Final Draft 3S Framework

Developed by The Nature Conservancy, in collaboration with Galina Churkina, for the Climate Smart Forest Economy Program (CSFEP)

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Overview:

Current estimates show that global building stock is expected to double by 2050, which adds a built area the size of Paris to the planet every week for the next 40 years[1]. Additionally, steel and concrete still dominate the construction market. A recent article in Vox highlighted that heavy industry is responsible for around 22% of global CO_2 emissions. 42% of that (about 10% percent of global emissions) comes from combustion to produce large amounts of high-temperature heat for industrial products like cement, steel, and petrochemicals. To put that in perspective, industrial heat's 10% is greater than the CO_2 emissions of all the world's cars (6%) and planes (2%) combined. In fact, we are seeing a rise in the use of forest products, specifically, mass timber as a construction material, especially engineered wood products like Glue-laminated Timber (Glulam) and Cross-laminated Timber (CLT). Wood products can help combat the emissions from the industrial sector on three fronts, because they have a sequestration, storage and substitution benefit. That is, greenhouse gas emissions are sequestered in the trees, they are stored in the forest products, like mass timber, and there is an additional substitution benefit from using a climate friendly product, as opposed to a carbon intensive product like steel or cement.

However, we have to (i) make sure that this is done in a way that ensures the safeguarding of forests, communities, and the environmental services on which all life depends; (ii) Build broad consensus, and a streamlined and agreed understanding of the benefits of forests.

To work towards these goals, TNC, with partners (including: Galina Churkina, WRI, Dalberg, World Economic Forum, with previous support from Efica, and with generous funding and partnership from Climate KIC), have developed the following report which includes:

- A preliminary compendium of existing research which highlights existing research on systems, scenarios and assumptions. It includes a preliminary repository of research gaps that imply a barrier to populating the framework and how to deal with them;
- Research on potential tools that the 3S framework can learn from;
- Results from initial stakeholder mapping exercises, and stakeholder interviews;
- A draft 3S framework, including flowcharts that outline how the framework/ tool may run;
- The report ends with a list of references, a repository of research, and a list of relevant annexes.

This framework, we hope, will ultimately serves as a decision tool/ accounting framework that will allow decision makers, across multiple sectors, to credibly assess how their choices can maximize the climate change impacts of forests and forest products. The instrument will help compare different scenarios in terms of carbon absorption and sequestration (the sink function), of carbon storage (the biocarbon stored in wood-based products) and carbon substitution (the fossil carbon emissions avoided). Currently, key stakeholders are unable to make informed choices as there are no decision-making or planning frameworks/ tools available that support users to explore the impact of their decisions. This results in either opposing views from different stakeholders, and in some instances, suboptimal allocation of financial resources. By combining sink, storage & substitution (3S) functions into a single framework, the latest knowledge on carbon accounting will become accessible to a broad range of users, thus unlocking the full climate potential of forests and forest products.

This report is the outcome of Phase 1, which was carried out over a 4-month period at the end of 2020. This is the first draft of several iterations that will take place between March 2021, and September 2022. Further iterations will continue to develop the 3S Framework by:

(i) Developing the design of the 3S framework through assimilating existing research into latest available knowledge on carbon accounting of forests and forests products, as well as the broader roles of forests for the planet.
(ii) Develop the 3S Framework that, based on the above, can capture the methodologies, assumptions and research needed to compute the carbon footprints of carbon functions relating to forests.
(iii) Continually seek stakeholder feedback and collaborate with partners and co-builders
(iv) Develop an early prototype of the tool and accompanying business plan for a fully functional online tool

Draft Compendium of Significant Literature Related To Forests And Forest Products

Introduction

The project "The 3S Framework for Forests" (3S F4F) aims to develop an instrument, and eventually an online tool (i.e. the "3S Framework") to allow stakeholders to credibly assess the feedbacks between forests and sustainable forest products, and ultimately how their choices can maximize the climate change mitigation potential of forests and sustainable forest products.

This review presents a critical appraisal of the *significant*, rather than the total, literature in the field relevant for drafting the 3S framework. We note that the draft compendium was developed over a shortened time period of 4 months rather than 1 year as originally intended. In Phase 2 of this project (discussed in the next steps section of the draft framework), we will develop a further, more robust compendium. This current compendium reviews recent refereed literature addressing two major streams of research relevant within the scope of the 3S framework such as:

- feedbacks between forests and climate, including harvest effects;
- impacts of different manufactured products on climate; namely long-lived wood products

as well as data and methods underlying both streams of research. While many of the complexities are analysed below, we note that for the first drafts of the 3S framework, the focus will be on carbon as the primary metric.

Feedbacks between forests and climate (including sequestration)

Nobody denies that forests are good for the environment and humans. They harbour much of the world's terrestrial biodiversity, providing habitat for various animals, including birds and insects. Forests are key to provisioning fresh water and are also a source for subsistence living in some cultures, where hunting and food gathering in forests contribute significantly to people's diets and lifestyles. They are also very valuable for the recreational opportunities they offer to humans. Moreover, forests are an important moderator of the Earth's climate. This function of forests is discussed below in detail.

Complexity of feedbacks between forests and climate

The feedbacks between forests and the climate of our planet are complex. The review below highlights some of the most important feedbacks. Planting trees changes the reflectivity of the Earth's surface, often measured with albedo, and therefore affects the Earth's temperatures. Scientists calculated the effect of increasing forest cover on the surface temperature, concluding that planting trees in the tropics would lead to cooling, but in colder regions, it would cause warming [1]. Forests emit a complex mix of chemical compounds including carbon dioxide (CO_2), methane (CH_4) [2], nitrous oxide (N_2O) [3], volatile organic compounds (VOC) [4], etc. VOC mix with fossil-fuel pollution from cars and industry so that an airborne harmful cocktail might be created. Nearly all plants emit VOCs during reproduction, growth, and as a defense. VOCs are used as a communication media between plants, on one hand, and between plants and insects, on the other hand. VOCs are not harmful to human health as long as they do not enter the chemical reaction with NOx leading to formation of ground level ozone or smoke. Chemical reactions involving VOCs emitted by all tree species produce ozone and methane, two powerful greenhouse gases, and form airborne particles that can affect the condensation of water vapor in clouds. Changes in tree VOC emissions might affect the climate on a scale similar to changes in the earth's surface albedo and carbon storage capacity [5].

Forests are also important in moderating the water cycle because of their evapotranspiration and shading functions. In the process of evapotranspiration, energy is absorbed, and surrounding air is cooled down. Tree cover effectively captures rainwater, prevents quick evaporation of rainwater from land surface, and reduces water runoff into the rivers. Forests cool the air by slowly releasing water extracted from soil and underground sources through evapotranspiration [6,7].

Forests play an active role in the greenhouse gas budget, because they absorb and emit carbon. In recent decades the world's forests have been a net carbon sink of 1.1 ±0.8 GtC/yr, with tree living biomass accumulating most of it [8] because they sequestered more carbon than they emitted. A recent study found a carbon sink of 0.85 GtC/yr in intact old-growth forest (because of the fertilizing effect of CO_2) primarily in the moist tropics and boreal Siberia, and 1.3 PgC/yr located in stands regrowing after past disturbance [9]. Therefore, net carbon uptake in forests slightly offset the anthropogenic emissions of carbon, which have been continuously rising and reached 11 Gt C per year in 2018[10]. Importantly, a large portion of the current terrestrial carbon sink is transient in nature. Forest fires and insect outbreaks, which become more frequent with climate change [11,12], release carbon stored in forests into the atmosphere [13]. In addition to carbon, these natural disturbances emit other chemical compounds and heat (in case of forest fire).

Among all ecosystems, forests store the largest amount of carbon globally (~791 GtC) followed by peatlands (~220 GtC) [14]. Peatlands and mangroves, however, have the highest fraction of stored carbon that is irrecoverable [14]. Globally, broadleaf (hardwood) forests occupy larger area (~ 17,502,000 km^2, 57% of the total forest area) and store more carbon (~442 GtC, 56% of the total forest carbon) than the coniferous (softwood) forests. Coniferous forests occupy 13,110,000 km^2 (43% of the total forest area) and store 349 GtC (44% of the total forest carbon). Most coniferous forests are located in the temperate and boreal climate zones, while most broadleaf forests are located in the tropical climate zone.

The feedbacks discussed in this section operate on different timescales. The short-term feedbacks include emissions of various gases and water. Accumulation and storage of carbon in forest biomass and soils belong to the long-term feedbacks.

What feedbacks between forests and climate have been quantified?

There is a large body of scientific literature focusing on quantification of various feedbacks between forests and climate briefly reviewed in the previous section. Most of these studies investigate one or two feedbacks [1,5-7] at a time because quantification of multiple feedbacks requires complex numerical models including coupled climate and forest dynamics.

Only one recent study [15] addressed those multiple feedbacks simultaneously using LMDzORCAN model, which incorporated climate and forest dynamics. The authors quantified trade-offs of using

European forests to meet climate objectives including several scenarios. Each scenario was associated with certain trade-offs, and none was perfect in mitigating changes in climate. They concluded that adapting forest to future climate with the goal of provisioning wood products and other ecological services is the best strategy. They also emphasized that forest management alone will not be sufficient to meet climate objectives in Europe.

Importantly, the contribution of forests to the greenhouse gas budget, e.g., by absorbing, storing and emitting CO_2, is only one of many impacts of forests on climate, which were discussed in the section above. Any large-scale effort in changing forest cover may lead to the additional feedbacks on climate discussed above.

Carbon uptake, storage, and release from forests

The focus of this section is on quantification of carbon storage in natural and managed forests, their ability to absorb carbon through photosynthesis from the atmosphere and emit carbon through respiration of trees and soils, forest fires and insect outbreaks. Photosynthesis is the fastest natural way to transfer carbon from the atmosphere to land or potentially ocean. Once carbon is absorbed, it can become incorporated in the plant material or transferred to soil after a plant dies. Carbon is released with respiration of plants or soils, fires, and insect outbreaks. Forests store most carbon in living and dead biomass as well as in soils.

