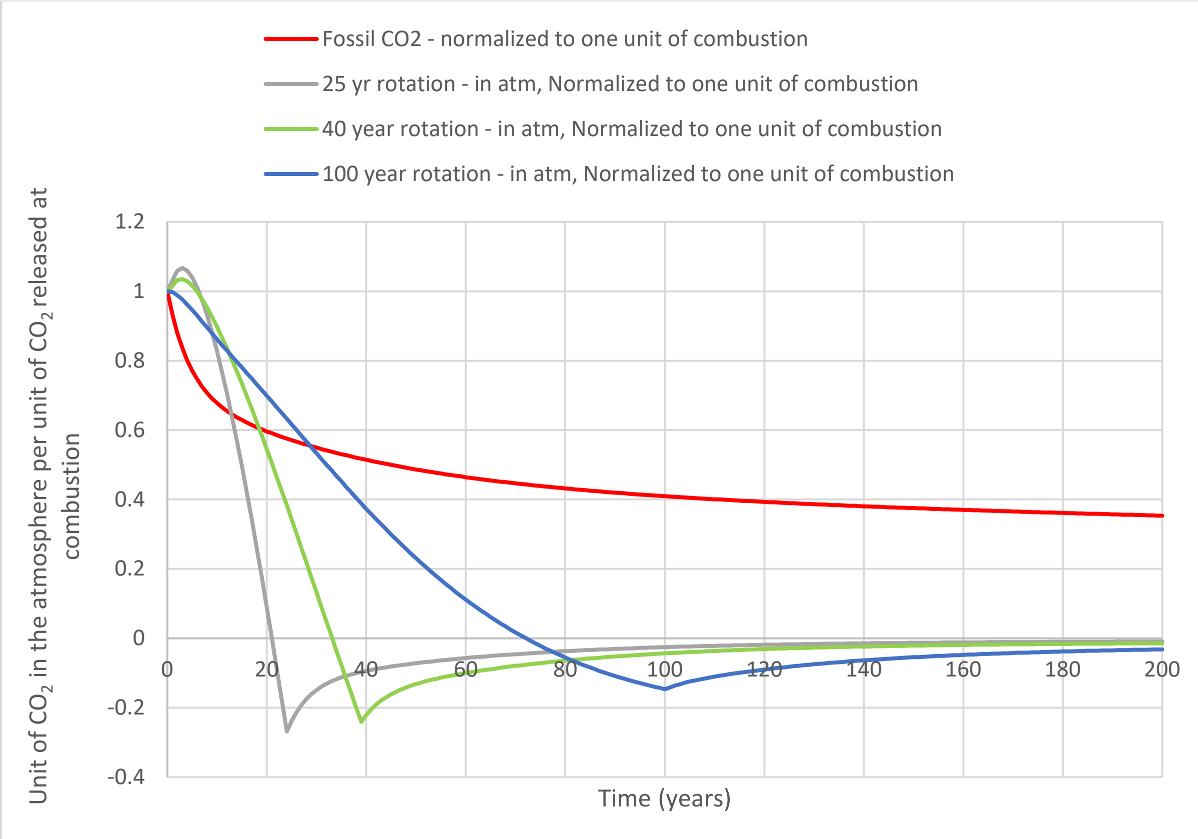

Figure 5. Amount of CO_2 in the Atmosphere from a Pulse Emission of Fossil Fuel CO_2 and CO_2 from Bioenergy Harvested from Norway Spruce Forests on Three Different Rotations

When starting the accounting at harvest, the pulse emission at shorter rotations is removed from the atmosphere more quickly. Amounts of CO_2 in the atmosphere become slightly more negative at shorter rotations because the residues constitute a somewhat larger fraction of total above-ground biomass. As a result, total regrowth is larger per unit of combustion emissions.

Emissions drop below zero at the end of a rotation period and then increase due to dynamic fluxes of CO_2 between the atmosphere and sinks. Although a complete explanation is more than is warranted herein, the situation can be understood as described here. Climate models estimate the dynamic effect of an emission of CO_2 on the amount of CO_2 taken up by oceans and terrestrial sinks. An emission of CO_2 increases CO_2 in the atmosphere and, in turn, increases the driving force for transferring CO_2 into these sinks. As a result, CO_2 flows from the atmosphere into the ocean. Removing CO_2 from the atmosphere has the opposite effect; that is, it provides a driving force for transferring CO_2 from these sinks to the atmosphere, resulting in gradual release of some CO_2 back into the atmosphere.

GWPs for CO_2 from wood harvested under the three different harvesting scenarios are calculated by comparing the areas under the curves for biogenic CO_2 to the area under the curve for fossil fuel CO_2. Results of these calculations are shown in Table 1. GWP_{bio} increases with longer rotations because the pulse of CO_2 remains in the atmosphere longer in the case of longer rotations when starting the accounting at harvest.

