Simultaneous Carbon Storage in Arable land and Anthropogenic Products (CSAAP): demonstrating a new concept towards well below 2°C

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**Abstract**

The removal of additional carbon dioxide from the atmosphere is indispensable for controlling global warming. This study proposed the concept of ‘biopump’, as plants capable of significantly transferring carbon into the soil. The Carbon Storage in Arable land and Anthropogenic Products (CSAAP) relates to the cultivation of ‘biopumps’ on marginal arable lands poor in soil organic carbon (SOC) and their conversion into long-lived anthropogenic products. Based on a list of twenty-seven biopumps assembled from a literature review, this study proposed a method for the regional prioritization of biopumps, considering among others their ability to increase SOC and adaptation. A list with eight woody and eight herbaceous biopumps was recommended for France. To illustrate the potential of the CSAAP strategy for products encompassing a variety of lifetimes, carbon flows, from biopump cultivation to biomaterial manufacturing and end-of-life, were tracked in time to calculate their influence on global mean temperature change. An illustration was performed on the basis of a French case study, where *Miscanthus* is grown on spatially identified marginal lands quantified as 11,187- 24,007 km2. Planting biopumps on these lands could increase by 0.23 to 0.49 Mt carbon stocked as SOC annually, which represents 0.19%- 0.41% of the annual French carbon budget during 2015-2018. If the carbon contained in the biomass is indefinitely kept in anthropogenic products, it could represent 13.07% of the same carbon budget. We concluded that biopumps could induce negative emission by 2100, with efficiency strongly depending upon carbon’ residence time in the anthroposphere. **Keywords**

Biopump; soil organic carbon; climate change mitigation; dynamic carbon flow; global mean temperature change

**1. Introduction**

The Paris Agreement calls for stabilizing the global mean surface temperature increase to well below 2°C above pre-industrial level(UNFCCC, 2015), a threshold that has endured in science to represent dangerous climate change(Sanderson et al., 2016). This target implies two key challenges. On the one hand, it implies to induce additional carbon dioxide removals (CDR, or so-called negative emissions)(Masson-Delmotte et al., 2018; Tanzer and Ramírez, 2019), at a rapid and large, or more modest deployment scale, depending on the ambition with regards to the well below 2°C(Hilaire et al., 2019). The potential of soil carbon sequestration as a negative emission strategy has attracted increased attention because of its considerable potential (up to 13 Gt CO2-eq year-1(Shukla et al., 2019); in comparison, China’s net emission was 12 Gt CO2-eq in 2018(Climate watch, 2021)). For example, Bastin et al. (2019) estimated a total of 0.9 billion ha of marginal land suited for reforestation worldwide, which could store 98 Gt C in total. Similarly,Poeplau and Don(2015) estimated, from their meta-analysis results, that through implementing cover crop on bare fallow land on 25% of the global cropland area, a soil organic carbon (SOC) increase corresponding to 0.21-0.26 Mg ha-1 year-1 (0.44 Gt CO2-eq year-1 in total) could be observed after 50 years, which could compensate ca. 8% of direct annual greenhouse gas (GHG) from agriculture. According to Zomer et al (2017), croplands worldwide could sequester an additional 0.9-1.85 Pg C per year, which represents 3.3 to 6.8 Gt CO2-eq (Zomer et al., 2017). The review of (Paustian et al., 2019) highlights that a near complete adoption of ‘best management practices’ for building soil carbon on current agricultural lands could lead to an upper limit of 4-5 Gt CO2-eq year-1. Minasny et al. (2017) suggest, considering global fossil carbon (C) emissions of 8.9 Gt C year-1 and a global SOC stock estimate of 2400 Gt (2m depth) (Batjes, 1996), an annual global SOC increase of 4‰ per year in order to offset anthropogenic C emissions. For example, estimations performed for France revealed that there are ca. 28,500 ha lands which could be subject to an increase of 4‰, with as much as 2.9-5.7 Tg C stored per year in the future 30 years(Rodrigues et al., 2021).

SOC changes are mainly due to changes in the balance between the input and output of carbon to soils (Amundson, 2001). On vegetated soils, plants capture and store C from the atmosphere through photosynthesis, shed part of the accumulated biomass-C as above- and below-ground residues(Karan and Hamelin, 2021), and may be subjected to external C amendments (e.g. manure, compost, biochars)(Paustian et al., 2019). While part of the C in the above- and below-ground biomass residues is, through microbial activity, humified to SOC by microbes, a significant share is emitted back as carbon dioxide (CO2) to the atmosphere through mineralization(Gross and Harrison, 2019), which is highly governed by climatic factors (soil temperature and moisture). Any changes in this input-output balance induces a temporary perturbation to the long-term SOC stock that will result in either SOC losses or gain, until a new equilibrium is reached.

The second challenge implied by the Paris Agreement target is to transit towards a low fossil carbon economy. Fossil CO2 represented more than 65% of global GHG emissions(2016 data; World Resources Institute, 2020). While some products and services can be supplied without any carbon (e.g. wind or solar electricity, which can in turn supply heat or transport services), other sectors of the economy (e.g. materials, chemicals) cannot be decarbonized and will require new C sources. In the low fossil C economy, biomass is the most abundant and accessible C source (Gautam et al., 2019; Office for National Statistics, 2019), at least until the large-scale deployment of technologies with lower readiness level is possible (e.g. direct air carbon capture with use of the carbon).

The carbon contained in the biomass and then in antropogenic products represents another potential carbon pool. Carbon storage in wood-based products was by far the most studied bio-based pool. A carbon inventory was estimated for construction materials, from post-harvest wood to product manufacturing and final landfilling (Ingerson, 2011). The resulting carbon pool depends on the product’s lifetime but also on the GHG emissions from manufacturing, which can offset the benefit. More recently, the potential for climate mitigation of wood-based products was assessed through dynamic life cycle assessment (DLCA) (Head et al., 2020; Ingerson, 2011), including carbon capture by trees, product manufacturing and end of life, through diferent time horizons. The temporality of such scenarios (i.e. when the diferent processes emit/capture CO2) is a key parameter: the benfit of carbon capture by trees will be lost sooner or later, depending on the product’s lifetime.