Below, the review includes studies focusing on afforestation, timber harvest, forest management and recorded responses of climate to those measures. In the estimates provided below, one ton of carbon equals 3.67 tons of carbon dioxide.

Effects of Afforestation

Because forests actively uptake carbon from air and store it long term in their biomass and soils, various actors from governments to businesses to NGOs are embracing efforts to mitigate climate change by reforesting cleared areas and planting trees on a massive scale from the city [16] to the country [17]. Scientists support these efforts by quantifying the benefits of afforestation but also caution about its possible unintended consequences, such as changes in albedo, VOC emissions, and a misguided prioritization of afforestation over emissions reductions. Bastin et al. [18] found that after excluding existing forests, agricultural and urban areas, there is space for an extra 900 million hectares of tree cover globally in areas that would naturally support woodlands and forests. This estimate was calculated under existing environmental conditions and would change with changing climate. These additional forests could store 205 GtC (752.35 $GtCO_2$, annual sequestration of 0.75 $GtCO_2$/ha) of carbon over 100 years. This addition would almost double the current carbon pool in living tree aboveground biomass ~220 GtC [19]. Cook-Patton et al. [20] estimated that 678 million hectares worldwide can support second growth forest and can absorb 48-73 GtC (31-48 GtC aboveground) over 30 years (from 2020 until 2050 with annual sequestration of 1.6-2.43 GtC or 5.9-9 $GtCO_2$). Fuss et al. [21] estimated that afforestation and reforestation can potentially sequester 0.5-3.6 $GtCO_2$ per year by 2050.

Although it is generally assumed that global forest area is decreasing, Song et al. (2018) claimed a net increase in tree cover by 2.24 million km^2 (+7.1% relative to the 1982 level). We have to distinguish between loss of native forests and gain of plantations, as well as planting of trees in non-forest ecosystems, considering not only climate impacts but also associated impacts on biodiversity and local communities. These trends are dynamic and vary with geography. After continuous increase in European forest area in the end of the 20th century, a recent analysis of remotely sensed data detected abrupt increase in harvested forest area (49 %) and increase in biomass loss (69%) for the period 2016-2018 relative to 2011-2015 [22]. This forest loss concentrated over Nordic and Baltic countries and the Iberian Peninsula and was attributed to increased biomass use for industrial purposes.

Cook-Patton et al. [20] analysed carbon accumulation rates in forests worldwide using over 2000 field samples from a literature review, which is the largest dataset available to date. Rates of total carbon accumulation in plant biomass were higher in warmer and wetter climates than in cooler and drier ones. In contrast, accumulation rates of soil carbon did not vary significantly across different biomes or with soil texture. Carbon did not accumulate significantly in litter and coarse woody debris of naturally regrowing forests during the first 30 years.

Holl and Brancalion [23] reviewed recent tree planting efforts worldwide including beneficial outcomes and unintended negative effects. They suggest that promoting afforestation as a simple silver bullet solution may overshadow other actions that have greater potential for addressing the drivers of specific environmental problems. These include rapid steps to reduce deforestation and greenhouse gas emissions from industry, transportation, and residential sectors.

Effects of forest management and climate change

Changes in management and climate can lead to additional storage of carbon in existing forests. The management measures include fire management, avoided wood fuel harvest, increased rotation time, reduction in overharvesting, etc. Griscom et al. [24] estimated that improved forest plantations, fire management, and avoided wood fuel harvest would sequester 16.22 Gt CO_2e per year by 2030.

High atmospheric CO_2 concentrations, longer growing seasons, warmer temperatures, forest regrowth, and increasing nitrogen mineralization have been identified as the main drivers of current increases in the productivity of vegetation globally [25-27]. Vegetation in 2018 was a sink of carbon of 3.8 GtC per year [10,], absorbing ~35% of the carbon emitted from burning fossil fuels and land use change globally. While local [28] and global [29] studies suggest that climate change will likely enhance forest growth in the future, it remains unclear how long CO_2 fertilization effects, especially in nitrogen-limited forests, will persist [30] and continue to mitigate climate change. Enhanced carbon sequestration in forests may be reinforced, counteracted or even offset by concurrent changes in surface albedo, land-surface roughness, emissions of biogenic volatile organic compounds, transpiration, and sensible heat flux [15].

Pugh et al [9] estimated that forests would accumulate an additional 69 (44-131) GtC in live biomass from regrowth alone if natural disturbances, wood harvest, and reforestation continue at rates comparable to those during 1981-2010.

Analysis of the absolute net annual increments, which indicates forest growth, and wood removals or harvest from 1990 to 2010 showed that 43 out of 65 evaluated countries [31] harvested less wood than grown by forests [32]. Overharvesting in countries where wood removals exceeded the net annual increment has declined from 0.09 GtC per year in 1990 to 0.05 GtC per year in 2010. These data imply that 66% of countries analyzed had the capacity to harvest more timber in 2010. Their unexploited harvest potential was 0.68±0.26 GtC per year in 2010.

Plantation forestry designed to provide multiple ecosystem services can reduce pressure on natural forests, and can even restore some ecological services provided by natural forests [33]. To date, planted forests occupy 7% of the world's forest area, but grow 40% of the wood harvested globally [34]. Annual wood production from planted forests is projected to reach 0.4-1.75 GtC in 2050 [35].

Projections of sustainable forest harvest estimated by the global vegetation model JSBACH [36] for non-protected forest areas showed that sustainable annual wood harvests could increase up to 3.6-4.9 GtC globally by 2050.

The increase in harvest rates required to sustain the increase in wood utilization will reduce forest carbon stocks at least in the short-term. Through sustainable forest management, a new steady state of growing stock could be achieved over time and the increased annual wood harvest could be sustained, but the transition to that point will likely result in increased carbon emissions from forest ecosystems. These emissions have been quantified for Canada [37] and Europe [38]. Pilli et al. [38] evaluated different management strategies until 2030 (ignoring climate change) and the climate change mitigation benefits. For Canada and Europe, they found that timber harvesting decreases carbon stocks and also that using wood for construction is a much stronger carbon sink than for bioenergy in the longer term (substitution effects were not considered). They found only a limited effect of natural disturbances (only fire had a substantial effect) on carbon stocks. They show that forest harvest in Europe captures 12% of annual net primary production (NPP) as merchantable wood. There are differences in the relationship of NPP and biomass stock between countries. Smyth et al. [37] evaluated different management strategies of Canadian forest and subsequent forest product use (long-lived forest products versus bio-fuel) in mitigating GHG emissions. Their results confirm that strategies focusing on long-lived products perform better than strategies focused on bioenergy, because of longer product lifetimes.

Storing carbon in forests over the long term becomes less reliable because of the changing dynamics of forest disturbances such as fire, wind, and insect outbreaks, which are closely linked to climate change [11,12] and can decrease forest growth and storage of carbon in forests [13]. For example, droughts and frequent heat waves have been shown to reduce forest productivity and net carbon uptake [39,40]. Lundmark et al. [41] showed that the storm Gudrun in 2005 turned the Swedish forest into a carbon source, indicating substantial risk to sequestering carbon in the forest. In North America, increasingly hot droughts killed most of the trees in an area of 1,200,000 ha in the Southwest and warming-driven pine beetle outbreaks affected forests in Northwest at a rate of 6,000,000-7,000,000 ha per year between 2005 and 2008[42]. These numbers are comparable to the recently reported deforestation rate of 5,000,000 ha per year[43].

Lemprière et al. [44] reviewed different climate change mitigation options and their trade-offs for Canada's forests. They emphasize a need for a system perspective, which highlights trade-offs between activities aimed at increasing carbon storage in the ecosystem, increasing carbon storage in harvested wood products and substituting them for mineral-based products or fossil fuels. Afforestation in Canada as in any other regions with snow cover may result in higher temperatures, because it decreases surface albedo. They concluded that in the short term, the largest climate change mitigation potential is in avoiding GHG emissions and maintaining carbon stocks in Canadian forests. Over the longer run, the largest mitigation potential is in activities that increase forest removals and substitute forest biomass for more emissions-intensive products and energy sources. Objectives addressing climate change mitigation require carbon emissions' reduction over a few decades.

Data and methods available for quantification

This section reviews methods, models, and data available for quantification of carbon storage, uptake and emissions from forests and their response to management and climate change.

Methods & Models

- Comprehensive coupled climate – vegetation model with forest management module, LMDzORCAN model [15];
- Global vegetation model JSBACH [36] includes climate change, natural disturbances and sustainable forest harvest;
- model-based approach to evaluate the GHG impacts of various forest management and wood use scenarios [37,45] does not include climate change impact on forests;
- Projections of carbon storage in forest plantations [35] under different management scenarios and climate change;

- Biome-BGC model - scalable ecosystem process model simulating carbon, nitrogen and water cycles using climate variables, CO2 concentration, nitrogen deposition as drivers;
- Additional models/tools reviewed in design and user requirements annex, including those from the Efeca report, which we previously collaborated on with Climate KIC.

Data sets

- Satellite data of forest extent and biomass (e.g., 200 m BIOMASS mission) – cover areas from region to the globe;
- Forest inventories – available for many countries;
- Forest annual increments and removal for 65 countries [31];
- Global map with carbon accumulation rates in naturally regrowing forests at 1 km resolution from ensemble machine learning model based on 2118 data points [20];
- Global database of carbon stocks and fluxes [46];
- Global forest age dataset [47];
- Climate projections
  - NEX-GDDP: NASA Earth Exchange Global Daily Downscaled Climate Projections data from Google Earth Engine, which allows for multiple greenhouse gas emission scenarios explained in the paper by Taylor et al. 2012. It allows for multiple scenario adjustments;
  - ISI-MIP climate projections.