Table 1. GWP$_{bio}$ for Three Different Rotation Periods in the Norway Spruce Forests Case Study

Temporal Horizon	GWP$_{bio}$		
	25-Year Rotation	40-Year Rotation	100-Year Rotation
100-year	0.20	0.28	0.60[a]
200-year	0.10	0.14	0.27

[a] Cherubini et al. (2013) calculated 0.63

4.2 Atmospheric Decay Models

Cherubini et al. (2013) used a multi-model mean developed by Joos et al. (2013) to calculate the disappearance of CO_2 from the atmosphere over time. IPCC has used a different model, which has changed over time. In Figure 6, the Joos et al. multi-model mean is compared to the model used by IPCC in the Fourth Assessment Report (FAR). Note that the Bern et al. model used by IPCC shows more rapid removal of CO_2 from the atmosphere than the Joos et al. model used in Cherubini et al. (2013).

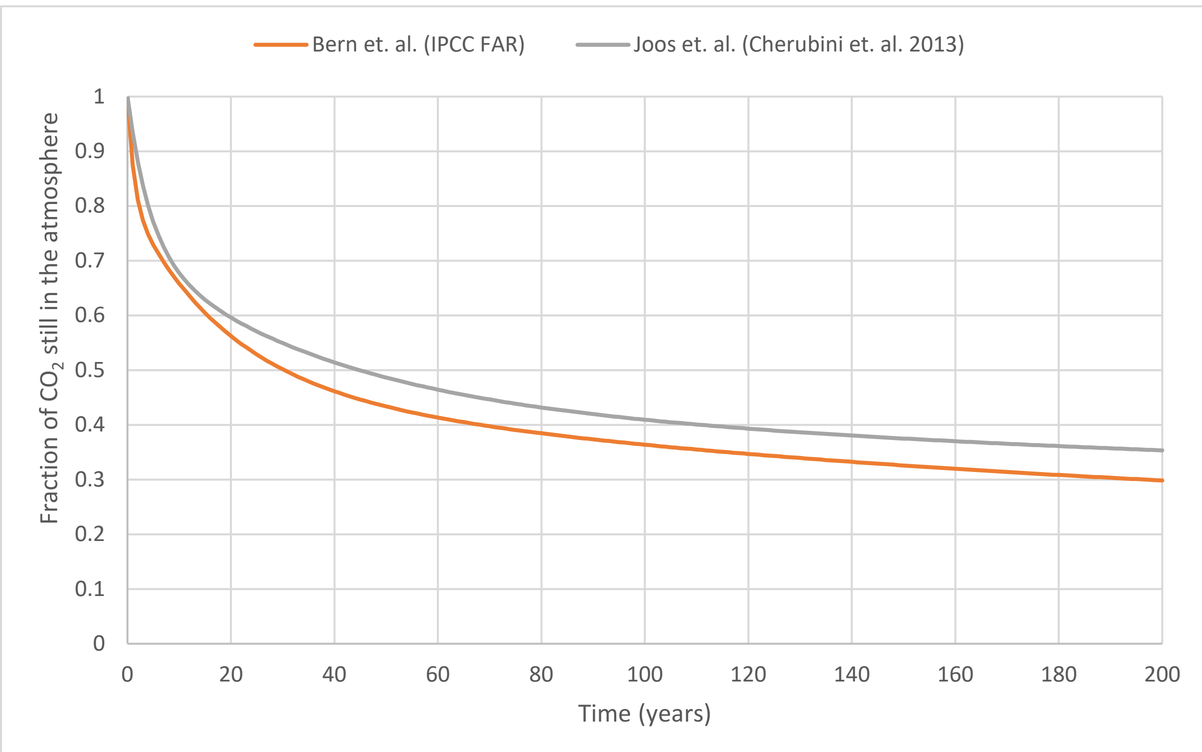

Figure 6. Atmospheric CO_2 models from Bern et al. (used in IPCC's FAR) and Joos et al. (used in Cherubini et al. 2013)

Calculations for the 100-year rotation Norway spruce have been repeated using the Bern et al. model in place of the Joos et al. model; results are shown in Table 2. Although the models appear to be significantly different, they have very little impact on calculated values for GWP$_{bio}$. This is probably because the models are applied to both fossil fuel CO_2 and biogenic CO_2 emissions. If calculating only the radiative forcing of biogenic CO_2, however, the two models would yield results that differed by more than the differences in GWP$_{bio}$.

Table 2. 100-Year GWP_{bio} Estimates using Different Atmospheric CO_2 Models

Model	100-Year GWP_{bio} for the 100-Year Rotation
Joos et al. model (used in Cherubini et al. 2013)	0.58
Bern et al. model (used in IPCC FAR)	0.60

4.3 Accounting Start Point

4.3.1 Effect of Changing the Accounting Start Point

Cherubini et al. (2013) began the plot-level carbon accounting at the time of harvest. There are other start points, however, that could be used. For instance, accounting could begin at the point where the tree begins to remove CO_2 from the atmosphere.

To understand the significance of the Cherubini et al. (2013) decision to start accounting at harvest, calculations for a Norway spruce forest on a 40-year rotation (previously described) have been repeated with the start point for the accounting moved to the point where the tree begins to grow. Results are shown in Figure 7. The difference is dramatic. Accounting that starts at harvest begins with a large emission that is slowly removed from the atmosphere by the trees that replace those that were harvested, whereas starting at planting begins with gradual removal of carbon from the atmosphere by growing trees with the carbon returning to the atmosphere when the tree is harvested.

