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Estimated climate impact of replacing agriculture as the primary food production system

Andrew H MacDougall[1,*], Joeri Rogelj[2,3] and Patrick Withey[4]

[1] Climate & Environment, St. Francis Xavier University, Antigonish, Canada
[2] Grantham Institute for Climate Change and the Environment, Imperial College London, London, United Kingdom
[3] International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria
[4] Department of Economics, St. Francis Xavier University, Antigonish, Canada
[*] Author to whom any correspondence should be addressed.

E-mail: amacdoug@stfx.ca

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Abstract

Global agriculture is the second largest contributor to anthropogenic climate change after the burning of fossil fuels. However the potential to mitigate the agricultural climate change contribution is limited and must account for the imperative to supply food for the global population. Advances in microbial biomass cultivation technology have recently opened a pathway to growing substantial amounts of food for humans or livestock on a small fraction of the land presently used for agriculture. Here we investigate the potential climate change impacts of the end of agriculture as the primary human food production system. We find that replacing agricultural primary production with electrically powered microbial primary production before a low-carbon energy transition has been completed could redirect renewable energy away from replacing fossil fuels, potentially leading to higher total CO_2 emissions. If deployed after a transition to renewable energy, the technology could alleviate agriculturally driven climate change. These diverging pathways originate from the reversibility of agricultural driven global warming and the irreversibility of fossil-fuel CO_2 driven warming. The range of reduced warming from the replacement of agriculture ranges from −0.22 (−0.29 to −0.04) °C for shared socioeconomic pathway (SSP)1 −1.9 to −0.85 (−0.99 to −0.39) °C for SSP4-6.0. For limited temperature target overshoot scenarios, replacement of agriculture could eliminate or reduce the need for active atmospheric CO_2 removal to achieve the necessary peak and decline in global warming.

1. Introduction

After the burning of fossil fuels, agriculture makes the second largest contribution to anthropogenic climate change [1]. Agricultural climate change is primarily caused by CO_2 emitted from land use change, CH_4 emissions from ruminants (mostly cattle) and rice paddies, and N_2O emissions from denitrification of natural and synthetic fertilizers [1]. Land use change also causes biophysical changes in albedo, transpiration, and turbulent energy exchange that cause cooling in extra-topical regions and may cause warming in the tropics [2]. In addition to these climate forcings inherent to agriculture, industrialized agriculture uses fossil fuels to power machinery and produce fertilizers and other inputs [1]. Overall agriculture is believed to be responsible for about a quarter of present day anthropogenic climate change [3]. For this study we separate fossil fuel driven and agriculturally driven climate change by considering agricultural climate change to be the climate forcings from agriculture that would continue following replacement of fossil fuels with alternative energy sources. That is, agricultural emissions of N_2O and CH_4, and emissions and biophysical effects from agricultural land use change.

Climate warming from fossil fuel CO_2 emissions is expected to last for millennia [4, 5]. In contrast, CH_4 and N_2O have atmospheric lifetimes of 9.8 ± 1.6 years, and 131 ± 10 years respectively [6], while

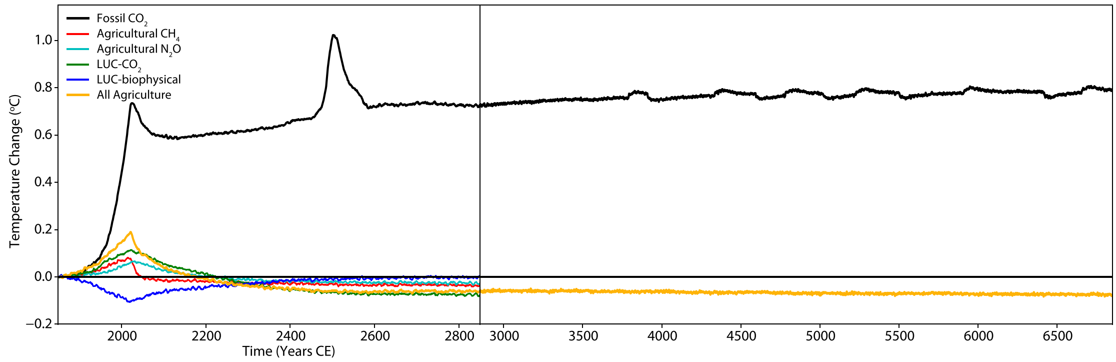

Figure 1. Global mean surface air temperature anomalies, relative to the 1850–1900 period mean, for zero emissions commitment experiments. In all experiments either emissions are set to zero or land use is released from agriculture in year 2020. LUC is land use change, LUC is separated into a CO_2 and a biophysical effect (e.g. albedo changes). The complex behavior of global temperature for the fossil fuel simulation, including the temperature spike around year 2500, is driven by instability in, and collapse of the meridional overturning circulation (see figure S1). Note the break in time-scale after year 2850.