This study aims to demonstrate a new concept simultaneously addressing these two challenges of CDR and emissions mitigation. We refer to this concept as CSAAP: Carbon Storage in Arable land and Anthropogenic Products. In a nutshell, it consists of inducing a net long-term biophysical removal of C from the atmosphere towards the soil, while using the produced biomass as a renewable C source to supply society’s demands for hydrocarbons. The plant species allowing to meet, in a given geographical context, this double challenge is here referred to as biopumps. To qualify as sustainable CSAAP, the vision is to ensure that (1) the cultivation of biopumps does enhance SOC stocks, while (2) not inducing competition for arable land nor adverse environmental trade-offs and (3) that biopumps are a source of C for anthropogenic products with a long lifetime, thus allowing for a net CDR for a time horizon as important and relevant as possible. To implement CSAAP on a territory, we propose a methodology with several steps: identification of suitable plants and selection of adapted biopumps, assessment of the marginal land with potential for SOC increase, and assessment of the climate mitigation potential of the whole chain, from CO2 capture by plants to bio-based products in technosphere and their end-of-life.

This concept is, to authors’ knowledge, novel; no such comprehensive methodology has been proposed for systematic investigation and assessment of coupled carbon pools, from soil to plant and products in the technosphere, as demonstrated herein. Further, it still remains unclear to which extent and under which local conditions such concept could effectively lead to controlling temperature changes below 2°C. In an endeavor to understand the potential importance of CSAAP for climate mitigation and bioeconomy strategy, we here applied and scaled the concept to France. The case of *Miscanthus* (*Miscanthus x giganteus*) as biopump was considered for illustration, with a representation of the atmospheric carbon flow induced in soils and maintained in the technosphere and its evaluation in time, as well as the related effect on global mean temperature change as indicator for climate change. .

**2. Materials and methods**

The CSAAP concept is built in four steps: (1) identifying suitable biopump candidates; (2) ranking these candidates through a semi-quantitative matrix; (3) quantifying the land areas that could be converted to biopumps cultivation, and (4) estimating the mitigation potential. The CSAAP was evaluated through carbon flow tracking in function of time for a selected biopump in the case of France.

**2.1 Identification and ranking of biopump candidates**

*2.1.1. Assessing the specie-dependent potential to enhance SOC*

The key determinant for labeling a plant as a “biopump” is its ability to induce net carbon sequestration in agricultural soils, reflected here by its ability to increase SOC over a long period, typically considered as 100 years in related studies(de Jong et al., 2019; Hamelin et al., 2012).

In order to pinpoint the plant species that could qualify as biopumps, the literature was screened in an endeavor to generate a meta-analysis investigating the plants reported to increase SOC over time, the yield of these plants along with the key parameters upon which their sequestration performance depends on. The recent work of Ledo et al (Ledo et al., 2019) represents the most comprehensive attempt to collect a comparable dataset on SOC changes due to perennial plants. The authors summarized SOC measurements (with standard deviations) before and after cultivation for 61 crop types on 709 sites all over the world, with harmonized documentation of site properties, including key parameters highlighted by Sanderman et al.(Sanderman et al., 2018) (climate, relief, lithology, and previous land use) as well as additional ones like soil depth, plantation lifetime, and agricultural management. For these reasons, the present work builds upon the study of Ledo et al(Ledo et al., 2020, 2019). All the crops reported by Ledo et al (Ledo et al., 2019) were classified here as ‘woody’ or ‘grass’, and the average annual SOC change (ΔSOC) were calculated from the concentration (i.e. data in g C kg-1 soil) and/or stock data (i.e. data in t C ha-1 land), considering the reported duration between the current and previous land use. This is summarized in table S1&S2, along with additional parameters extracted from Ledo et al (Ledo et al., 2019) database (available online), such as the soil depth for SOC measurements, or the location and number of plots. Among the 61 crop types presented in this database, 42 had a negative average annual ΔSOC. These were excluded from further consideration as candidates for biopumps. To this remaining list of crops, 10 additional plants were added, collecting from a selection of 38 articles from recent literature (2005 - 2019).

*2.1.2. Ranking the candidates*

A semi-quantitative scoring framework adapted from(COWI A/S and Utrecht University, 2019) was built in order to rank the biopumps identified in the previous step, in the perspective of achieving the highest performance in terms of C sequestration, biomass yield, agricultural intensity, and risk of invasion, and to ensure suitability in a given geographic context. Accordingly, five specific criteria were defined in table 1. Each criterion was associated with a score ranging from 0 to 3, where each score corresponds to a quantitative/qualititative value like plant yields <2 t DM ha-1 year-1 is assigned a score of 0. The SOC increase capacity is based on the screening work of section 2.1.1, the capacity of the different biopumps for SOC enhancement was divided into four classes, ranging from 0 to 1 g kg-1 or Mg ha-1. If a candidate has scored in both SOC concentration and stock, the higher value will be chosen in ranking.

The rationale used for yield criteria was to assign the top score to a threshold yield necessary to ensure SOC sequestration with a target of 4‰ increase annually (‘4 per 1000’ initiative mentioned in the introduction), which roughly translates in a global average sequestration rate of 0.6 t C ha-1 annually(Minasny et al., 2017). If we treat this sequestration rate as the target (4‰), with plant’s anabolism and C content around 15% and 45% respectively (i.e. 15% of biomass containing 45% C will enter the soil (Hamelin et al., 2012; Nguyen, 2003)), the biopump yield must reach at least 9 t DM ha-1 year-1 (score 3 set for yield >10 t DM ha-1 year-1). Data recorded in commercial scales were considered, data from private gardens, potted plantations or greenhouses were not used. It should be noticed that not only the plants as binomial names recorded in table S3 but subspecies and varieties were also considered in data collection. For example, blueberry was recorded as [*Vaccinium corymbosum*](https://en.wikipedia.org/wiki/Vaccinium_corymbosum), while *Vaccinium angustifolium L, Vaccinium darrowii Camp, Vaccinium virgatum Aiton, Vaccinium elliottii Chapm* were also adopted as varieties(Michalska and Łysiak, 2015).

The agricultural intensity criterion was divided into 3 sub-criteria to reflect the capability of the biopumps to grow with a minimal need for additional water, fertilizer, and pesticide input. For fertilizers, we only regarded nitrogen, due to its importance on global warming (N2O emissions) and our concern for GHG neutrality. The mean value of the three sub-criteria was used as the score for ‘agricultural intensity’. The risk of invasiveness of the biopump candidates was also assessed on the basis of a qualitative scoring. The invasion risk was judged based on databases like Invasive Species Compendium(CABI, 2021), Global invasive species database(Invasive Species Specialist Group (ISSG), 2000), and Global invasive species database in France(Invasive Species Specialist Group, 2020). Finally, the overall score by biopump was obtained by summing the five criterion scores.