GWP_{bio} is a function of the time an emission is in the atmosphere. Thus, it is to be expected that these two approaches would give dramatically different estimates. GWP_{bio} calculated for the case where accounting started at planting is –0.25 compared to +0.28 when starting at harvest.

Another way to compare the two starting points is to use a period extending from the start point to a time 100 years after the emission. For a 40-year rotation, the calculation period starting at planting would be 140 years long compared to 100 years for the case starting at harvest. In both cases, the radiative forcing for fossil fuel CO_2 is calculated over 100 years. The GWP_{bio} calculated for a start point at planting and extending for 140 years is –0.22, which is even lower than when using a 100-year calculation period.

These calculations demonstrate the need for careful selection of a start point for determining the impact of forest-based products and fuels. The appropriate start point may not be the same for all circumstances.

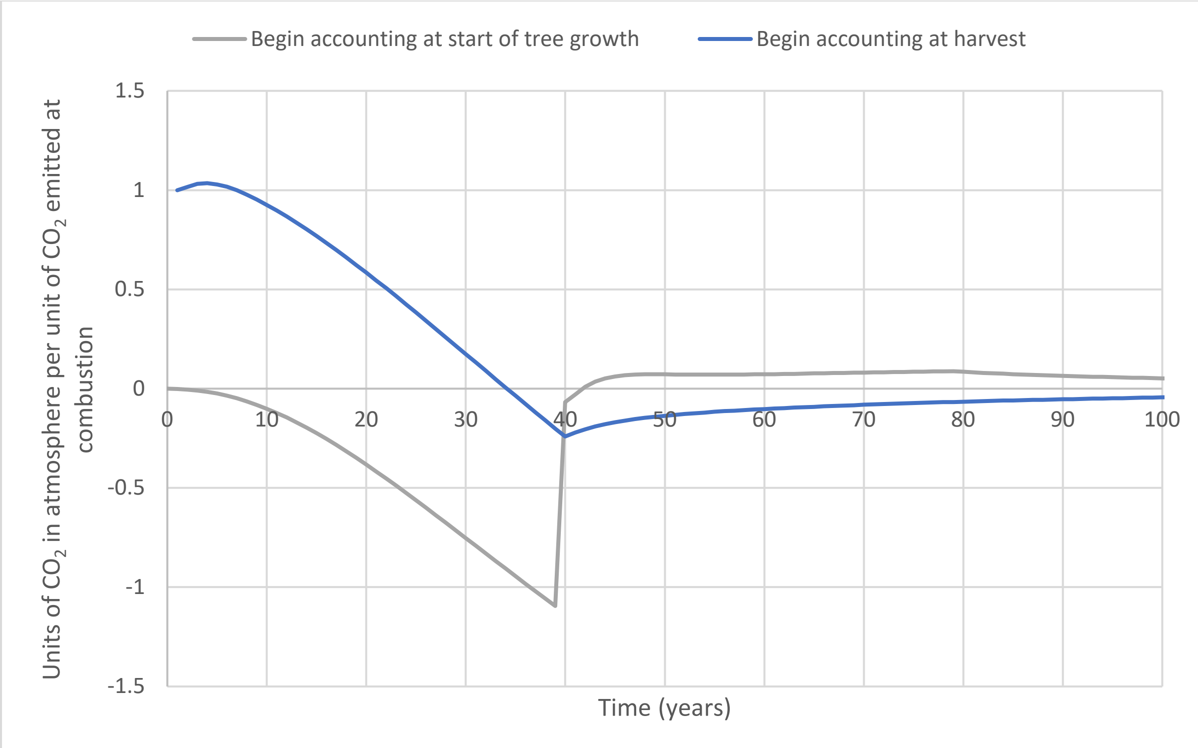

Figure 7. Effect of Moving the Starting Point for Calculating GWP_{bio} on a 40-Year Rotation Norway Spruce Harvest on the Quantity of CO_2 in Atmosphere Per Unit of CO_2 Emitted at Combustion

4.3.2 Discussion of the Relevance of Different Start Points

There are circumstances where there is a clear rationale for beginning the accounting when trees begin to grow. Perhaps the most obvious is where a plot is afforested. Another less obvious example might be where a landowner decides to let an area return to forest instead of continuing to use it for agriculture.

However, starting the accounting at the beginning of tree growth may not differentiate sustainable forest management from deforestation. Harvesting of original forest (i.e., forest that has never been harvested) could logically be examined using accounting that begins at harvest. Another situation where starting the accounting at harvest could be valid is in cases where a new demand for biomass is introduced (Cintas et al. 2017), if the purpose is to evaluate the implications of "incentivizing bioenergy, the definition of time period for accounting is less clear since land owners and other actors in the forest sector can respond to bioenergy incentives in many different ways and forest management might be adapted to anticipated bioenergy demand in advance of the first biomass extraction and use for bioenergy".