Impacts of different manufactured products on climate (including storage and substitution effects)

In the first instance, the 3S framework will focus on the impacts and potential of long-lived wood products such as mass timber. However, several manufactured products are discussed below for completeness in the preliminary research. The manufacturing of products has multiple impacts on climate. These include emissions of greenhouse gases and heat, contribution to the urban heat island effect in densely built-up settlements (for building materials only), and disturbance of ecosystems through resource extraction (e.g., mining). The most studied effect is the emissions of greenhouse gases from burning fossil fuels associated with energy generation for raw material extraction, transport, product manufacturing, its use, and its disposal. These emissions have been quantified for different types of materials used in construction [48].

Emissions of heat accompany all life cycle stages of a material. This heat is often referred to as waste heat. Research to date has not defined estimates of heat associated with manufacturing and use of specific products and their direct impacts on climate. Usually, the estimates of waste heat and their influence on climate are reported at an aggregated level. For instance, the waste heat emitted from cities was shown to be responsible for the Northern Hemisphere winter warming [49]. Most building materials accumulate heat during the day and release it at night. The ability of a material to accumulate heat is referred to as thermal conductivity. The difference between average thermal conductivities of different materials is very large from 0.2 W/mK (wood) to 1.25 W/mK (concrete) to 60 W/mK (metals) [50]. The ability of materials to absorb and release heat is an important contributor to the urban heat island effect, which was shown to influence the climate of densely populated regions such as Europe for example [51]. A recent study documented a downwind footprint of the urban heat island of Chicago, USA not only on air but also on lake temperatures. Over the Lake Michigan the magnitude of the heat plume was reduced by half suggesting the lake was acting as a sink for the exported urban heat [52]. The heat accumulating in water does not disappear but is slowly released in the atmosphere and can further contribute to regional warming.

Contemporary construction across the world has two additional poorly researched yet relevant impacts on the carbon cycle and potentially climate: first, the production of cement, concrete, asphalt, glass, etc. requires vast amounts of sand extracted from beaches, rivers, and seafloors; second, mining can lead to extensive local deforestation. The sand mining not only exerts substantial pressure on available deposits, which have become an increasingly scarce global resource, but also compromises the carbon uptake capacity of the aquatic ecosystems disturbed during extraction [53]. Together, the mining infrastructures and the development of mineral commodity supply chains are responsible for a disproportionate loss of forests surrounding mines and resulting loss of stored carbon. Mining-induced deforestation in Brazil alone was responsible for 9% of all Amazon forest loss in 2005-2015: twelve times more than the area deforested within permitted mining leases [54]. The below mostly focuses on the emissions of carbon dioxide associated with production of different materials, because assessments of the other two impacts (waste heat release and material thermal properties) on climate are outside of the 3S scope.

Climate mitigation strategies focusing on increased use of wood products rely on benefits of an increased carbon pool in harvested wood products and avoidance of emissions from fossil-based, e.g., plastic and polyester, or energy-intensive materials, e.g., concrete, steel, glass. Review studies (e.g. [55,56]) suggest that substitution of mineral-based materials by bio-based ones can provide substantial climate mitigation benefits. Such a strategy can be realised by increased wood harvesting (with trade-offs in the biomass carbon pools) as well as by intensifying recycling rates and extending the useful life span of wood products [57]. While substantial progress has been made in determining the size and changes in the harvested wood product carbon pool, quantifying the magnitudes of substitution effects remains a challenging undertaking.

The climate benefits of using wood can best be estimated by comparing emissions of greenhouse gases of a product designed from wood to a product made of other types of materials (e.g., cement and steel [32]) and ideally by taking into account the full life cycle of the manufactured product (production, use, and end of life). However, it is not always feasible to estimate emissions for all individual types of products and their substitutes. Instead, to date, a more general substitution factor (or displacement factor) has been developed to describe how much greenhouse gas emissions would be avoided if a wood-based product were used instead of another product to provide the same service - be it a chemical compound, a construction material, an energy source or a textile fibre. Overall substitution effects can then be estimated by combining the quantity of wood products that are produced or consumed, with product-specific substitution factors. Leskinen et al. [58] found that the large majority of substitution factors found in the literature indicated that the use of wood and wood-based products are associated with lower fossil and process-based emissions when compared to non-wood products. Most of the substitution factors found in literature are related to construction, with most emphasis on the manufacturing stage. Substantially fewer substitution factors were available for other product types, e.g., furniture, packaging, textile fibres and biochemicals [58, 59].

Although many assessments of the substitution benefits to date rely on the substitution factors, this method has been recently heavily criticized. Harmon [60] demonstrated that such assessments may have overestimated the product substitution benefits by 2- 100-fold. These factors do not stay constant over time because changing manufacturing methods impact embodied energy of materials, recycled materials might replace raw materials, the mix of fossil fuels used to generate energy can change over time, and carbon storage of some mineral- based materials can be enhanced.

Mineral-Based Materials

A recent study concluded that if the global population increases to 9.3 billion by 2050 then the emissions from the development of new infrastructure could claim 35-60% of a remaining carbon budget [61] based on limiting global temperature increase to 2°C. Further reductions in the energy demands and associated greenhouse gas emissions associated with the manufacture of mineral-based construction materials will be challenging, as these industries have already optimized their production processes. Future improvements in energy efficiency per ton of material are thought to be limited to 24% for steel and 13% for cement [61], which dominate materials energy use worldwide [62]. Replacing fossil fuels by renewable energy sources will never reduce CO_2 emissions from steel and cement manufacture to zero because of emissions that emanate from associated chemical reactions [63]: calcination in cement production and use of coke from coking coal to reduce iron oxide in steel production. In 2014, these represented 1320 Mt CO_2 for cement and 1740 Mt CO_2 for steel [63]. For cement production, about 60% of the total emissions [64] stem from calcination, with some of it[1] recaptured slowly through the subsequent carbonation of exposed surfaces of concrete structures and waste [65].

The buildings and construction sector currently accounts for about half of all global steel demand [66]. The associated energy demand in steel production could be reduced by 60 to 95% [67] by using secondary rather than primary raw materials. The supply of secondary materials is however limited to 30 to 40% of primary input [68] because of the several-decade time lag between metal products first use and the end of their useful life [69]. The end-of-life recycling rate of steel in construction is at 85% with expected efficiency gains of up to 90% by 2050 [69]. Further efficiency gains in steel recycling will not change the magnitude of available old scrap if the steel demand continues to grow over the same period [70].

All construction materials store carbon, but in different chemical forms and amounts of radically different magnitudes. The carbon content of steel is 0.4% by weight [71] and does not change over time. The carbon is incorporated in the initial blast furnace process by adding "coking coal" (a high-quality coal) to the molten iron [72]. The average carbon storage of steel is 0.004 tC per ton of steel. Fresh cement contains no carbon, but it changes over time because calcium oxide in cement materials is not stable. Carbonation occurs when CO_2 diffuses into the pores of cement-based materials and reacts with cement-hydrated products in the presence of water. Carbonation starts at the surface of a cement product and moves inside of material over time. Rate of carbonation depends on air pressure, temperature, humidity, and atmospheric CO_2 concentrations [73]. The maximum possible carbon storage in cement after full carbonation, i.e., when it turns into calcium carbonate, is 0.12 tC per ton of cement. The carbon content of cement can be increased further by adding biochar instead of sand at the manufacturing stage, which also improves product properties [74].

Bio-based Materials

Biomass from many plants has historically been used for production of different products. These include timber, bamboo, hemp, straw, rattan, etc. [75]. However only timber and bamboo can be used in design of primary structure of buildings, which is its heaviest part and has the potential to store the largest amount of carbon. A recent study suggested that the primary superstructure accounts for the largest share of carbon storage (~80%) in a building assembly, while enclosure composed of cross-laminated timber (CLT) and cellulose insulation only accounts for ~20% of the total [32].

Carbon emissions from manufacturing biomass-based materials depend on the harvesting practices, transport distance, the type of material produced, as well as the amount of energy used in manufacturing [75,76]. The emissions range from 0.3 kg CO_2 per kg of material (lumber) to 0.7 kg CO_2 per kg of material (glulam, glued laminated timber) [48]. The largest share of carbon emissions from laminated timber products stems arguably from glue production [76].

The amount of carbon stored in timber materials depends on the wood type and its carbon to wood ratio as well as wood to glue ratio for timber products containing glues, e.g., plywood, fiberboard, etc.

[1] We note that these numbers are debated, so are not included here.

Usually, the amount of glue relative to wood is assumed to be negligibly small. The average and the range of carbon storage values in one ton of timber can be calculated as a product of wood mass (1 t) and global wood to carbon ratio (0.476± 0.04) obtained from an analysis of the database of 2,228 wood to carbon values representing 636 tree species across all forested biomes [77].

Bio-fuels

Bio-fuels are currently the largest use of timber products globally [78]. Almost 50% of harvested timber will be turned into fuels and burned within two years after timber harvest. Production of biofuels is almost never carbon neutral. Neutrality is based on the assumption that after harvest, forest regenerates and its carbon sequestration will offset the CO_2 combustion emissions from burning biomass if forest is allowed to return to its pre-harvest C stock level before next harvest[2]. During regeneration the forest may become a carbon source for decades. In addition, if forest is harvested too often and carbon stocks of forest do not regenerate to the pre-harvest level, then C neutrality is compromised.

The fundamental difference in using timber for long-lived products rather than biofuels is the fate of carbon after timber harvest. While all carbon contained in one ton of timber is emitted to the atmosphere when timber is burned, this carbon will be retained on land if timber is converted to long-lived wood products. In the latter case, carbon has a potential to be stored on land indefinitely once technologies are developed to process and safely landfill unrecyclable wood from demolished buildings. Re-directing roundwood from use as a fuel to long-lived products would be the most beneficial for climate change mitigation; its benefits have been demonstrated for Canada[37] and Europe[38].