*2.1.3. Possible utilization of biopumps*

The aboveground biomass can be transformed into bioeconomy products depending on the plant components, classified as cellulose, hemicellulose, lignin, proteins, sugars, and lipids, with various other specific molecules that can be extracted, separated, and further processed. The main possible product categories are materials, chemicals, energy, and food/dietary supplements. In the perspective of CSAAP, the lifetime of the final product (and eventual co-products) should be as long as possible, to keep a maximum of carbon out of the atmosphere for as long as possible. While materials may have a use phase greater than 10-20 years, energy, food, and most feedstock chemicals are produced and used rapidly, typically with a turnover of a year or less(Bataille, 2020). As an illustration, a non-exhaustive inventory of 29 plant-to-bioeconomy products is presented in the SI (table S6), including the main transformation process, product lifetime, and replaced conventional product.

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| --- | --- | --- | --- | --- | --- |
| Table 1 Semi-quantitative criteria matrix used to select the biopumps potentially adapted for France. | | | | | |
| Overall criteria | Sub-criteria | 0 | Score  1 | 2 | 3 |
| Yield (harvestable) |  | <2 t DM ha-1 year-1 | 2~5 t DM ha-1 year-1 | 5~10 t DM ha-1 year-1 | >10 t DM ha-1 year-1 |
| SOC increase capacity |  | <0 g kg-1  or <0 Mg ha-1 | 0~0.1 g kg-1  or 0~0.35 Mg ha-1 | 0.1~0.3 g kg-1  or 0.35~1 Mg ha-1 | >0.3 g kg-1 or  >1 Mg ha-1 |
| Agricultural intensity | Water | Need irrigation regularly | Need irrigation in a certain period | Could live without irrigation but water would prompt the yield. | Survives with rainwater only in the region of origin, tolerant to drought |
|  | Fertilizer | >180 kg N ha-1 year-1 | 120-180 kg N ha-1 year-1 | 60-120 kg N ha-1 year-1 | <60 kg N ha-1 year-1 |
|  | Pesticides | Susceptible to get pest/weed problem;  Pesticides necessary. | There is at least one pest or weed problem that would cause a serious disease;  Pesticides typically used. | There is at least one pest or weed problem but not serious;  Pesticides sometimes used. | Great resistance against the pest;  Pesticides seldom used. |
| Suitability to grow in France |  | Not currently growing in France or countries with similar conditions. | Grows in countries in other continents but have a similar environment to France (altitude, climate, latitude) | Grows in European countries with similar conditions | Already grows in France |
| Invasion risk |  | Invasive and difficult to control | Invasive but can be contained | No information about the invasion, judged to be non-invasive / the species in table s3 is not invasive but subspecies and varieties would be. | Proved to be non-invasive |

**2.2 Scaling up the potential to a country**

The scale of biopump cultivation is important in order to estimate the mitigation potential. Additional SOC sequestration is governed by a long-term equilibrium reflecting a balance between the C input rate to soils and the rate of losses via decomposition (CO2) (Paustian et al., 2019). Albeit mineral soils with high organic matter levels may still be suitable for further C gains (defined as >5% C by mass by Paustian et al.) (Paustian et al., 2019), the C loss during land conversion of such soils can take decades to a century to be compensated (Harper et al., 2018). The vision of CSAAP is therefore to grow biopumps exclusively on areas with low SOC content. Using Food and Agriculture Organization’s Global SOC data (FAO, 2019), the soils were classified into five SOC classes, namely <40, 40-50, 50-60, 60-70, and >70 t C ha-1. A treshold can then be selected for ‘carbon-rich’ soils.

Not all kinds of land covers are suitable to be converted, thus the land use types need to be identified, and screened which suit biopump cultivation. The definition from (Inglada et al., 2017) was adopted for identifying the land use types. According to the principle that C removal should not endanger food security, only the lands whose use was not foreseen to lead to the demand for additional arable land could be envisaged for biopump cultivation. The lands which might be converted are called marginal lands, as their values under present usages are less than ideal, may be better lands available in another context (Richards et al., 2014). The context in this study is climate change mitigation. Learning from previous experience of marginal land selection (Guénon et al., 2016; Thomas et al., 2021; Zhang et al., 2020), the principles in screening marginal lands focused on three aspects:

1) to minimize disruption to existing activities;

2) to avoid competition with crops;

3) to exclude unsuitable areas.

Some studies tried to fully use the urban abandoned land, while the feasibility is controversial because of the high urban land value and labor cost(Saha and Eckelman, 2015). Converting 1 ha of urban land to farm would cost €4,3000, and this price would be even higher in the present metropolis(Chin et al., 2013). Besides economic cost, getting land access and ownership would be tough, since 85% of potential urban marginal lands are in private hands(Ackerman, 2012). Thus in this study, urban lands were not considered. Then, areas like glaciers, that are obviously not suitable for biopump growing and SOC stock plan are excluded. To protect food security, lands cultivating crops like cereal are totally excluded. Finally, because of the existing high C stock, and potential high GHG emission in land use change, forest lands would not be converted for biopump cultivation(Müller-Wenk and Brandão, 2010). Another aspect is the biodiversity, not evaluated as the purpose here is the C sequestration(Searchinger et al., 2018). The biodiversity or other ecosystem values need to be analyzed separately, which is out of the scope here.

**2.3 Demonstrating CSAAP – carbon flow accounting**

The CSAAP concept involves a strong time component of crucial effect on climate when emission and capture processes are combined. To investigate the viability of CSAAP, carbon flows are tracked from biopump cultivation through producing biobased products, to the disposal. The potential benefit of biopump cultivation and utilization is ultimately determined by the net carbon capture and storage over time.

The CO2 from the atmosphere is photosynthesized in biomass (plant), part of which is decomposed on/in the soil and stored as SOC accompanied by CO2 release. The other part is harvested and enters the technosphere. From the technosphere, the biogenic carbon can be released into the atmosphere in different amounts depending on the anthropogenic products manufacturing and use. The global biogenic carbon balance can be written as:

(1)

where are the variation of carbon quantity in compartment i, and the carbon flow (t year-1) from compartment i to compartment j, respectively. Finally, the biogenic carbon stored is given by:

(2)

With: (3)

(4)

(5)

The carbon released into the atmosphere:

With: (6)

‘tech’=technosphere, ‘plant’= the entire plant, ‘air’=atmosphere, ‘soil’ =soil and subsoil, ‘air, plant’ =C captured from the atmosphere by photosynthesis. ‘plant,air’=C released by bio-based product at end-of-life. ‘soil,air’=C released from the soil. ‘plant,soil’= part of the plant remained on/in the soil. ‘tech,soil’=biogenic C from the technosphere possibly added in the soil, e.g., a waste biomass used as fertilizer (manure). ‘plant,tech’=biogenic C harvested (fraction of the biopump), transformed and used in the technosphere.