Most situations, however, fall between the deforestation and afforestation extremes, requiring careful thought as to the appropriate start time for carbon accounting. Starting the accounting in the middle of the rotation (i.e., between planting and harvest) and stopping after the equivalent of one rotation (e.g., from –20 years to +20 years in the case of a 40-year rotation) would lead to a GWP_{bio} close to zero. Note that applying a landscape-level accounting approach to attributional situations does not require definition of an arbitrary start point because carbon stocks are evaluated in the year of harvest.

Applying a landscape-scale approach assumes that all removals occur at the time of harvest, thus leading to a GWP_{bio} of zero where forest carbon stocks in the supply area are stable.

It becomes clear that deciding on a start time involves several considerations, many of which relate to policy rather than to carbon accounting.

4.4 Accounting for Repeated Harvest Over a Given Supply Area

Cherubini et al. (2013) examined the use of a supply area to calculate GWP_{bio} and compared the results to those obtained at the plot level. Their example was a Norway spruce forest on a 100-year rotation. To examine the effects of supply area (landscape-level) accounting, they simply repeat the plot-level accounting annually for 100 years, starting the accounting on each plot when it was harvested. Figure 8, developed by NCASI but replicating the Cherubini et al. calculations, shows carbon stocks on the two assessment areas. The top of the figure shows carbon stocks on a single plot that releases 1 tonne C from fuel combustion at time zero and then the trees regrow. The bottom of the figure shows carbon stocks on an assessment area that expands by one plot every year ("expanding" supply area) to include the plot being harvested so that the assessment area supplies 1 tonne C in fuel per year. This continues until 100 plots are included in the analysis, which is adequate to provide ongoing supply on a 100-year rotation.

The information used to calculate GWP_{bio} from these scenarios is shown in Figure 9. The left-hand side of the figure shows the calculation of the 100-year GWP_{bio} from the single plot scenario. The GWP_{bio} for this scenario is the ratio of *cumulative CO_2 in the atmosphere* at 100 years from 1 tonne C in biomass fuel emitted at time zero (the area under the green curve) to the *cumulative CO_2 in the atmosphere* at 100 years from 1 tonne C in fossil fuel emitted at time zero (the area under the orange curve). The right-hand side shows information used to calculate 100-year GWP_{bio} for the expanding assessment area scenario, where calculations include one additional plot every year until 100 plots are included, allowing ongoing supply for a 100-year rotation. The GWP_{bio} for the expanding assessment area scenario is the ratio of *instantaneous CO_2 in the atmosphere at 100 years* from 1 tonne C in biomass fuel emitted per year to the *instantaneous CO_2 in the atmosphere at 100 years* from 1 tonne C in fossil fuel emitted per year The findings are as described in Cherubini et al., that is, values for GWP_{bio} are the same. We repeated the analysis for a 40-year rotation forest and found, as expected, the same result. The finding that GWP_{bio} is the same for the two scenarios is the basis for Cherubini et al. concluding that "results at a single stand and landscape level coincide, so making the direct climate impacts associated to biogenic CO_2 emissions valid irrespective of the spatial scale at which the analysis is undertaken."