In response to rising fuel prices and increasing public scrutiny, mineral-based industries have been looking into reducing their energy demand and exploring alternatives to fossil fuel energy sources. A study reviewing the potential for renewable energy use in major mineral producing countries found that most of their CO_2 emissions (71%) arise from burning fossil fuels used in thermal applications with the rest coming from indirect electricity generation [79]. The highest theoretical potential for reduction of emissions was attributed to the *increased use of biofuels and charcoal* instead of fossil fuels (up to 46% of total industry net emissions), followed by using renewable hydrogen (28%), hydropower (22%), and solar, thermal and electrical production (2–7%). Burning biofuels and charcoal instead of fossil fuels is not the best option, if we are to restore the carbon cycle as these options do not enhance, but reduce carbon stocks on land [80] and pose competition to long-lived timber products for harvested timber.

Data and Methods available for quantification

Methods & Models

- Global Forest Product Model (GFPM)[81];
- Assessment of carbon emissions from manufacturing building materials and carbon storage in buildings [32];
- ToSIA developed by the European Forest Institute (http://tosia.efi.int/). ToSIA analyses environmental, economic, and social impacts of changes in forestry-wood production chains, using a consistent and harmonised framework from the forest to the end-of-life of final products.
- Life cycle assessments (LCA) – provide environmental and economic impacts of different products

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[2] Lemprière, T.C., Kurz, W.A., Hogg, E.H., Schmoll, C., Rampley, G.J., Yemshanov, D., McKenney, D.W., Gilsenan, R., Beatch, A., Blain, D., Bhatti, J.S., Krcmar, E. (2013) Canadian boreal forests and climate change mitigation. Environmental Reviews 21, 293-321.

    - GABi – software combining LCA modelling and reporting software, content databases with intuitive data collection and reporting tools;
    - SimaPro LCA software package.
- Additional models/tools reviewed in design and user requirements annex.

Data

- Existing life cycle inventory databases provide data for generic technologies. The database is usually taken as a departure point. Then, more detailed data for specific products replace data in the database to get a more precise estimate. Available databases include
    - ECOINVENT – focusing on European industry;
    - USLCI – focusing on US industry, it can be downloaded for free www.lcatextbook.com.
- Substitution factors [60, 58];
- Carbon emissions coefficients [82];
- Material Intensity data for buildings from 300 data points [83].

Research Gaps

The research gaps described below stem from an extensive literature review presented in the compendium, reviewers' comments to the earlier repository draft, and preliminary interviews with the stakeholders. The division of research gaps into sub-categories and respective sub-sections below follows the logic used in the compendium. Description of each category starts with brief explanation of its relevance to the 3S Framework and concludes with potential impacts of these gaps on the outcomes of the 3S Framework and potential pathways to close the gaps.

Feedbacks between forests and climate

The objective of the tool "3S framework" is to allow stakeholders assessing how their choices can optimize the benefits of forests and forest products for climate change mitigation, while maintaining and enhancing forest biodiversity. The feedbacks between forests and climate are fundamental for understanding and predicting consequences of any action applied to forests. Therefore, it is important to take a holistic view on the feedbacks between forests and climate and identify the unknowns in these feedbacks.

Gaps in knowledge

- Uncertainty in the future of forest growth, its responses to natural disturbances such as heat, fire, insect outbreaks, and changes in climate which all have profound impact on the forest carbon cycle;
- Response of climate to complex feedbacks between changing forests and climate such as albedo effects, emissions of biogenic volatile organic compounds, evapotranspiration, which may strengthen of mitigate climate change.

These gaps can be filled using outputs from ongoing field observations of forest responses to natural disturbances and changing climate in natural conditions and specially designed experiments, e.g., Free Air Carbon Dioxide Enrichment (FACE) experiments. In addition, numerical models can provide various scenarios for forest growth responses. Forest ecosystem models capturing biogeochemical processes would be preferable to the forest models based on tree growth inventories or neural networks algorithms, as they can better predict forest growth under climate conditions, which forests did not experience in the past. A coupled ecosystem-climate model is needed to investigate complex feedbacks between changing forests and climate. The climate model ideally should have atmospheric chemistry module able to trace the impacts of biogenic volatile organic compounds on ground level ozone formation and aerosols. While forest (ecosystem) models of various complexity exist, there are very few numerical tools able to simulate feedbacks between changing forests and climate and none of them includes atmospheric chemistry. This is currently an active field of research.

Although the 3S Framework will not be able to quantify these complex feedbacks, it should raise awareness about those feedbacks, which may become important as transition to timber cities and extraction of timber scales up. Moreover, tools for quantification of these feedbacks may become available in the future and at some point incorporated in the advanced version of the 3S Framework.

Forest management, carbon cycle, and climate

Effects of various forest harvesting techniques on forest carbon uptake and storage capacities are at the core of the 3S Framework, because the first of three "S" refers to carbon *sink* function, which is the capacity of the forest to absorb carbon from the atmosphere and sequester it in above- and below-ground biomass.

Gaps in knowledge

- Effects of forest management on the carbon uptake and storage capacity of forests under climate change are uncertain, because management has to be adapted to climate change. The records of those interactions are limited to recent decades, fragmented, and limited to a few geographical regions;
- How to leverage existing natural forest management methodologies, e.g. moon wood harvesting, etc. and create a repository of those.

Gaps in methods & data

- Annual forest growth increments and wood removals for some countries do not exist, because growth increments are difficult to estimate for countries with large forest areas like Canada or Russia;
- Effects of different forest management techniques on forest carbon does not exist for certain regions of the world

There is a large body of literature focusing on the interactions between forest management, carbon cycle, and climate. These interactions are usually addressed using various numerical models. However, the traditional forestry models simulating forest growth and productivity under various silvicultural practices historically did not include forest carbon cycle or climate drivers. Although many of these models have been adjusted in the last few decades to include those as well, representations of carbon cycle and feedbacks between forest management and climate in those models, remain weak. The knowledge about forest management, its adaptation to changing climate, and their implications for the carbon cycle is fragmented and limited to a few regions of the world, where relevant data is abundant, e.g., Europe.

These gaps will result in uncertainties of estimates for carbon uptake and storage in forests and their responses to forest management and changing climate, which 3S Framework tool will provide. These uncertainties will be most likely larger in regions where data are scarce and smaller for regions with ample research and relevant data.

Safeguards

Gaps in knowledge and consensus

- What are the appropriate safeguards/ sustainability standards for implementation to ensure to that using long-lived timber products do not have adverse impacts on forests/forest management/forest quality?
- More collaboration, research and effort is needed to answer the above. Reaching consensus on this particular issue will take time, as there are many differing views.

Impacts of different manufactured products on climate

The second “S” in the 3S framework denotes the carbon *storage* function, which is the capacity of wood- based products (timber buildings, bridges, furniture, etc.) to store carbon for a significant period of time.

The third “S” in the 3S Framework refers to the carbon *substitution* function that results from the capacity of forestry-based products to substitute fossil-based products and avoid the greenhouse gas (GHG) emissions of these products.

The gaps in knowledge listed below refer to barriers, which have to be overcome if we want to accurately estimate storage of carbon in manufactured products made of wood and the substitution effect of forestry-based products for mineral-based products on GHG emissions and climate. Not all gaps listed below have to be filled before 3S Framework tool is able to provide quantitative estimates and guide the choice of stakeholders of products. However, massive transition to timber construction in cities will change not only forests, but also cities and their feedbacks with climate. It might even mitigate urban heat island effect. Even though we are not yet in the position to quantify these effects, the stakeholders should have a well –balanced view of multifaceted alterations that this transition might bring for cities.

Gaps in knowledge

- Waste heat release from individual product manufacturing and its implications for climate. This is relevant for assessing indirect material substitution effects on climate.
- Difference in contributions of material thermal properties to urban heat island effect and to regional climate. This is relevant for assessing indirect material substitution effects on climate.
- Effect of mining on forests and their carbon balance (deforestation, soil pollution, reduced carbon uptake of forest remnants). This is relevant for assessing indirect material substitution effects on climate and carbon cycle.
- Effect of sand extraction needed for cement manufacturing on the carbon uptake of aquatic ecosystems. This is an indirect effect on the carbon cycle, which is currently not included in any material substitution assessment.
- Differences in the life span of buildings designed with timber materials versus cement and steel buildings. Preliminary findings from Getty Institute suggest that wood and stone buildings live longer than steel and concrete. Finding refereed publications covering this issue are crucial for understanding the residence time of carbon in wooden buildings and long-term material substitution effect.

Gaps in methods & data

- How harvested wood is utilized and for how long different wooden products remain in use, i.e., contribute to the sink function;
- Data for carbon emissions (energy requirements) during material's use and end of life are scarce. There is no good source of data for the manufacturing stage of bio-based materials.
- Energy needed for the manufacturing of different materials. This is different from the embodied energy, which is the sum of energy consumed by all the processes associated with the construction of a building and production of building materials. A new study (Puettmann et al. in preparation) reports that timber buildings have higher embodied energy than concrete buildings, because biomass fuels with lower energy content and lower efficiency than non-renewable energy is used for lumber production. Because CO_2 released from combustion of biofuels is not included in the estimations of global warming potential (GWP), the GWP of mass timber building is lower than the one of concrete building.

This section highlights substantially more gaps than the previous ones. Filling many of these gaps will require not only additional targeted literature search and data collections, but also creating new methods for estimating those complex impacts as well as designing and conducting special experiments. The estimation methods will have to go beyond the ones used in life cycle assessments.