Carbon flow accounting allows further analysis on climate change impacts, for example by calculating climate parameters like the Global Mean Temperature Change, which is an estimate of the surface mean temperature variation with respect to the pre-industrial era (Stocker et al, 2013).

**3 Result and discussion**

**3.1 Selected biopumps**

*3.1.1. Identified candidates*

The identified biopump candidates were grouped as woody and herbaceous and are provided in tables S1 and S2 (Appendix I). The SOC was extrapolated from Ledo et al.’s dataset as the difference from the SOC level in the same land before and after plant growth(Hamelin et al., 2012). Here, we report SOC both as concentration (e.g. g C kg-1 ) and stock (e.g. Mg C ha-1), as stated in the original meta-study of Ledo et al.(Ledo et al., 2019), since the depth and bulk density of the parcels were not always available to compile SOC changes as either concentration or stocks.

Tables S1 and S2 report both the minimum, maximum, and average SOC changes observed for a given biopump candidate, along with additional information on the number of measurements reported, their duration, location, and associated soil depth, as well as the expected plantation lifetime. Although SOC changes are intrinsically tight to site-specific physical and managerial conditions(Sanderman et al., 2018), tables S1 and S2 nevertheless provide indications of which biopumps may inherently lead to greater transfers of carbon from the atmosphere to the soil than others. For instance, it can be noticed from table S1 that only acerola (*Malpighia glabra L.*), araucaria (*Acacia mangium*), and blueberry were not associated with dataset reporting SOC losses. Furthermore, olive (*Olea europaea* [L.](https://en.wikipedia.org/wiki/Carl_Linnaeus)), blueberry, and araucaria can be highlighted as the woody species associated with the greatest SOC changes (table S1), while hemp (*Cannabis sativa L.*), ryegrass (*Lolium perenne L.*), and opuntia ficus-indica (*Opuntia ficus-indica (L.) Mill*) outstand from the herbaceous species (table S2). Tables S1 and S2 also highlight that some biopump candidates have been much more studied than others; *Miscanthus* (*Miscanthus x giganteus*), switchgrass (*Panicum virgatum L.*), and willow (*Salix spp.*) notably present much more measurements data than the other candidates. It should be noticed that SOC situations could differ a lot due to the climate, soil moisture, considered depth, etc., thus plants that could increase the SOC in this area might not suit another area, this explained why some plants identified in two tables have SOC decrease records. An on-site investigation is recommended when applying biopump in a specific region. Therefore, France was chosen to illustrate the CSAAP application.

*3.1.2 Selected biopumps for France*

The results of the semi-quantitative selection criteria matrix (table 1) applied to France and on the basis of biopumps presented in table S1-S2, are presented in table 2. Accordingly, some species associated with high (or higher) SOC sequestration potential (tables S1-S2) do not figure on top of the list because of e.g., their low yield (e.g. opuntia ficus-indica, bungeana (*Stipa bungeana*)). As highlighted in table 2, the mean score for all woody and herbaceous candidates is similar, with 11.2 and 11.5 respectively (dimensionless, the maximum score being 15). The range of observed scores is greater for the woody candidates (8-14.3) than the herbaceous ones (6.3-13.3). For the woody candidates, there are eight species with scores above the mean, these are all already found in France, except microphylla (*Caragana microphylla*), which grows in Eastern Europe(POWO, 2021). For the herbaceous candidates, eight presented scores above the mean, and these are all currently found in the French ecosystem.

The yield of woody candidates (varying from 4.13 to 63 Mg DM ha-1 year-1; table S5) is on average 38% higher than the yield of herbaceous candidates (varying from 1.6 to 40 Mg DM ha-1 year-1; table S5), and this is reflected in the scoring (average of 2.6 vs 2.2 for this criteria) since the top score was attributed for yields above 10 Mg DM ha-1 year-1. The potential to enhance SOC was inventoried both in terms of concentration and stock, and concentration data were available for most candidates. The mean SOC concentration of woody candidates is similar to herbaceous candidates, and there are some species with outstanding values in both wood and grass (acacia and olive for wood, ryegrass for herbaceous). Hence woody and herbaceous candidates obtained the same score for the SOC criteria (table 2). In terms of agricultural intensity, the average score for herbaceous candidates is slightly higher (14%) than their woody counterparts, with korshinsk peashrub (*Caragana korshinskii Kom*) standing out from the woody candidates while *Miscanthus* and bahiagrass (*Paspalum notatum Flüggé*) for the herbaceous ones. Most candidates are already grown in France, while acacia is suitable for warmer regions, most in Latin America(CABI, 2021). Ramie (*Boehmeria nivea L.*) and bungeana grow in East Asia, but they suit the hardy environment well, therefore might be able to live in France too(Xu et al., 2019; Yu et al., 2009). Woody and herbaceous candidates are similar according to the invasion risk; some wood species miss this kind of information. Poplar (*Populus spp*)and alder (*Alnus glutinosa*) grow in France, but korshinsk peashrub does not, and invasiveness needs to be studied. While grass could become weeds if planted in an inappropriate place(Plants For A Future, 2010).

In summary, among the fourteen woody and thirteen herbaceous candidates, eight were proposed in each group as potentially suitable biopumps in France. However, among the selected woody candidates, some species supply a third service on top of C sequestration and biomass production, namely the production of marketable fruits (i.e. blueberry). In these cases, albeit not reflected in table 2, the risk not to comply with the sustainable boundaries identified herein for agricultural intensity is higher than for the other candidates.

*3.1.3 Bio-based products*

The composition of the selected biopump candidates is presented in table S4. For the woody candidates, the cellulose content varies between 20% and 60% of the dry matter, while for the herbaceous selected candidates, it varies between 20 and 76% of the dry matter, highlighting suitability

for possible uses as long-lived fiber products. Table S6 outlines a documented inventory of twenty-nine biomass-to-bioproducts conversion pathways mainly focusing on building materials, vehicle panels, packaging, and textiles, where the product’s lifetime varies between days (e.g., fast-moving consumer goods (FMCG) such as food and energy) to potentially 100 years (e.g., hemp-based plaster material for walls, often referred to as “hemp concrete”(de Bruijn et al., 2009; Ip and Miller, 2012)).

Biopumps identified could provide products with short lifetime e.g., fruits or energy materials (opuntia ficus-indica, poplar), or products with longer lifetime using extracted fiber or shives (e.g. *Miscanthus*, hemp). More, some traditional ways should not be forgotten though they are not listed in the table S6. For instance, wood could be used as furniture or as chips included in particleboard, which are long-lived products lasting for decades(Couret et al., 2017; Spitzley et al., 2006).