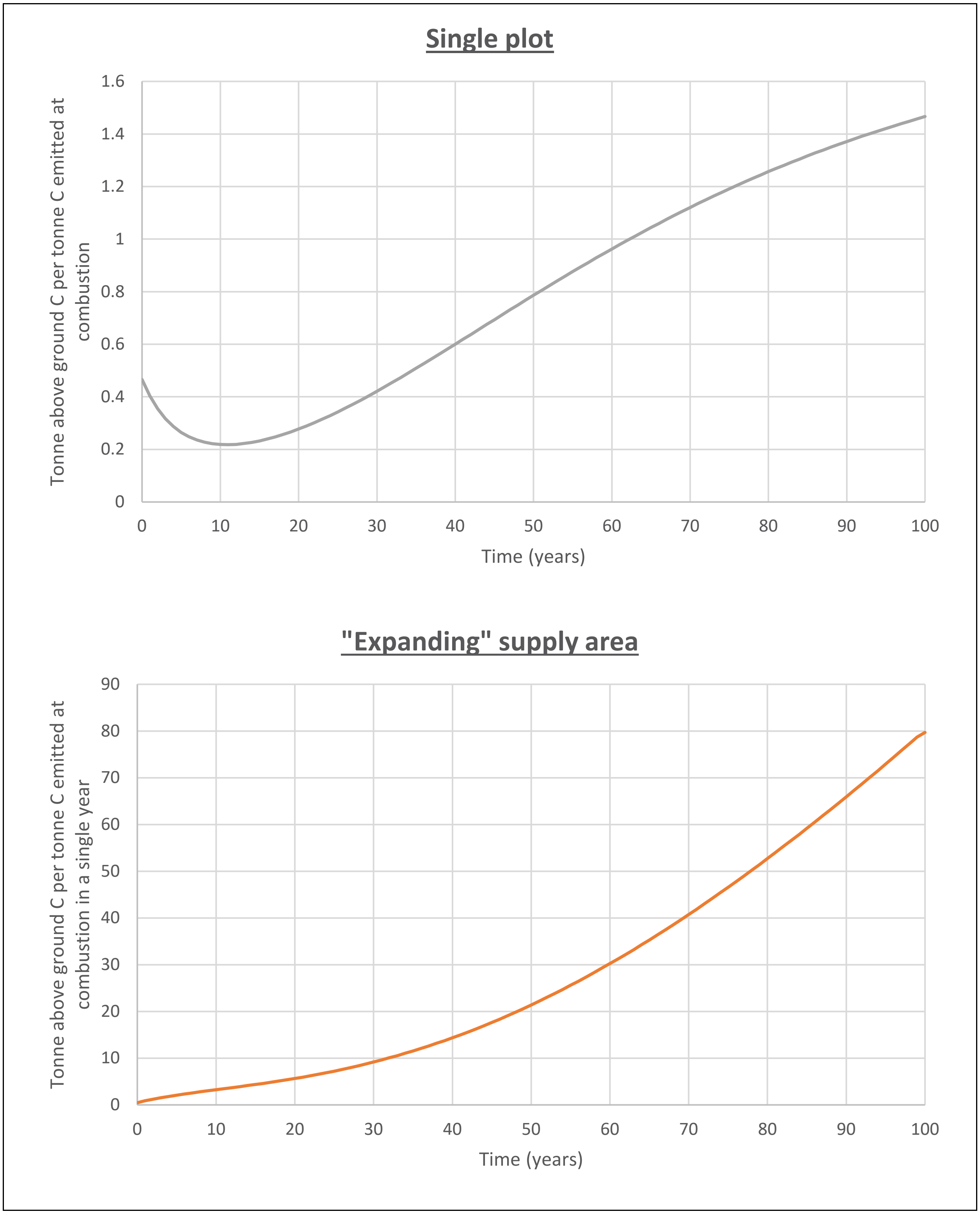

Figure 8. Carbon Stocks on the Assessment Area for the Norway Spruce Example

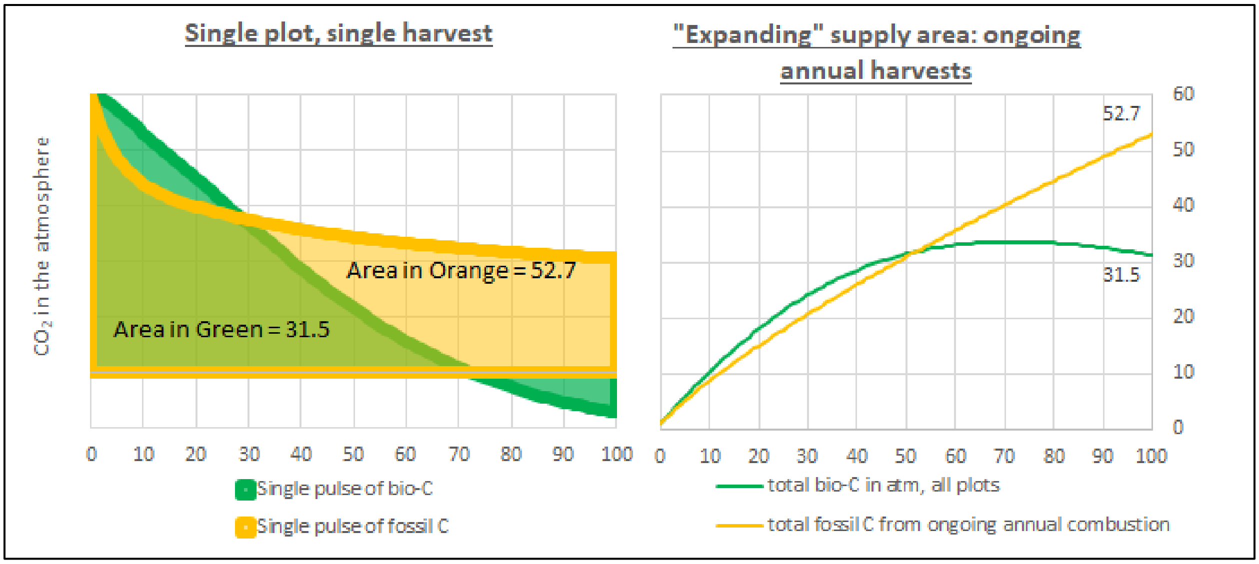

Figure 9. Comparing Single Plot and Expanding Supply Area Calculations for the Cherubini et al. (2013) 100-Year Rotation Norway Spruce Forest [all values normalized to one year's emission of either biogenic C or fossil C]

Some may argue that this means that a single-harvest GWP_{bio} can be used in perpetuity across a landscape. It is important, however, to consider the implications of this. In Figure 10, we apply the Cherubini et al. (2013) "expanding" supply area approach, beginning the accounting at harvest, to energy produced from wood harvested from a sustainably managed forest with stable carbon stocks on a 25-year rotation. We compare carbon emissions from the ongoing emissions of a comparable amount of fossil fuel carbon. After 25 years, when all 25 plots have been added to the assessment, biomass fuel is produced from the forest on an ongoing basis while accomplishing zero net annual emissions. The fossil fuel continues to release the same amount of carbon as in year 1.