Gaps in Stakeholder/ user needs

- More stakeholder interviews and workshops will need to be conducted to understand user needs and interests. Further information can be found in the deliverable related to stakeholder engagement.

Summary

This repository contains information about major research gaps, which may pose a barrier for populating the 3S framework and suggestions how to fill them. The gaps are divided into five categories including 1) feedbacks between forests and climate; 2) feedbacks between forest management, carbon cycle, and climate; 3) safeguards needed for implementation of the 3S framework; 4) impacts of different manufactured products on climate, 5) needs of stakeholders and potential users of the 3S framework. For each gap category, we explain why and how this category is relevant to the 3S framework and suggest pathways for filling some of those gaps.

The major gap, which we have identified, is linking two types of feedbacks: between forests management - carbon cycle - climate and product manufacturing – climate. 3S framework should cover this gap along with a few others listed in this repository, which do not require extensive numerical or field experimentation.

There was more research performed and therefore we have better understanding of the feedbacks between forest management, carbon cycle, and climate than between different manufactured products, carbon cycle, and climate. Efforts of various intensity are needed for filling those gaps: from in-depth literature and data searches to designing and conducting targeted numerical model or field experiments. The major gap, which we have identified, is linking those two types of feedbacks. 3S framework should cover this gap along with a few others listed in this repository, which do not require extensive numerical model or field experimentation.

Draft 3S Framework

We have also developed deliverable on design and user requirements for the eventual 3S framework/tool. Those findings provide critical input for the draft framework as we collaboratively develop a 3S framework that builds on the strengths of existing tools and aims to overcome the challenges of previous related tools in scientific accuracy and successful use by target audiences. Simply put, we want the 3S tool/ framework to be both credible and accessible.

We reviewed 25 models which have relevance to the 3S framework[3]. A full spreadsheet documenting the examined models/tools and the criteria used is available at this link[4], while high-level descriptions and conclusions are offered in the text below.

We reviewed 25 models which have relevance to the 3S framework. Each of the models was reviewed for high-level content (including relevance of the model/tool to the 3S framework) and user-friendliness, including ease of use as well as transparency of assumptions, with the intention of gathering lessons learned for building the 3S framework. The review identified strengths, limitations, and roadblocks for further review, including barriers to use such as whether tools/models were open source or had a user interface. For those models/tools that were not open source or otherwise accessible, reviews were based on articles written about the models rather than direct use. Because not all information was equally available for all models/tools, the review took a qualitative approach (rather than a quantitative approach such as in Brunet-Navarro et al.'s 2016 review[5] of wood product models).

Of the models reviewed, three of the 25 included some aspect of all 3S's; however, the extent to which each of these meet the aims of the 3S framework is unknown due to the model not being open source (CARBINE), requiring expert consultation (CO2FIX), or having so many variables that the direct feedbacks between the 3S's were unclear (Global Calculator). While 13 of 25 were open source, only half of those had user-friendly formats. Some models, for example, had open source code, but did not have an accessible format such as a user interface. Each of the models/tools examined is designed to answer specific questions, at particular scales, and has strengths and limitations. For example, seven of the 25 are designed to be globally applicable, while the others are geographically specific. Some, such as LCA tools, are designed to address a single building, or a specific wood product, rather than considering carbon emissions and savings from building as well as forests. Moreover, LCA analysis often excludes forest management practices and considers a generic factor for wood. Most of the existing models/tools examined have specific target audiences for which they were designed, while a few are meant for broader groups of stakeholders. Existing models include forest ecosystem models and wood product models, including examples given in the Compendium above, and with few offering linkages between these model types. Identifying both the strengths and limitations of existing tools and models has provided a menu of potential aspects to carry forward into the eventual 3S tool. It has also outlined challenges to overcome which other existing tools have faced. These inputs are invaluable as we embark on phase 2. Aspects that we will consider including in the eventual tool, include:

- Framework and tool development are driven by stakeholder engagement, with a goal of solving problems and building consensus

[3] Research includes building off of recommendations from colleagues as well as existing research already conducted in the Efeca report.

[4] Please note the spreadsheet lined above includes several tabs, including an overview and user guide, written details of 3S-related tools that expands on the Efeca Annex VI and includes links to the tools and their references, a color-coded table of 3S-related tools and criteria to visualise high-level trends and characteristics, links to other tools collected but not extensively reviewed, a potential outline for the eventual 3S tool, and considerations for strategizing ways to maximise the utility of the eventual 3S tool. When downloadable, tool examples and relevant references were collected.

[5] Brunet-Navarro, P., H. Jochheim, and B. Muys. 2016. Modelling carbon stocks and fluxes in the wood product sector: a comparative review. Global Change Biology 22, 2555-2569.

- Framework/tool combines sink, storage, substitution, and end-of-life functions
- Tool and related methodology and assumptions are free and open-source, transparent, and accessible to all stakeholders
- Model includes such considerations as: biogenic C vs. fossil C; allows user to understand, and potentially establish, baseline scenario; includes Sustainable Forest Management; considers economic factors; considers policy; is adaptable by geography (country or ecoregion); and provides clarity and flexibility of timescale.

Potential challenges that we foresee based on our research include:

- Creating a tool that will help solve multiple stakeholder-identified problems (rather than, for example, trying to "convince" stakeholders to use it)
- Creating a holistic tool that is globally applicable by many different stakeholders/audiences
- Making a tool that is both scientifically robust and user-friendly (doesn't require expert help to use it)
- A tool that is accurately able to quantify the climate impacts and carbon debts incurred from forest harvest, and how those carbon debts will be made up over time through replanting, and the storage and substitution of the forest products produced.
- Determining what type of tool would be most useful and would be used in a meaningful way for decision-making
- Balancing the ability to seek feedback and interact with users without unintentionally discouraging use through steps such as registration
- Accounting for how tool is ultimately used including determining reasons why stakeholders might make decisions beyond climate benefit

Designing a tool that is both complex enough to accurately represent a complex system and user-friendly enough to be accessible for a wide range of stakeholders will be challenging. With few exceptions, models that are sufficiently complex to integrate the 3S's often are not also user-friendly for a wide variety of stakeholders. However, prior to undertaking this endeavour, it will be critical to complete additional stakeholder interviews to ensure that the stakeholders whose problems this tool might most pressingly solve will find the 3S tool credible, accessible, useful, and easy to use. Most of the existing models/tools examined provided insights for one or more aspects of the 3S framework and offer promising examples off which the 3S model and eventual tool could be built. In terms of content, some of the more promising models—i.e., those that seemingly include the 3S's—are lacking in transparency of assumptions or require inputs that are complex. For example, CO2FIX requires the user to supply most of the input data including stand biomass, carbon content, wood density, turnover rate, mortality, harvest rotation length, raw material allocation, process losses, fuel type for substitution, end of life, and recycling life span.

Next steps will include analysing which existing models/tools are promising enough to invite further exploration, including examining which models most closely and accurately represent the needs we are seeking to address. Later in Phase 2, model and web development expertise will be needed to help frame possibilities for tool design.

Guiding questions

Design of the 3S framework, including the numerical aspects, begins with defining the guiding question(s), which steer the model development. Tentative guiding questions for the 3S Framework are listed below. We note that these questions are helpful for defining the framework but are more broadly questions that we seek to gain a more holistic understanding of in relation to forests, sustainable forest products and climate. Each question reflects primary interests of different stakeholder groups. Stakeholder groups are broadly represented in **Figure 1**, and eventually the 3S framework/tool should serve to benefit all identified user groups. However, in the first instance, our analysis tells us that we should start by focusing on policymakers and investors as the priority stakeholders and users of the 3S Framework. Further, our analysis tells us that the framework/tool should not address benefits of a particular manufactured product or a building but provide general guidelines to the above mentioned stakeholders how their choices can maximize the potential of forests and forest products to mitigate climate change.

- Is it beneficial (in all meanings of the word) to use wood for construction?
- Shall we preserve forest or sustainably harvest it? In what places and under what circumstances is one of these options preferable over the other?
- How should the forest be used, or not used?
- How are sustainability / safeguards highlighted throughout the 3S framework?
- How can we build a framework/tool that is holistic and appeals to the broad group of stakeholders who would benefit from its use?
- How do we develop a tool that builds on what already exists? For example, we are aware that there are several tools already in existence that calculate the carbon benefit of building with mass timber, but they are complex, and much data is needed to get full usability from such a tool.
- Based on the question above, how do we build something that begins to connect the complex and developed forestry and LCA systems, which in many cases, seems to be the missing link?
- How do we include important factors such as end of life, and transportation emissions in the framework itself?
- Assuming sustainable rates of forest regrowth at the landscape level (under current and future climatic conditions), what percentage of forests in that landscape could be harvested sustainably? (For example, the WWF biogenic carbon footprint calculator for harvested wood products includes forest regrowth rates that assume that the species harvested are regrowing in the ecoregions from which they were harvested.)
- What is the impact on land available for food production if demand for sustainable forest products, and associated increased need for afforestation, continues to rise?

Assumptions for the numerical model

Because any numerical model is a highly simplified abstraction of a real-world system, we need to make assumptions about the major building blocks and processes underlying the dynamics of the modelled system.

1. The modelled system consists of the following building blocks: forests (ecosystems) and the built environment as well as potentially manufacturing facilities and atmosphere (climate);
2. The major “currency” is carbon (or CO2e) – major element that the building blocks of the model exchange.

We note that this list will be revised and extended as we proceed with development of the model.