Disposal ways of biobased products are similar to the traditional products they replaced, and, notably, they are biodegradable. Recycling technologies are also in development(La Rosa et al., 2013). The short lifetime reduces the carbon stock, but recycling being possible, one feasible compensation is to increase the number of cycles. Notably, whatever bio-based products are used in building or FMCG, what they replace are mainly various fossil based plastics. This replacement reduces the GHG emission indirectly not only through avoiding fossil use but also by solving the long-running problem of waste plastic disposal. Concerning the used fraction of the harvested plant, it is case specific depending on the plant composition and transformation process (e.g. table S7). Possible plant residues (or by-products), obtained in different proportions, can be used in various manners, like back to soil or combustion for energy production.

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| Table 2 Biopump ranking results | | | | | | | | | |
| Biopump | Criteria | | | | | | | | Total score |
| 1)Yield | 2)SOC increase capacity | 3) Agricultural intensity | | | | 4)Suitabilitya | 5)Invansion risk |
|  |  |  | Water | Fertilizer | Pesticides | Total |  |  |  |
| Woody plants | | | | | | | | | |
| Black locust | 3 | 3 | 3 | 2 | 2 | 2.3 | 3 | 3 | 14.3 |
| Atriplex | 3 | 3 | 1 | 3 | 3 | 2.3 | 3 | 3 | 14.3 |
| Microphylla | 3 | 2 | 3 | 3 | 0 | 2.0 | 2 | 3 | 14.0 |
| Olive | 3 | 3 | 2 | 1 | 1 | 1.3 | 3 | 3 | 13.3 |
| Araucaria | 3 | 2 | 1 | 3 | 2 | 2.0 | 3 | 3 | 13.0 |
| Rhamnoides | 2 | 3 | 2 | 2 | 0 | 1.3 | 3 | 3 | 12.3 |
| Blueberry | 3 | 3 | 0 | 0 | 1 | 0.3 | 3 | 3 | 12.3 |
| Poplar | 3 | 2 | 2 | 3 | 1 | 2.0 | 3 | 2 | 12.0 |
| Alder | 2 | 1 | 2 | 3 | 2 | 2.3 | 3 | 2 | 10.3 |
| Willow | 3 | 1 | 1 | 2 | 2 | 1.7 | 3 | 1 | 9.7 |
| Acerola | 2 | 2 | 3 | 3 | 2 | 2.7 | 1 | 2 | 9.7 |
| Korshinsk peashrub | 1 | 2 | 3 | 3 | 3 | 3.0 | 1 | 2 | 9.0 |
| Acacia | 3 | 3 | 3 | 3 | 0 | 2.0 | 0 | 1 | 9.0 |
| Guava | 3 | 1 | 0 | 0 | 0 | 0.0 | 1 | 3 | 8.0 |
| *Mean* | 2.6 | 2.2 |  |  |  | 1.8 | 2.3 | 2.4 | 11.5 |
| *Standard deviation* | 0.623 | 0.748 |  |  |  | 0.804 | 1.030 | 0.728 | 2.110 |
| Herbaceous plants | | | | | | | | | |
| Switchgrass | 3 | 2 | 3 | 2 | 2 | 2.3 | 3 | 3 | 13.3 |
| Hemp | 3 | 2 | 2 | 2 | 2 | 2.0 | 3 | 3 | 13.0 |
| Miscanthus | 3 | 1 | 2 | 2 | 2 | 2.0 | 3 | 3 | 12.0 |
| Ryegrass | 3 | 3 | 3 | 0 | 3 | 2.0 | 3 | 1 | 12.0 |
| White clover | 3 | 3 | 1 | 3 | 1 | 1.7 | 3 | 1 | 11.7 |
| White mustard | 1 | 3 | 1 | 1 | 3 | 1.7 | 3 | 3 | 11.7 |
| Red clover | 2 | 1 | 2 | 3 | 2 | 2.3 | 3 | 3 | 11.3 |
| Giant reed | 3 | 2 | 1 | 3 | 3 | 2.3 | 3 | 1 | 11.3 |
| Opuntia ficus-indica | 0 | 3 | 3 | 2 | 1 | 2.0 | 3 | 3 | 11.0 |
| Ramie | 3 | 3 | 1 | 3 | 1 | 1.7 | 0 | 3 | 10.7 |
| Alfalfa | 1 | 1 | 2 | 2 | 1 | 1.7 | 3 | 3 | 9.7 |
| Bahiagrass | 3 | 2 | 3 | 3 | 2 | 2.7 | 1 | 1 | 9.7 |
| Bungeana | 1 | 2 | 2 | 2 | 3 | 2.3 | 0 | 2 | 6.3 |
| *Mean* | 2.2 | 2.2 |  |  |  | 2.1 | 2.4 | 2.3 | 11.1 |
| *Standard deviation* | 1.026 | 0.769 |  |  |  | 0.316 | 1.146 | 0.910 | 1.093 |
| a: Suitability to grow in France on identified land | | | | | | | | | |

**3.2 Quantifying carbon vulnerable arable lands**

As mentioned in section 2.2, the selection premise in this study is land with low SOC. Soils with SOC > 60 t SOC ha-1 are considered as carbon-rich based on national assessments thus would not be included(Launay et al., 2019). To screen land types with low initial SOC stock, the GSOC map was therefore cross-referenced with French high-resolution land cover maps (year 2018)(Theia, 2021) to identify the suited areas. SOC values were extracted by masking the global map with the French boundary data obtained from the GADM database(GDAM, 2018).

After applying the selection rules (section 2.2), four of twenty-three lands types in French territory were identified, which are rapeseed lands, natural grasslands, woody moorlands, and part of intensive grasslands (table 3). For rapeseed lands, not all harvested rapeseeds are used for cooking, a large percentage of yield is designed for biodiesel production now(Gylling et al., 2016), while its market share is squeezed by vigorous perennial grasses(like *Miscanthus* used in the later case study). Therefore, in the bioenergy field, rapeseed is a marginal plant in the market, has a high possibility to be replaced by other alternatives come into this market(Ekvall, 2019). Studies estimated if rapeseed lands are replaced by other bioenergy grass, a higher yield could be expected with lower GHG emission(Hamelin et al., 2021; Larsen et al., 2017), from table 2, many biopump could provide the bioenergy function and replace the role of rapeseed. Plus, because most GHG reduction was achieved through avoiding counter fossil fuel by bioenergy, GHG emission from land use change or management is minimal(Larsen et al., 2017). For intensive grasslands, the situation is more complex. Intensive grasslands occupy 14% of all lands that the SOC stocked between 40-50 t ha-1, the vast areas lead to a high potential for biopump strategy. Intensive grasslands are covered by dense grass, but not under a rotation system. Although these lands are covered by dense grass, the SOC stock is still not saturated. Because the herbaceous plants have similar anabolism and C content in the biomass, judging from the low SOC stock, the biomass yield on intensive grasslands may not be very high. Considering relative high biomass yields from vigorous perennial biopumps and extra SOC stock, to some extent, part of intensive grasslands could be converted to grown biopump, while the extent is not sure here, assuming from 0-100%. The natural grasslands are determined by grass, and woody moorlands are covered by spontaneous woody or semi-woody vegetation. The biomass productivity on both these two lands is low, thus they were selected to plant biopump.