The information contained in Figure 10 has important policy implications when considering the calculation and application of the GWP_{bio} concept. Using plot-level accounting and expanding system boundaries, every annual harvest in the future produces wood with the same GWP_{bio}, calculated from the cumulative radiative forcing of a single harvest over a specified time. However, we see in Figure 10 that at some point in the not-distant future the atmosphere sees net-zero emissions from ongoing harvesting and growing activities.

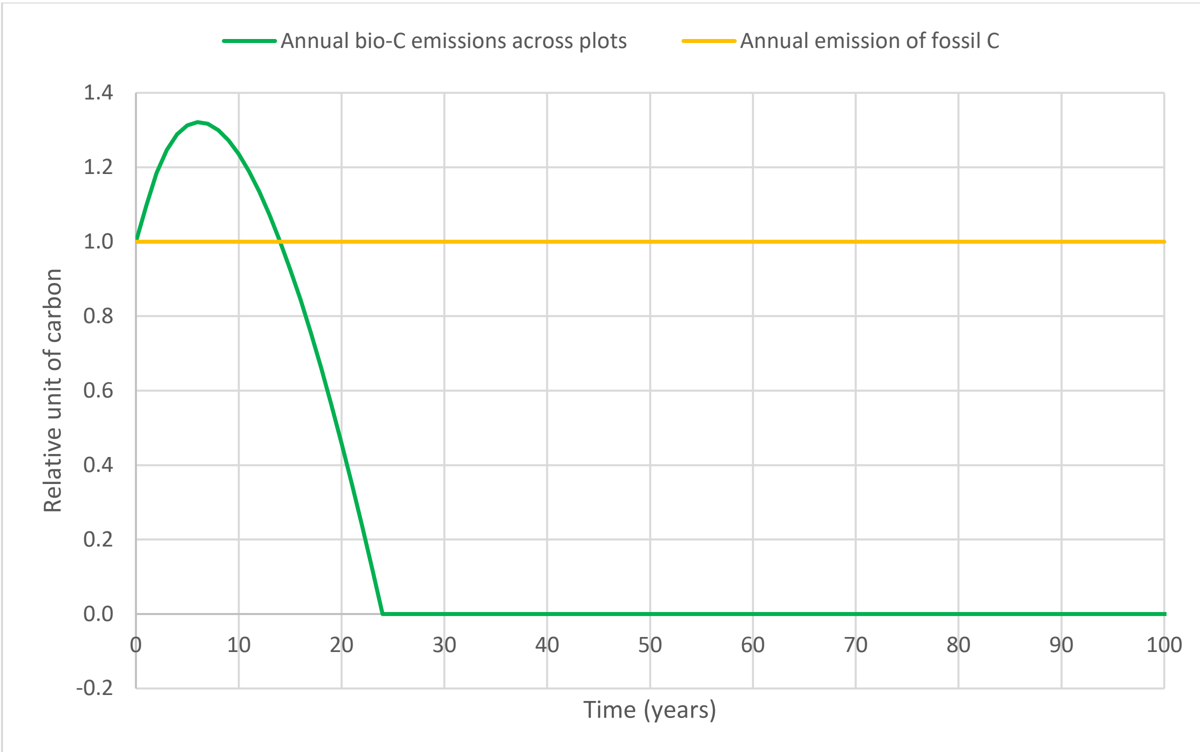

Figure 10. Annual Carbon Emissions from a Fuel Based on Ongoing Sustainable Forest Management on a 25-Year Rotation Compared to Ongoing Emissions of the Same Annual Amount of Fossil Fuel Carbon [based on a supply area that expands until it includes 25 plots]

It is important to note that NCASI's findings are consistent with those in Cherubini et al. (2013). We suggest, however, careful consideration of the significance of these findings. Specifically, an important policy question is whether it is appropriate to apply a metric such as GWP_{bio} to an ongoing activity when it assigns an impact even at a point where the atmosphere is seeing no impact from that activity. One must further ask how one knows where to begin accounting for a sustainably managed forest that has been producing wood on an ongoing basis.

Other limitations of a single-plot approach to assessing forest carbon have been identified in multiple studies. Cintas et al. (2017) and others demonstrated the importance of market-based decisions by landowners that affect forest management on plots to be harvested in the future and that will alter carbon outcomes. Other researchers have found that demand for wood not only improves forest management, but helps retain land in forest and even expand forested area (e.g., Galik and Abt 2012; Favero et al. 2020). These factors are missed in plot-level assessments.

While a constant system boundary, landscape-based approach can be more complex, especially when attempting to capture market-based effects, it avoids many of the shortcomings of an expanding system boundary, plot-based approach. Cintas et al. (2017) provided a succinct summary of the advantages, noting that "the approach that uses constant spatial boundaries is preferable because it captures all carbon flows in the forest landscape throughout the accounting period, supporting comprehensive quantification of all changes that may occur within the system boundaries in association with forest management transitions".