Methodology

Methodology of a numerical model is based on the guiding question(s) and assumptions. The 3S framework encompasses a snapshot of the urban carbon cycle, which represent cycling of carbon between city and hinterland as well as within a city. Urban areas concentrate carbon fluxes because of the dense urban population, the size of the urban economy, and the production of energy for the built environment, which is closely connected with the emissions of carbon from fossil fuel burning. Urban areas rely heavily on the ecosystems outside of their administrative boundaries, the hinterland, to acquire energy, materials, food, and other resources and to discharge waste. In cities, carbon cycles through natural (vegetation, soils, animals) and anthropogenic (buildings, transportation) pools. Photosynthesis of urban vegetation is the only significant pathway for carbon uptake within a city. Some of the sequestered carbon is stored in biomass of urban trees and soils. In addition to that, accumulation of carbon in other urban pools, e.g., buildings, results from carbon transfer from hinterland to the city. Therefore, the urban carbon pools and fluxes are closely linked with carbon pools and fluxes of ecosystems in the hinterland (urban carbon footprint).

The 3S framework tool should simulate cycling of carbon between ecosystems and city and as well as associated emissions of carbon into the atmosphere. This framework will connect urban pools of carbon such as buildings, vegetation, etc. with the ones of the ecosystems through transfer of carbon from ecosystem to the built environment. Our research shows that to date, a framework that connects these complex and well-developed/ researched systems does not yet exist, but would be welcomed by the community, and would fill research gaps about the trade-offs/ co-benefits of climate and forests/ forest products. Below is a description of the possible building blocks of the 3S tool and processes underlying carbon cycling between and within these components. Where appropriate, the underlying principles of the models currently available are reviewed.

The major building blocks include ecosystems and the built environment/ the city. Additional building blocks could include sawmills, manufacturing facilities, and the atmosphere.

Ecosystem

Ecosystems stores carbon in living and dead biomass as well as in soil. Green plants uptake carbon through the process of photosynthesis and thereafter allocate carbon to stem, roots, leaves, etc. As long as a plant is alive, it respires carbon because of growth and maintenance processes. Carbon is also released into the atmosphere from decomposition of organic matter in litter and soil. There is a net carbon release into the atmosphere from an ecosystem damaged by insect outbreaks, fire, drought, or harvest.

Drivers of ecosystem carbon uptake, release and storage

Various environmental factors including climate, soil composition, fire, as well as anthropogenic factors such as air pollution, acid deposition, fertilization, and management practices influence vegetation growth as well as the rates of carbon uptake, release, and accumulation. Different methods exist to estimate forest productivity from environmental conditions. A traditional method to estimate forest growth and yield is based on stand age, density and site index [84]. This method works well for natural stands and individual trees where data on past growth can be used to predict future growth. Under changing environmental conditions, this method is not very useful. A different method called gap forest modelling is based on the dynamics of individual trees: disturbance, recruitment, and mortality processes, which are determined by site variables including climate [85]. These models, however, are of limited use on a large spatial scale because of the increasing complexity of simulations. They are also not applicable to other vegetation types.

Biogeochemical models estimate growth of different vegetation types using seasonal dynamics of canopy carbon and nitrogen balances. An advantage of the biogeochemical modelling approach is that it not only allows estimating productivity of different vegetation types over large areas, but it also quantifies causes of possible decline or increase in vegetation productivity. For instance, the biogeochemical model BIOME-BGC [86,87] estimates stem primary productivity (*SPP*) of forests using the following factors:

SPP = f (T; P; VPD; SW; SRAD; CO2; NDEP; LAI; SOILC; SOILN);

where *T* is the air temperature, *P* is precipitation, *VPD* is the vapor pressure deficit, *SW* is the soil water content, *SRAD* is the solar radiation at the top of canopy, *CO2* is the atmospheric carbon dioxide concentration, *NDEP* is the atmospheric nitrogen deposition, *LAI* is the leaf area index, *SOILC* is the carbon concentration of soil, and *SOILN* is the nitrogen concentration of soil. Thus, BIOME-BGC is able to capture effects of a number of abiotic (temperature, vapor pressure deficit, soil water, solar radiation, atmospheric CO2 concentration, and atmospheric nitrogen deposition) and biotic (leaf area index, soil carbon and nitrogen contents) controls on stem productivity.

Impact of anthropogenic and natural disturbances on ecosystems

The anthropogenic disturbances include forest harvest, clearing land for mining, as well as contamination of ecosystems by liquid and gaseous pollution accompanying mining. The natural disturbances include droughts, fires, storms, and insect outbreaks. All these disturbances reduce photosynthetic uptake of carbon by ecosystems and enhance carbon release from ecosystem into the atmosphere, e.g., ecosystem respiration. An ecosystem often becomes a net source of carbon after a disturbance.

For instance, release of carbon usually accompanies timber harvest. Carbon is emitted from soils disturbed by harvest, from decomposition of biomass, which remains on site, as well as from machinery used in logging operations. Harvest efficiency varies widely among different countries. In some regions with active logging operations, emissions of carbon reach disproportionally high levels: the net emissions from forest sector amounted to 50% of emissions from energy sector including transportation, residential/commercial, industrial, and agriculture emissions in Oregon, USA [88]. To reduce damage to the forest ecosystem as a whole, various harvesting practices have been developed over the centuries. These include for instance harvesting in winter (i.e., when the soil is frozen), taking into account moon phases (when the tree sap is at its minimum [89]), selective cutting, or careful attention to such issues as road width and felling damage (e.g. reduced-impact logging for climate change mitigation, RIL-C). In contrast, clearcutting forest practices, which are cost-efficient and can be performed, but substantially more destructive for ecosystems, are still widely used in many countries. A reduction in emissions can be achieved by improving efficiencies of forest harvest and product manufacturing, longer forest rotations, using renewable energy sources, using lignin-based adhesive technologies or mechanical lamination[90] techniques. These latter improvements would avoid the massive increase in production of synthetic glues and adhesives and their potentially harmful chemicals residues in wood waste at the end of a building's life.

Although timber-harvesting practices have been continuously improving, large volumes of wood residues and salvable material remain unused in logged areas [86]. Forest residues remaining on logged sites include small trees, cull and broken logs, tops, and dead timber. A primary barrier to more efficient utilization is the added cost of recovering residue material. Typically, the value of residues will not cover the costs of harvesting them, unless the volume of recoverable material is extremely high. The amount of residues left after logging depends on the type of logging operation, topography, forest type, logging crew skills, and some other factors [91]. In the U.S., at least 15% of the wood fibre in a typical timber harvest is left behind as broken or defective [92]. In the former Soviet Union, the efficiency of logging operations is much lower; 30–50% of all cut logs are left on the ground or lost during transportation [93].

Ideally, the effects of mineral extraction and forest harvest on carbon uptake and release of ecosystem should be compared in the 3S Framework tool.

Manufacturing of construction materials

Any raw material is transported to the manufacturing facilities after extraction. Production of construction materials at a manufacturing facility is accompanied by emissions of waste heat and CO_2 from energy generation and from chemical reactions accompanying cement and steel production [63]. Production of construction materials is currently under pressure to improve efficiency, reduce energy demand, and accompanying carbon emissions. Below we briefly discuss how emissions from mass timber manufacturing might be reduced.

After harvest, timber is transported to the mass timber manufacturing facilities, which are usually located adjacent to the forest. Mass timber refers to engineered wood products that are laminated from smaller boards or lamella into larger structural components such as glue-laminated (glulam) beams or cross-laminated timber (CLT) panels. Methods of mass timber production include finger-jointing, longitudinal, and transverse lamination with both liquid adhesive and mechanical fasteners. These new approaches address the natural inconsistencies of wood and make its mechanical performance in large structural members more predictable [76]. Smaller boards or lamellae, easily inspected, graded, and with defects identified and removed, can be distributed throughout a structural cross section based on strength characteristics and specific load-bearing requirements. This approach optimizes both the manufacturing yield from harvested wood fibre and the strength of the structural components.

Only a fraction of timber transported to the manufacturing facility is converted into long-lived products. This is usually estimated at 50% of the delivered timber [32]. The rest is often utilized as fuel although it could have been converted to biochar or biochar products, which preserve carbon on land [94]. Elements of modern timber buildings are often prefabricated at the manufacturing facilities.

Although the most widely used method to estimate emissions from manufacturing construction products is a life cycle assessment, its applicability is usually limited to single buildings. More generic methods for estimating emissions associated with production of construction materials [32] might be more useful for the 3S Framework.

Built Environment

Cities store most carbon in vegetation, soils, buildings, and landfills [95]. In addition to those major carbon pools, we will need to include minor carbon pools relevant in the 3S context. These include reclaimed wood, e.g., wood available from demolished buildings, and wood from urban trees trimming. A five-story residential building structured in laminated timber can store up to 186 kgC/m^2 in the primary structure [96], which is more than in the aboveground biomass of natural forest with the highest carbon density (52 kgC/m^2 typical for the Coast Range ecoregion of North America [97]).

There are two mechanisms for carbon uptake in a city. The first one is the urban tree uptake carbon through the process of photosynthesis. The second mechanism is the direct uptake of CO_2 by concrete urban infrastructures. This process is called carbonation. Atmospheric CO_2 reacts with CaO in concrete to form calcite ($CaCO_3$). This is the reverse reaction of the calcination process used in cement making. The main controls behind CO_2 uptake in concrete are atmospheric CO_2 concentrations, air temperature, air humidity as well as water content, chemical composition, and porosity of materials [98]. The carbonation process is relatively slow as atmospheric CO_2 has to diffuse into the solid material and to dissolve in its pore fluid. For instance, the total amount of carbon, which can be captured in the American concrete infrastructures in one year is two orders of magnitude smaller than that captured by urban forests of the US [99]. The rate of carbon uptake is not constant and depends on the degree of cement exposure to outside elements.

The processes which might be simulated here include accumulation of carbon in building stock over time, transfer of reclaimed wood and wood from urban trees to the manufacturing facilities, as well as transfer of wood from demolished buildings to the landfill. Release of carbon currently accompanies all these processes because required energy is generated predominantly from fossil fuels. In a landfill, emissions of CO_2 and CH_4 accompany decomposition of wood products [100].