Table 3. Land cover types in France.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Land cover type | SOC< 40 t/ha | | SOC in 40- 50 t/ha | | SOC in 50- 60 t/ha | |
| km2 | % | km2 | % | km2 | % |
| Continuous Urban Fabric | 39.71 | 0.27% | 47.11 | 0.06% | 0.05 | 0.06% |
| Discontinuous Urban Fabric | 1467.99 | 10.05% | 5744.71 | 6.88% | 13.81 | 16.68% |
| Industrial and Commercial Units | 1446.31 | 9.91% | 5293.52 | 6.34% | 6.24 | 7.55% |
| Road Surfaces | 64.14 | 0.44% | 167.81 | 0.20% | 0.29 | 0.35% |
| Rapeseed lands a | 155.90 | 1.07% | 4618.16 | 5.53% | 0.76 | 0.92% |
| Cereal Straw | 1173.59 | 8.04% | 17645.57 | 21.13% | 8.59 | 10.38% |
| Legumes and Protein Crops | 79.75 | 0.55% | 1073.66 | 1.29% | 0.39 | 0.48% |
| Soybean | 126.47 | 0.87% | 657.99 | 0.79% | 0.00 | 0.00% |
| Sunflower | 585.94 | 4.01% | 3411.81 | 4.09% | 0.07 | 0.09% |
| Corn/Maize | 425.19 | 2.91% | 5123.82 | 6.14% | 3.61 | 4.36% |
| Rice | 6.06 | 0.04% | 73.45 | 0.09% | 0.00 | 0.00% |
| Roots and Tubers | 29.44 | 0.20% | 1998.12 | 2.39% | 3.01 | 3.64% |
| Intensive Grasslands a | 1023.82 | 7.01% | 11796.17 | 14.13% | 12.69 | 15.33% |
| Orchards | 372.83 | 2.55% | 641.16 | 0.77% | 0.00 | 0.00% |
| Vineyards | 2790.64 | 19.11% | 3112.15 | 3.73% | 0.05 | 0.07% |
| Broad-leaved Forests | 1594.55 | 10.92% | 11769.37 | 14.09% | 19.78 | 23.90% |
| Coniferous Forests | 1037.90 | 7.11% | 4745.61 | 5.68% | 7.91 | 9.56% |
| Natural Grasslands a | 1505.60 | 10.31% | 3170.81 | 3.80% | 0.88 | 1.07% |
| Woody Moorlands a | 384.03 | 2.63% | 1352.99 | 1.62% | 1.65 | 1.99% |
| Bare Rock | 32.20 | 0.22% | 46.17 | 0.06% | 0.21 | 0.25% |
| Beaches, Dunes and Sand | 22.60 | 0.15% | 47.56 | 0.06% | 0.69 | 0.83% |
| Glaciers and perpetual Snow | 0.84 | 0.01% | 0.46 | 0.00% | 0.00 | 0.00% |
| Water Bodies | 234.98 | 1.61% | 969.26 | 1.16% | 2.06 | 2.49% |
| Total | 14600.48 | 100% | 83507.43 | 100% | 82.76 | 100.00% |

a : chosen as carbon vulnerable land

From the SOC map, it was obtained that the areas with SOC <40, 40-50, and 50-60 t ha-1 represent approximately 14,600 km2, 83,507 km2, and 83 km2, respectively (table 3). The areas of intensive grasslands and natural grasslands are several times higher than rapeseed lands and woody moorlands, which indicates the priority of the herbaceous biopump cultivation due to a reduction in GHG emissions resulting from the land use change. Furthermore, among the four marginal lands, the cover type intensive grasslands may not be available everywhere, hence, two situations were considered: (i) without intensive grasslands covering, and (ii) including intensive grasslands covering. In situation (i), the lands with SOC < 40, 40-50, 50-60 t ha-1 are 2,045 km2, 9,142 km2, and 3 km2, respectively, while in situation (ii), marginal lands are 3,069 km2, 20,938 km2, and 16 km2, respectively. Given the relatively low carbon stock potential and the small area, marginal lands with a SOC of 50-60 t ha-1 are thus not included. Based on the analysis above, in France, land with SOC below 50 t ha-1 was defined as ‘carbon vulnerable arable land’ (CV-land), ranging from 11,187 km2 (case i) to 24,007 km2 (case ii), equal to 11.4%-24.14% of total areas with SOC< 50 t ha-1 in France. The intensive grasslands occupy around half of CV-lands, thus thir detailed situation is worth further investigation for determining their availability. Comparing case (i) and (ii), intensive grasslands mainly distributed in the center and southwest France. The CV-lands mainly locate in central, southwest, and south of France, biopump adapted to the climate there could be paid special attention to.