Studies that examine the carbon response of a forested landscape to dynamic market forces may yield results that lack the perceived precision of a metric such as GPW_{Bio} and other plot-level metrics. It is also true, as noted in Cherubini et al. (2013), that a landscape approach will assign "carbon neutrality" to all wood from sustainably managed forests where carbon stocks are stable, even when the forests have very different growth rates. In addition, landscape-level accounting will indicate that there is no warming associated with use of forest bioenergy when forest carbon stocks remain stable because emissions are removed by concurrent growth, eliminating the delay between emission and subsequent removal associated with plot-level accounting. However, suggesting that these aspects of landscape-level accounting are shortcomings misses the fact that where forest carbon stocks are stable, landscape-level accounting represents what the atmosphere is actually seeing from wood harvested for wood products produced from these forests.

5.0 ADDITIONAL CONSIDERATIONS

We have described some of the limitations in applying the GWP_{bio} metric. In short, as defined in the current literature, GWP_{bio} would seem to be applicable to situations where stand-level accounting and starting accounting at harvest are appropriate. Here, we discuss this and other considerations further.

5.1 Apparent Ease of Application

Because it is possible to generate matrices of GWP_{bio} values for products from various rotations and "storage time in the anthroposphere" (Guest et al. 2013), it is sometimes argued that use of the GWP_{bio} metric is relatively easy. In reality, its simplistic application (e.g., via lookup tables) makes a number of hidden assumptions that may or may not be appropriate for a given situation. Adequate application requires significantly more data and context.

First, we noted that the GWP_{bio} metric as originally proposed (Cherubini et al. 2011, 2013; Guest et al. 2013) is only applicable to situations where stand-level accounting and a "starting point at harvest" modeling approach are appropriate.

In addition, the Cherubini et al. (2013) GWP_{bio} metric only applies to situations where emissions associated with a product occur in a single pulse, limiting its use to forest products that are burned either during use (i.e., fuels) or at end-of-life. There are many circumstances, therefore, where it cannot be used.

Finally, additional guidance is needed when applying GWP_{bio} to situations in which land use change occurs or where management activities cause a significant difference between pre-harvest carbon stocks and carbon stocks in regrown plots. Cherubini et al. (2013) addressed this by simply adjusting the starting carbon stocks in the GWP_{bio} calculation. However, this involves an implicit allocation decision that may not align with the requirements of a given GHG reporting standard.

5.2 Encouragement of Land Conversion to Shorter Rotations

Like other approaches that begin accounting at harvest, GWP_{bio} yields values that are lower (better) for products from shorter rotation. Thus, application of this metric may inadvertently incentivize conversion of longer, carbon-richer rotations to shorter, carbon-poorer ones. In practice, if this were to happen through application of the GWP_{bio} approach, the result would depend on several factors:

- Carbon stocks in the longer rotation;
- Carbon stocks in the shorter rotation;
- The period over which GWP_{bio} is calculated;
- Whether there is a difference in the “storage time in the anthroposphere” from the products made from the two rotations; and
- The allocation methods for land use change.

6.0 CONCLUSIONS

The GWP_{bio} metric provides a means for incorporating the biogenic carbon cycle into estimates of the warming impact of biogenic CO_2 emissions. However, while the metric provides useful information and can be easily calculated for simple scenarios, it contains several embedded assumptions and conventions that have large impacts on the results and may not always be appropriate. For instance, the GWP_{bio} metric, as applied in Cherubini et al. (2013) and elsewhere, begins carbon accounting at harvest. This may not be appropriate in cases where forests were established specifically for purposes of ongoing wood production. This decision is policy-based rather than accounting-based and should be made with an understanding of the circumstances to which the accounting is being applied.

In addition, as proposed by Cherubini et al. (2013), the GWP_{bio} calculated for a given type of wood would be applied to subsequent harvests in perpetuity unless conditions changed. This means that calculated net emissions from wood production and use would remain greater than zero in perpetuity, even after net emissions associated with the production and use of wood from a supply area would, in fact, be zero.

Several criticisms of landscape-level or supply area-based accounting were examined by Cherubini et al. (2013). While some can be addressed based on accounting principles, others involve important questions about how landscapes or supply areas are defined and whether market forces are considered. In light of these broader questions, one possible policy approach is to look at wood demand more generally instead of attempting to characterize carbon fluxes associated with each harvest. In this broader policy context, production of wood from sustainably managed forests with stable carbon stocks can be seen as having carbon benefits, raising questions about the use of metrics such as GWP_{bio} that attribute ongoing emissions to such activities.

Forest carbon stocks are affected by a series of complex biometric and economic factors. This study, and many others, find that plot-level assessments are unable to properly account for these factors. Landscape-level accounting allows these factors to be addressed, although often at the cost of additional complexity and uncertainty. Nonetheless, research shows that focusing on plot-level biometrics and ignoring landowner responses to market forces can produce misleading forest carbon results.

REFERENCES

BSI. 2008. *Specification for the assessment of the life cycle greenhouse gas emissions of goods and services*. PAS 2050:2011. London, UK: British Standards Insittution.

Cherubini, F., Guest, G., and Strømman, A.H. 2013. Bioenergy from forestry and changes in atmospheric CO_2: reconciling single stand and landscape level approaches. *Journal of Environmental Management* 129:292-301. https://doi.org/10.1016/j.jenvman.2013.07.021.

Cherubini, F., Peters, G.P., Berntsen, T., Strømman, A.H., and Hertwich, E. 2011. CO_2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. *GCB Bioenergy* 3(5):413-426. https://doi.org/10.1111/j.1757-1707.2011.01102.x.