degraded soils can recover carbon and forests can regrow on decadal to centennial timescales, depending on the ecosystem [7], suggesting that agricultural climate change will have a much shorter intrinsic lifetime. Studies that have simulated the effect of setting anthropogenic CH_4 and N_2O emissions to zero have suggested that reductions in temperature happen almost immediately following cessation of emissions [8–12]. Studies examining the reversibly of land use changes have also shown similar results [13, 14]. Thus these studies heavily imply that agricultural climate change is reversible on decadal time-scales.

To illustrate this effect explicitly, a series of zero emissions commitment experiments were conducted with the University of Victoria Earth System Climate Model (UVic ESCM, section 2.1) wherein fossil fuel, agricultural emissions and/or land-use cease in year 2020 (see supplementary information S1 (available online at stacks.iop.org/ERL/16/125010/mmedia)). The results of these simulations are shown in figure 1. The simulations suggested that by the 2050s half of the industrial era agricultural warming has dissipated, and by the 2260s industrial era agricultural warming has dissipated entirely (figure 1). Although these results are for only a single climate model, and post emission cessation inter-model climate trajectories vary substantially [15], the basic principle is evident: by eliminating emissions from agricultural activities, agricultural climate warming is likely reversible on human time-scales, while warming from burning fossil fuel CO_2 emissions is not.

These results open up the question of how much agricultural warming can be reversed, with the upper limit defined by a world without agriculture. This limit may be unobtainable. However, recent advanced in microbial biomass growing technology have opened a food production pathway that uses electricity in place of photosynthesis to power primary production [16].

The concept of using microbial biomass as a food source for livestock and humans has existed for decades [17]. Recently there has been renewed interest in the technology, spurred by studies that have examined the potential for microbes to provide primary production of food for long-duration spaceflight [18]. Many pathways exist to produce microbial biomass exploiting substrates including CO_2, CH_4, and various forms of organic matter, with potential energy sources from organic matter, CH_4, and hydrogen [19]. In this study, we focus on hydrogen oxidizing bacteria because they decouple primary production from photosynthesis, provide a particularly efficient chemosynthetic pathway, and have under laboratory conditions converted 55% of input energy (electricity used in water electrolysis) into biochemical energy [20]. Thus systems have been envisioned, which would combine the existing technologies of water electrolysis, bacterial fermentation, and atmospheric or point source CO_2 capture to grow vast quantities of biomass for animal [21] or human [16] consumption. Such a technological system would break the link between photosynthesis and primary food production. Variants of the system design that exploit renewable energy and direct air capture of CO_2 also break the link between food production and fossil fuel use. Commercialization of this technology is underway [18]. Bacterial biomass cultivation for food has not yet been given a concise name and has thus far has been referred to by variants of 'Bacterial protein for food and feed generated via renewable energy and direct air capture of CO_2' [16]. Following the example of 'vermiculture' (the cultivation of worms) we propose 'bacilliculture' from the Latin 'bacillus' for bacterium and 'cultura' for cultivation. Such a coining fits the pattern of agriculture, horticulture, silviculture, and aquaculture.

The technology of bacilliculture does not require a consistent energy supply [16] and thus harmonizes well with intermittency of solar and wind power. The estimated energy required for producing a kg of dried microbial biomass from bacilliculture is 11 kWh of electricity, with thermal energy requirements provided by waste heat [16]. The 2019 levelized cost of new utility scale solar power is 0.068 USD kWh^{-1} [22] and thus producing a kg of biomass from bacilliculture would cost 0.75 USD in electricity alone. However the cost of solar power dropped 82% between 2009 and 2019, and is expected to continue to decline [22]. Accounting for the social cost of carbon [23] and range of possible costs of bacilliculture there may already be markets where bacilliculture would be lower cost than agriculture (see supplementary information S2). Under future conditions of high grain cost, and high energy storage cost, it is possible (though not necessarily probable) that renewable energy could flow towards bacilliculture instead of being used to replace fossil fuels. Thus there is an urgent need to assess the potential impact of bacilliculture on climate change before the technology reaches commercialization.