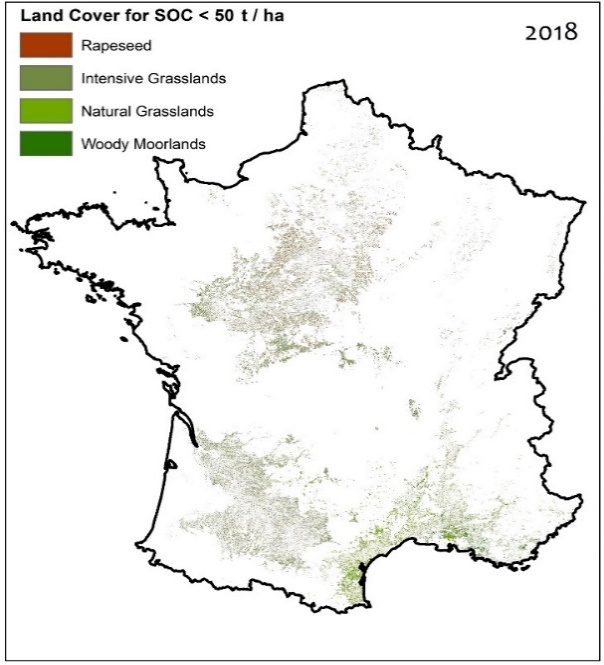
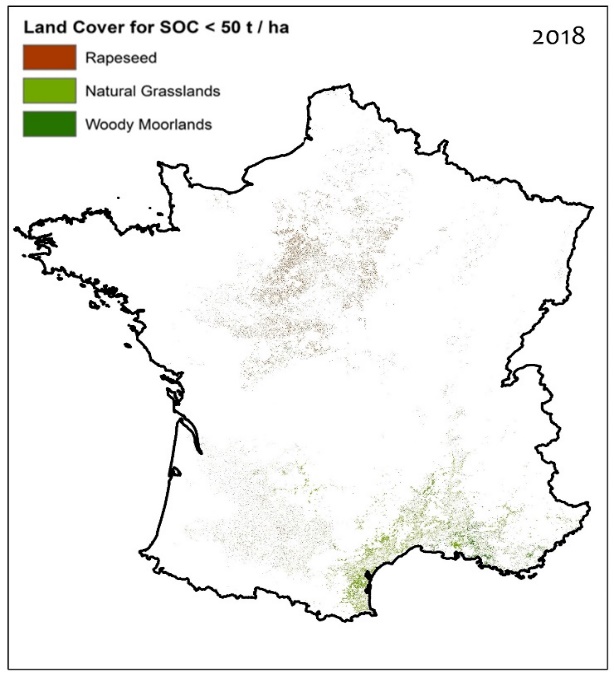


Fig. 1 Carbon vulnerable lands identified as potentially suitable for biopumps implementation in France, without (left) and with (right) intensive grasslands.

**3.3 Dynamic carbon flows and climate mitigation potential**

Hereafter, the example of *Miscanthus* was considered for ilustrating the mitigation potential of CSAAP.

*3.3.1 Case study of Miscanthus cultivation in a CV-land in France*

*Miscanthus*, one of the biopumps identified in table 2, is used as an illustrative biopump to illustrate the CSAAP concept, based on the available data on the above- and below-ground carbon flows for this plant. *Miscanthus* also has the interest that its rotation (ca. 20 years(Hamelin et al., 2012)) is in between those of herbaceous and woody plants. In France, *Miscanthus* is widely grown (6500 ha in 2019 with a growth rate of ca. 10% per year), leading the European *Miscanthus* cultivation (Ben Fradj et al., 2020; France Miscanthus, 2019).

*3.3.2 SOC simulation and C sequestration*

Herein a continuous plantation from 2020 to 2100 was assumed with a rotation time of *Miscanthus* of 20 years, including the first year of land preparation and the second year of establishment (no yield the first two years, 60% yield the third). Thus the land occupation was expected to last from 2020 to 2100, corresponding to four rotations(Hamelin et al., 2012). The evolution of SOC over the chosen time horizon was modeled with the C-TOOL software(Taghizadeh-Toosi et al., 2014). Information for the specific targeted sites were used: i) soil characteristics were considered according to the identified areas in section 3.2, retrived from Harmonized World Soil Database(Nachtergaele et al., 2012), and for a soil depth of 1 m; ii) present and future meteorology data in France from 2020 till 2100, as predicted by SICLIMA(DRIAS CERFACS, IPSL, last updated May 2013), for the RCP4.5 climate trajectory (Representative Concentration Pathway(Chen et al., 2021)), downscaled by the model CNRM-CERFACS-CM5/CNRM-ALADIN63. All inputs are shown in appendix II (in C-TOOL sheet).

According to the C-TOOL simulation, after four rotations the SOC increased from 42.35 (initial SOC) to 58.52 Mg ha-1, which represents a 4.8‰ annual increase. This is in accordance with the 4‰ objective(Minasny et al., 2017). Expanding to the identified CV-land, there will be 0.23 to 0.49 Mt C, i.e. 0.83 to 1.78 Mt CO2 ,(over 11,187 km2 and 24,007 km2, respectively) sequestered in France in the soil every year. These amounts represent 0.19% to 0.41% of CO2 emissions annually from the 2015-2018 French carbon budget (431 Mt CO2-eq)(The High Council on Climate team, 2019). This offsetting effect could be one of the CSAAP solutions and would be more important when the whole biopump lifecycle is considered. The combination of soil capacity with the long-term use of bio-based products will significantly increase the overall storage capacity. Assuming that all harvested carbon is embedded in long-life products (e.g. 6.4 t C/ ha for *Miscanthus* in F100L100 scenario), an additional 6.93 to 14.87 Mt C could be stored in the technosphere, which increases the CO2 offsetting potential substantively to 6.09 -13.07%. This coupled effect of SOC and storage in technosphere is analysed in details hereafter.

*3.3.2 Dynamic C flows accounting*

The case study aims at illustrating the partitioning of biogenic carbon between soil, technosphere and atmosphere, considering 1 ha CV-land, and a 100 years time scope (2020-2120), encompassing the biopump cultivation and the anthropogenic products lifetime, with a 1-year time step. The biogenic fraction of the carbon from the harvested biopump(F) ending up stored in the anthropogenic products, as well as the anthropogenic products lifetime (L) are two key parameters. In this illustrative example, we consider three abstract narratives defining different F and L, namely:

* F100L100: the net biogenic C harvested is stored in anthropogenic products with very long lifespan (e.g. a bio-based composite wall for buildings) and with multiple recycling loops, i.e. an overall storage time of more than 100 years. No biogenic C is lost as gas.
* F100L1: the whole harvested C is used as anthropogenic products with short lifespan (1 year), with incineration as end-of-life (e.g. a biofuel).
* FxLy/Fx’Ly’: part of biogenic C harvested is lost during the manufacture, with C fractions Fx and Fx’ in the product and lost respectively. Several lifetimes Ly are considered while the L1 means immediate C emission to the atmosphere. All biogenic C is emitted as CO2 at the product end-of-life (e.g. incineration). Several values considered for this example are F70L10/F30L1, F70L20/F30L1, F70L50/F30L1 (other values were used in Appendix I).

The year per year flows of biogenic C involved, from/to the atmosphere, were calculated through a mass balance, as detailed in appendix II. The actual year per year effect on global mean temperature change (GMTC) was calculated based on the impulse response function approach recommended by IPCC(Stocker et al., 2013) and using a Python software developed in a previous study (Shimako et al., 2018) and available at https://www.insa-toulouse.fr/fr/recherche/labo/lisbp/outil-de-calcul-changement-climatique.html. For tractability reasons, it was considered that there are no differences in terms of CO2 and other GHG emissions from the background activities (e.g. electricity, fertilizers, etc.) of the narratives illustrated herein. Therefore, the focus is maintained on the differences in biogenic carbon flows induced by different L and F only.