Conclusions and Next Steps

There is more research and better understanding of the feedbacks between forests and climate than between manufactured products and climate (reduced to products' GWPs). The major gap is in linking these two types of feedbacks. The 3S framework aims to begin to build a bridge between these two complex systems and cover this gap. Our generous funding from Climate KIC over the past 4 months has allowed us to begin to answer critical questions, and fill research gaps.

Additionally, through generous funding from Private European Foundations, and in close collaboration with Climate KIC and other critical partners, TNC will kick off the next phase of the 3S framework project in early 2021. There are various areas in which we plan to advance this work over the next 18 months, including:

- Finalize the compendium and develop a more final draft of the 3S framework that incorporates further stakeholder input. We envision sharing these draft accounting framework ideas with stakeholders to begin to develop a sense of what would serve as the most *useful* end result. This includes validating our assumption that the 3S framework should be geared towards policy makers and investors in the first instance, while working to develop a holistic tool that is eventually *useful* to all users.
- Develop a process for tool development that will help end users better understand the following information and put that information into climate action:
    - Forest management systems
    - Carbon storage of forests (at landscape level) and carbon storage in the built environment in various forms
    - How the carbon sink is affected by a harvest
    - The carbon "value" of a forest product
    - The climate impact of biofuels
    - Links the cycling of carbon between both mineral and biomass-based materials in the 3S framework, where we focus not only on forests, but also include other ecosystems, which could be disturbed by raw material extraction such as mining.

    - Incorporates long term perspectives, including end of life of forest products, the feasibility of wood supply, disruptions to forests caused by climate change, certification frameworks, and safeguards.
    - The overall climate objectives aligned with improved forest management and the use of sustainable forest products
- Define principles for tool development, including building an open source tool that is user friendly
- Further our research and come to a joint decision on whether a new framework/ tool is built from scratch, or whether something is built that incorporates existing tools and methods.
- Analyse which existing models/tools are promising enough to invite further exploration, including examining which models most closely and accurately represent reality and the complexity of the system.
- Seek model and web development expertise to help frame possibilities for tool design.
- Use the draft framework/tool to build consensus among stakeholders and users and identify research gaps
- Working with stakeholders to understand where the 3S framework could obtain maximum utility (ie in linkages to the Greenhouse Gas Protocol and Science Based Targets Network).
- Understand other core need areas, including ideas like the need and appetite for the 3S platform to incorporate a clearinghouse
- Develop collaborations with existing projects that can be used as a testing ground and preliminary case studies for the 3S framework, particularly through existing Climate KIC projects, and the Climate Smart Forest Economy Program
- At first, we plan to first work towards defining a tool that aligns with the climate impacts of mass timber, but eventually encompasses several sustainable forest products.

Figure 1. Diagram of different players contributing with methods or interested in using 3S Framework.

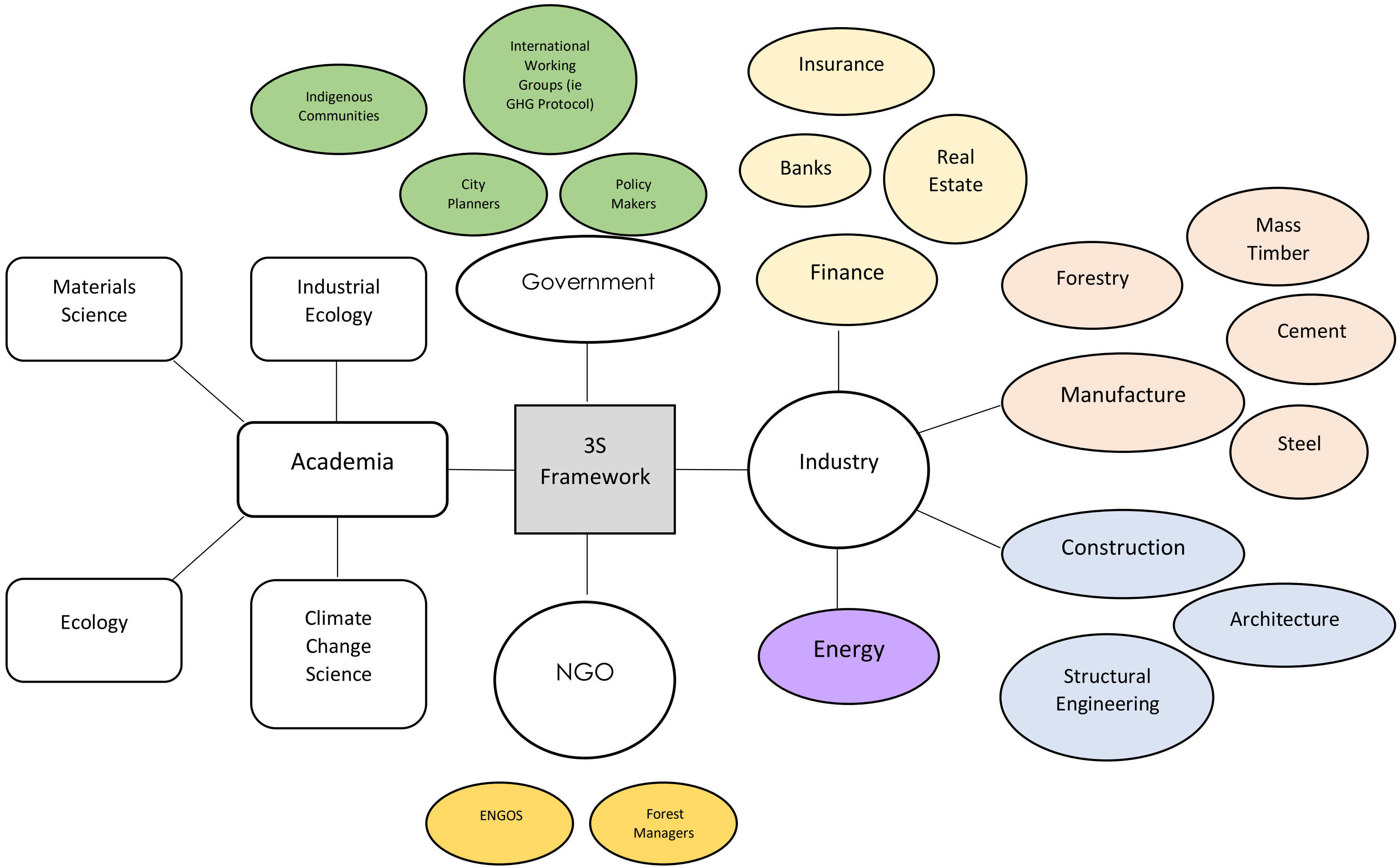

Figure 2. High-level overview available with final tool that builds awareness of the climate mitigation potential of sustainable forest products

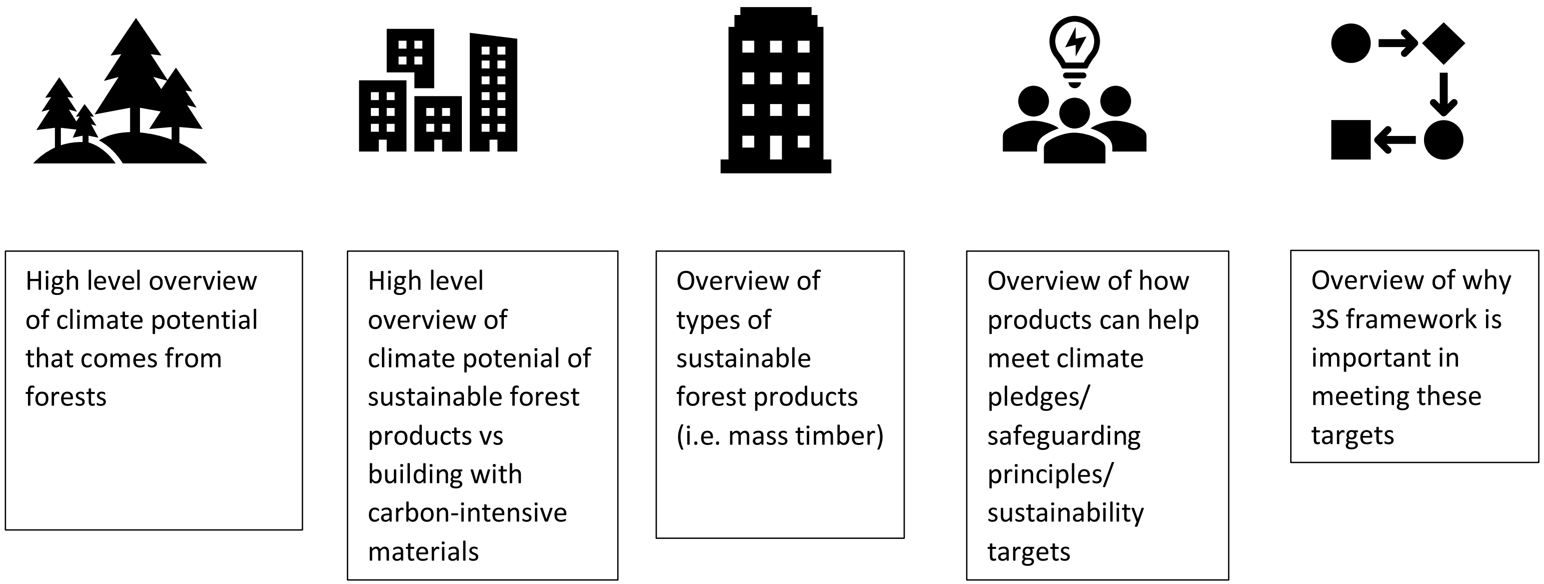

Figure 3. Possible flow chart of 3S Framework. Decision-making on material choices and their environmental impacts.