Between 1961 and 2017 global production of cereals rose from 800 million tonnes to 2.76 billion tonnes [24], outstripping the contemporary growth in global population [25]. However, this transition to industrial agriculture has brought with it a host of environmental problems, including excess nitrogen and phosphorus flows, overuse of freshwater, and threats to biosphere integrity [26]. In addition, agriculture both contributes to, and is vulnerable to, climate change [1]. The promise of bacilliculture technology is that it could mitigate these environment crises, while simultaneously increasing the global food supply and allowing much of the land surface to return to a wild state. However, replacement of agriculture could also cause profound social disruptions, as billions of families work in the agricultural sector [27], and food production is a central aspect of most cultures [28]. Although bacilliculture is a technology that has immense potential to protect the integrity of the Earth system, while simultaneously improving the material condition of humanity, it also comes with deep social and environmental risks that need careful study and consideration.

To explore the potential impact of bacilliculture on climate change we here examine the potential increase in CO_2 emissions from diverting renewable energy to bacilliculture, the abatement potential of bacilliculture as measured by CO_2 equivalent emissions estimated with 100-year global warming potentials, and future climate scenarios modified to incorporate bacilliculture. In the future climate scenarios we examine a maximalist assumption wherein bacilliculture replaces 90% of agriculture. These scenarios are intended as a thought experiment to establish the maximum contribution bacilliculture could make to reduce climate warming. Realistically the technology would have to overcome substantial nutritional (see supplementary information S3) and cultural hurdles to become more than minor supplement to agriculture.

2. Methods

2.1. UVic ESCM

The University of Victoria Earth System Climate Model (UVic ESCM) is a climate model of intermediate complexity, with a full ocean general circulations model and a simplified energy and moisture balance atmosphere [29]. The latest version of the model, version 2.10, is described in detail in Mengis *et al* [29]. UVic ESCM 2.10 includes a full representation of the global carbon cycle including dynamic vegetation and a permafrost carbon pool on land, and a highly developed ocean biogeochemistry module. Land use change is represented in the model by prescribing a fraction of each grid cell which can only be covered in C3 or C4 grasses. The standard version of UVic ESCM 2.10 has been augmented here to include a representation of atmospheric CH_4 and N_2O. This feature was migrated from the module used by MacDougall and Knutti [30] into UVic ESCM 2.10. Radiative forcing for CH_4 and N_2O were updated to the equations of Eyring *et al* [31]. This version of the model does not include dynamic representation of CH_4 and N_2O sources and hence natural emissions are prescribed.

By modifying the flow of outgoing longwave radiation to space as a function of global mean surface temperature anomaly, the equilibrium climate sensitivity of the UVic ESCM can be modified [29, 32]. Additionally by scaling the aerosol forcing by a uniform factor, aerosol cooling can be changed to keep historical temperatures within the observed range when conducting experiments with modified equilibrium climate sensitivity [29].

Like all Earth system models [33] the UVic ESCM can be forced with either CO_2 concentration pathways or CO_2 emissions. Additionally the UVic ESCM can be set-up to track a prescribed global temperature trajectory with compatible CO_2 emissions and atmospheric CO_2 concentration diagnosed by the model [32].

2.2. Illustrative energy transition model

One of the advantages of bacilliculture is that the technology has already achieved an efficiency at capturing solar energy 3–10 times greater than crop photosynthesis [20]. However at an estimated 11 kWh kg^{-1} [16] of dried biomass, deploying bacilliculture at scale implies an immense requirement for electrical generating resources. In this section we estimate the additional energy burden bacilliculture could place on our present energy transition to renewable energy and the potential additional CO_2 emissions from diverting renewable energy to bacilliculture, assuming a baseline energy transition compatible with the Paris Agreement [34].

We estimate the energy required for bacilliculture from human caloric need, human population and the estimated efficiency of bacilliculture. Depending on age, activity level, sex, and body size, humans require between 1000 and 3200 kcal per day to remain healthy [35]. There are 4184 J in 1 kcal and 86 400 s in 1 day, thus humans require a power input of 48–155 W. If we take an average power need of 110 W and the present human population of 7800 000 000 people [25] we arrive at an energy requirement of 0.86 TW. The efficiency of bacilliculture is estimated to between 15-35% [16, 36], including processes needed to produce hydrogen, capture CO_2 and separate and dry the biomass. We use 20% efficiency in our estimate, consistent with [21]. Thus 4.3TW of electricity are needed to provide 0.86 TW of food energy for human consumption ($0.86/0.2 = 4.3$). We then round 4.3 TW up to 10 TW to account for food waste [37], pets [38], and population growth [25]. The 10 TW of power is sufficient to completely replace agricultural primary production if biomass from bacilliculture is eaten directly. If biomass from bacilliculture primary production must be feed to other organisms to become nutritionally (see SI S3) and culturally acceptable for the human population, devoting 10 TW to bacilliculture would only be sufficient to partially replace of agriculture.