Cintas, O., Berndes, G., Cowie, A.L., Egnell, G., Holmström, H., Marland, G., and Ågren, G.I. 2017. Carbon balances of bioenergy systems using biomass from forests managed with long rotations: bridging the gap between stand and landscape assessments. *GCB Bioenergy* 9(7):1238-1251. https://doi.org/10.1111/gcbb.12425.

FAO. 2015. *Global Forest Resources Assessment 2015*. Rome: Food and Agriculture Organization of the United Nations.

Favero, A., Daigneault, A., and Sohngen, B. 2020. Forests: carbon sequestration, biomass energy, or both? *Science Advances* 6(13):eaay6792. https://doi.org/10.1126/sciadv.aay6792.

Fearnside, P.M., Lashof, D.A., and Moura-Costa, P. 2000. Accounting for time in Mitigating Global Warming through land-use change and forestry. *Mitigation and Adaptation Strategies for Global Change* 5(3):239-270. https://doi.org/10.1023/A:1009625122628.

Galik, C.S., and Abt, R.C. 2012. The effect of assessment scale and metric selection on the greenhouse gas benefits of woody biomass. *Biomass and Bioenergy* 44:1-7. https://doi.org/10.1016/j.biombioe.2012.04.009.

Guest, G., Cherubini, F., and Strømman, A.H. 2013. Global warming potential of carbon dioxide emissions from biomass stored in the anthroposphere and used for bioenergy at end of life. *Journal of Industrial Ecology* 17(1):20-30. https://doi.org/10.1111/j.1530-9290.2012.00507.x.

Head, M. 2019. *Improvement of Biogenic Carbon Accounting in the Life Cycle of Wood used in Construction in Canada*. PhD thesis. Montreal, QC: École Polytechnique de Montréal.

IPCC. 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK and New York: Cambridge University Press.

———. 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M. (eds.). Cambridge, UK and New York: Cambridge University Press.

Joos, F., Roth, R., Fuglestvedt, J.S., Peters, G.P., Enting, I.G., von Bloh, W., Brovkin, V., Burke, E.J., Eby, M., Edwards, N.R., Friedrich, T., Frölicher, T.L., Halloran, P.R., Holden, P.B., Jones, C., Kleinen, T., Mackenzie, F.T., Matsumoto, K., Meinshausen, M., Plattner, G.-K., Reisinger, A., Segschneider, J., Shaffer, G., Steinacher, M., Strassmann, K., Tanaka, K., Timmermann, A., and Weaver, A.J. 2013. Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. *Atmospheric Chemistry and Physics* 13(5):2793-2825. https://doi.org/10.5194/acp-13-2793-2013.

Levasseur, A. 2013. *dynCO2 Dynamic Carbon Footprinter*. Montreal, QC: CIRAIG. http://ciraig.org/index.php/project/dynco2-dynamic-carbon-footprinter/.

Levasseur, A., Lesage, P., Margni, M., Deschênes, L., and Samson, R. 2010. Considering time in LCA: dynamic LCA and its application to global warming impact assessments. *Environmental Science & Technology* 44(8):3169-3174. https://doi.org/10.1021/es9030003.

Levasseur, A., Lesage, P., Margni, M., and Samson, R. 2013. Biogenic carbon and temporary storage addressed with dynamic life cycle assessment. *Journal of Industrial Ecology* 17(1):117-128. https://doi.org/10.1111/j.1530-9290.2012.00503.x.

Miner, R.A., Abt, R.C., Bowyer, J.L., Buford, M.A., Malmsheimer, R.W., O'Laughlin, J., Oneil, E.E., Sedjo, R.A., and Skog, K.E. 2014. Forest carbon accounting considerations in US bioenergy policy. *Journal of Forestry* 112(6):591-606. https://doi.org/10.5849/jof.14-009.

Moura Costa, P., and Wilson, C. 2000. An equivalence factor between CO_2 avoided emissions and sequestration – description and applications in forestry. *Mitigation and Adaptation Strategies for Global Change* 5(1):51-60. https://doi.org/10.1023/A:1009697625521.

O'Sullivan, O.S., Hopkinson, L., Crockatt, M.E., Laird, P., and Bebber, D.P. 2016. Stable forest carbon stocks support current assumption of biogenic carbon neutrality in the case of European-manufactured beverage cartons. *The International Journal of Life Cycle Assessment* 21(1):118-128. https://doi.org/10.1007/s11367-015-0989-1.

Oswalt, S.N., Smith, W.B., Miles, P.D., and Pugh, S.A. 2019. *Forest Resources of the United States, 2017: a technical document supporting the Forest Service 2020 RPA Assessment*. General Technical Report WO-97. Washington, DC: United States Department of Agriculture, Forest Service. https://doi.org/10.2737/WO-GTR-97.

Quantis. 2019. *Accounting for Natural Climate Solutions: Guidance for Measuring GHG Emissions from Land, Forests, and Soils Across the Supply Chain*. https://quantis-intl.com/strategy/collaborative-initiatives/accounting-for-natural-climate-solutions/.