The evolution of the annual stocks is shown in fig. 2a as a fraction of the C absorbed i.e. , for each couple of parameters (L, F). Positive values indicate the stock formed while negative values indicate stock consumed per year. The decrease in stock every 20 years corresponds to the break between 2 rotations (land preparation). One should note the variety of behaviors and the difficulty of qualifying the mitigation potential of each case.

a

b

Fig. 2 Carbon flows analysis (a) fraction of biogenic carbon stored per year, (b) global mean temperature change

The behaviors vary between two extreme situations: F100L100, i.e. all the harvested carbon is embedded in a product with a very long lifespan, and F100L1, i.e. all the harvested carbon is released to the atmosphere due to the end of life of very short-lived products. While the former has significant stocks over the entire time horizon (except the inter-rotations period), the latter, on the contrary, retains few carbon and even offsets a part of the SOC formed after two rotations. For the other three situations, we observe a reduction of stock formation in time. For example, F70L50/F’30L’1 creates stocks until about 2070, when end-of-life emissions start for the first products; at this time, the biogenic C embedded in the products is released as CO2, and the process replicates each year for the subsequent products. The positive peaks (stocks) observed (especially in the case of F70L10/F’30L’1) correspond to years when no product reaches the end of life (no emissions). Then, the C fraction incorporated into the long-lived products affects the stock amount, visible on the plateau values for F100L100 and F70L50/F’30L’1. It can be concluded that the higher the fraction stored and the longer the lifetime, the longer the time horizon over which the stocks are effective. According to the balance equations, the CO2 flows follow the same shapes (fig. S2), with emissions associated with negative stocks and with capture associated with positive stocks.

Fig. 2b represents the effect of biogenic C balance (for 1 ha of land) on GMTC. Negative values indicate a beneficial effect (temperature decrease) and can be considered as targets. This representation clearly indicates that the short-lived products with end-of-life emissions in less than 1 year (e.g. F100L1) have few mitigation capacity, which vanishes after two rotations. On the contrary, the more the end of life emissions are postponed (or suppressed), the greater the beneficial effect. Here also an optimal period with a negative GMTC peak is observed, corresponding to the lifespan of the first products manufactured, and postponed by several years due to thermal inertia of Earth (e.g. in 2077 for F70L50/F’30L’1). After this time, the benefit diminishes until circa 80 years when the biopump culture and transformation into products are stopped. Till 2100, all scenarios except F100L1 are negative in GMTC, contributing to mitigating climate change. After 2100, the end-of-life effect is observed with a positive spread of GMTC over time until the last product disappears from the technosphere. Within the time boundary 2020-2120, C in F70L10/F’30L’1 is released to the atmosphere, causing GMTC rise above 0 K; the same happens in F70L20/F’30L’1 but later. The benefit of suppressing the end-of-life emissions can be countered by a lower utilization fraction F in long-lived products, and a trade-off situation between parameters L, L’, F, and F’ can occur (other examples are given in Appendix I, fig. S3). Many other parameters influence the carbon stocks and their evolution in time, therefore detailed analyses are necessary before practical implementation of a biopump. For example, the effect of initial SOC (100 Mg ha-1) and temperature (higher by 2℃) on GMTC results for F100L1 (all biogenic C is released within 1 year) is presented in Appendix I, Fig S4, in these conditions there is no more mitigation potential.

**4. Conclusions**

In this study, the concept of CSAAP has been demonstrated to meet the challenges of inducing additional CDR and transiting towards the low fossil-C involved economy. It builds up on the biopump concept, i.e. plants able to stock carbon as SOC and long-lived bio-based products in anthroposphere. CSAAP, as general methodology that could be applied on any region, is composed of four steps: i) identification of biopump candidates, ii) selection and ranking of biopumps, iii) identification and selection of lands suitable for biopump plantation, iv) assessment of the mitigation potential.

Switchgrass and black locust could be the most suitable herbaceous and woody plants for France, respectively, as they rank on the top of the biopump candidate list. To cultivate biopumps in France, four among twenty-three land cover types were selected to be converted: rapeseed lands, woody moorlands, natural grasslands, and part of intensive grasslands. Among these four types of lands, the areas with SOC lower than 50 t ha-1 were chosen because of the relatively high potential to store additional SOC. These areas, called CV-lands, occupy up to 24, 007 km2, expecting to stock 0.49 Mt SOC every year. This could represent up to 0.41% of CO2 emissions annually from the 2015-2018 French carbon budget, and up to 13.07% if all produced biomass is stored in the technosphere.

Following the analysis of dynamic C flows from biopump cultivation to biomaterial disposal, biopumps could be efficient solutions in global warming mitigation if the biomass is kept in the technosphere as long as possible (embded in bio-based materials). In these conditions, they contribute to negative GTMC untill at least 2100. In contrast, the biomass use as bio-energy (biogenic carbon released within one year) cannot contribute to carbon removal, but rather will offset the benefice of SOC increase, which demonstrates the need to decarbonize the energy whatever the source of carbon. However, several limitations can be identified and prospected.

- The results obtained are based on available studies, mainly on Ledo et al., but more data on SOC potential and suitability of biopump growth are needed.

- The equal weight given to the selection criteria could be a bias, which can be alleviated by considering regional cultivation specificities with eventual constraints.

-Albeit the focus is here on CO2 emissions, other greenhouse gases and emission flows need to be fully considered.

The goal at this stage was not to determine the optimal biopump-anthropogenic product combination, but to present a methodology to do so, and to assess the magnitude of CSAAP as a strategy for controlling global warming. The real benefit of the implementation in the real world must be evaluated by integrating the entire anthropogenic system with associated technological GHG emissions and conventional product replacements (e.g. fossil-based), by DLCA methodology for instance(Beloin-Saint-Pierre et al., 2020). Also, an on-site experiment of cultivating biopumps on CV-lands could validate the results, and further on other parts of the world.

The proposed approach shows that the combination of biopump – anthropogenic products is of great importance if zero or negative GHG emissions are aimed at the target time horizon. This work is the basis for future research to propose concrete, reliable applications for France.

**Note**

The authors declare no competing financial interest.

**Acknowledgments**

This work was carried out within the research project Cambioscop (<https://cambioscop.cnrs.fr>), financed by the French National Research Agency, Programme Investissement d’Avenir (ANR-17-MGPA-0006) and Region Occitanie (18015981). Additional funding was supplied by the Chinese Scholarship Council (201801810082).

**Appendix**

Appendix I provides tables and figures. Appendix II is an excel sheet with carbon flow calculations for the given example.

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