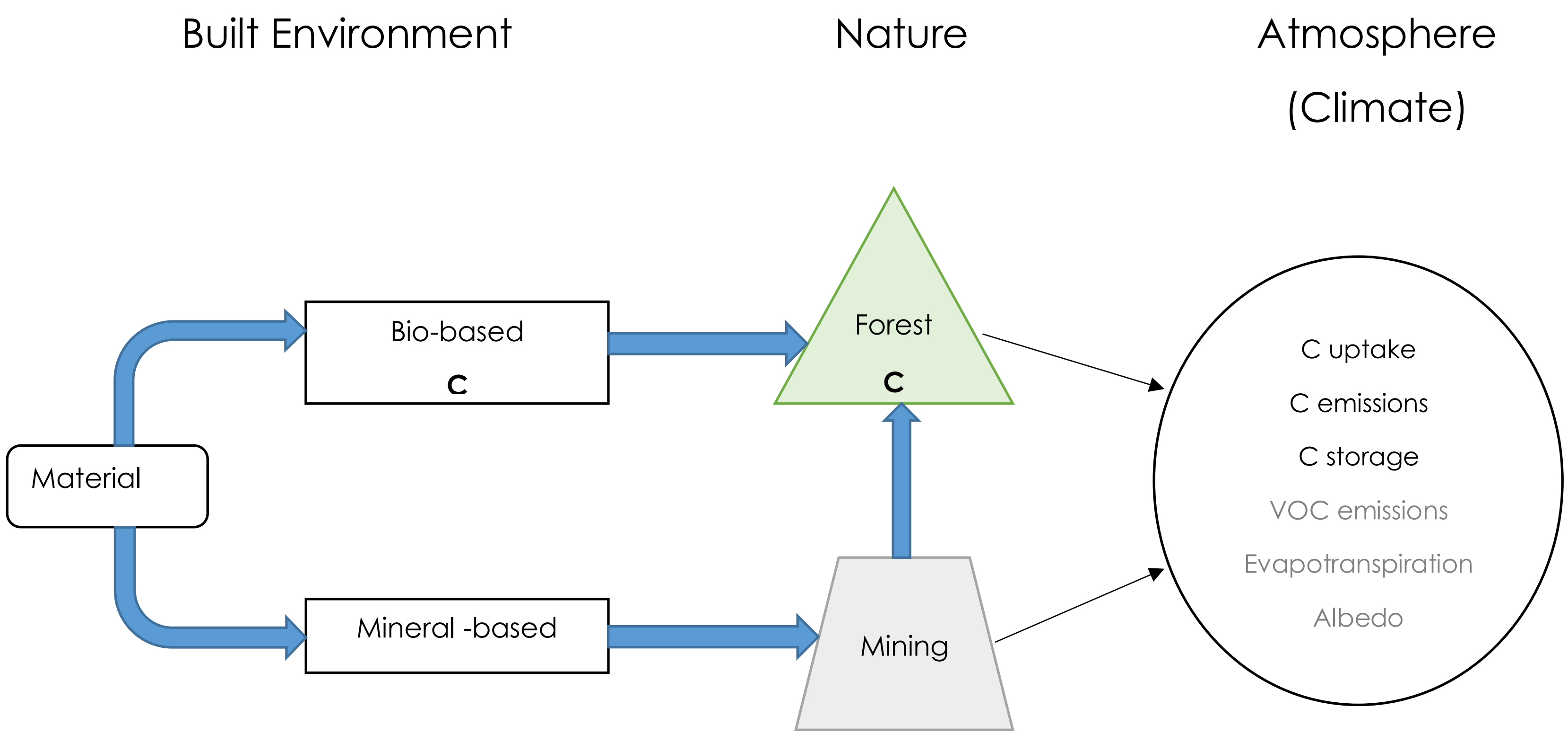

Figure 4. Possible flow chart of the 3S Framework.

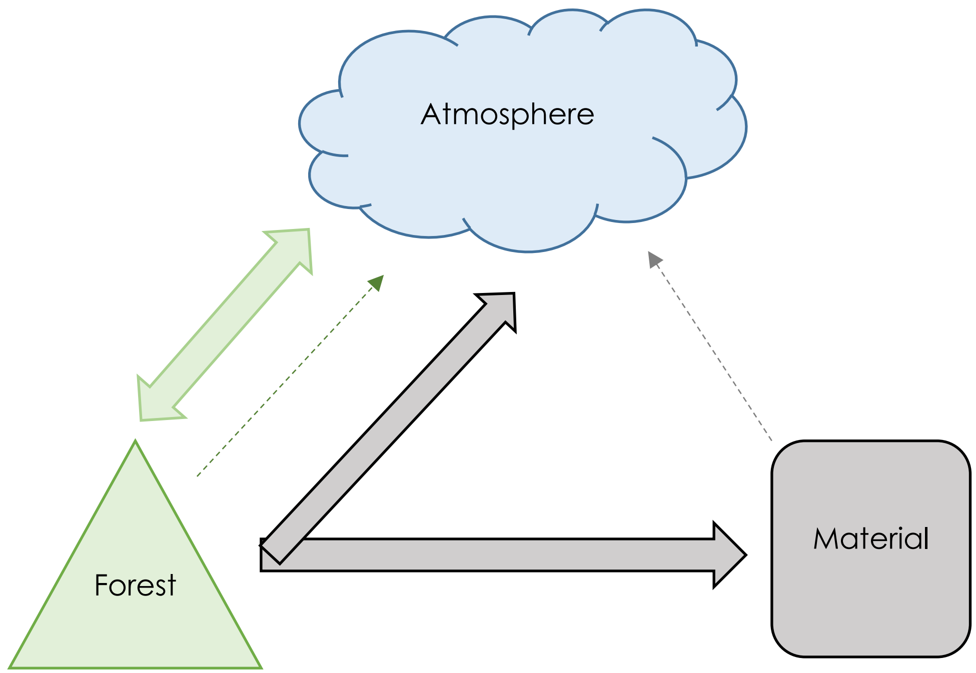

Figure 5. Possible flow chart of the 3S Framework.

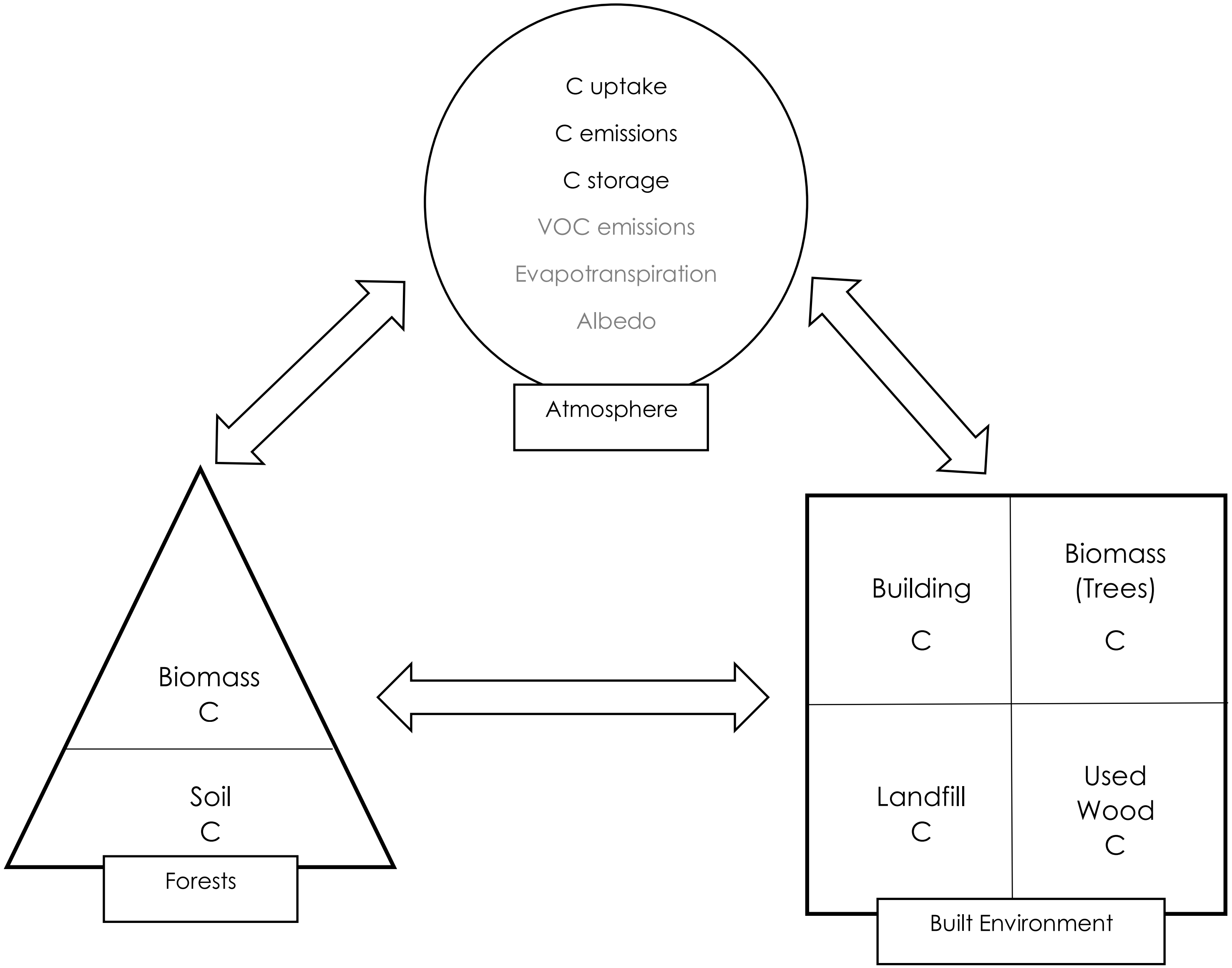

Figure 6. Possible flowchart of the 3S Framework.