To examine the possible effects of diverting renewable energy from decarbonization to bacilliculture a simple illustrative model was devised. In this model the installation rate of new renewable energy rises logistically, while the total power production from renewable energy is an integral of the past 25 years of installation (measured in electricity generation—not system capacity). That is, there is an assumed fixed 25 year lifespan of solar panels and wind turbines. Total power output at equilibrium is set at 795.2 EJ yr^{-1} (220.9 PWh yr^{-1}), the sum of present day fossil fuel derived energy (478.8 EJ yr^{-1}–133 PWh yr^{-1}, [39]) and our estimated energy required for full replacement of agriculture with bacilliculture (10 TW–315.72 EJ yr^{-1}–87.7 PWh yr^{-1}). The logistic equation for the rate of deployment is:

$$I = \frac{I_{eq}}{1 + e^{-r(t-t_m)}}, \tag{1}$$

where I is the installation rate, I_{eq} is the equilibrium installation rate, r is the growth in the deployment rate, t is time and t_m is the mid-point of the function. The r and t_m were found by fitting the model to the total deployed wind and solar power between 2009 and 2018 [40] and a remaining carbon budget of 1371 $GtCO_2$ compatible with keeping global average temperature increase below 1.75 °C [41]. Fossil fuel emissions are assumed to have a carbon intensity of 27.5 $\times$ 10^{-5} $GtCO_2$/TWh [39]. Thus the second criteria for model fit is achieved by minimizing the difference between the integral of fossil fuel power multiplied by the carbon intensity and the remaining carbon budget (assuming all new renewable power goes to replacing fossil fuel power).

The idealized model is used to calculate how much extra CO_2 emissions will result from diverting a given fraction of new renewable energy to bacilliculture. For each integration the cumulative energy devoted to bacilliculture is used to compute extra carbon emissions up until either the total power devoted to bacilliculture reaches 315.72 EJ yr^{-1} (10 TW), or the total power devoted to decarbonization reaches 795.2 EJ yr^{-1}. After the threshold is reached all new renewable energy is devoted to the unfulfilled goal.

2.3. Abatement potential of bacilliculture

The potential of bacilliculture to reduce warming can be estimated based on emissions of N_2O and CH_4 from crop agriculture, and conventional CO_2 equivalency metrics. The affect of afforestation from abandoning agricultural land is left aside in this section. Afforestation causes both cooling from carbon uptake and warming from biophysical effects [2] with the net balance being localized and uncertain at the global scale, and thus is best addressed within a Earth system modeling framework [2], as is employed in section 2.4.

For each gas we examine the maximum potential based on recent estimates. The CH_4 emissions from rice paddies are estimated to be between 24 and 40 Tg CH_4–C yr^{-1} [42]. For N_2O we base our estimates on the recent review of Tian [43]. Tian [43] suggests that 3.8 Tg N_2O–N yr^{-1} are directly from agriculture, with 3.3 Tg N_2O–N yr^{-1} from crops. Additionally inland waters and coastal areas contribute 0.4 Tg N_2O–N yr^{-1} originating from nitrogen leaching, 0.6 Tg N_2O–N yr^{-1} from biomass burning, and atmospheric deposition adds 0.9 Tg N_2O–N yr^{-1}. We assume that half of biomass burning is due to burning crop residues, and that 65% of atmospheric deposition originates from agricultural emissions of NH_3 and NO_x [44]. Applying the crops to non-crop ratio (87% crops) to all agricultural sources we arrive at an estimate of 4.7 Tg N_2O–N yr^{-1} from crop agriculture. Note that the estimate includes emissions from crops used to feed livestock, and that other papers have estimated higher fractions for animal agriculture [45].

We divide agricultural crop emissions by the global average crop yield from 2007 to 2016 (to match the time frame for the N_2O emission estimates [43]). Crop production data was taken from the United Nations Food and Agriculture Organization (FAO) database [24]. Cereal, potatoes, sweet potatoes, Cassava, Yams, sugarcane, sugar-beats, soybeans and common beans, where considered. Note FAO gives a combined total production for all cereal crops. The mass of sweet potatoes, Cassava, and Yams was corrected for their higher water content than grains. Tuber statistics are collected for a standard 75% water mass [24] while cereal statistics are collected for a standard 13% water mass [24]. Mass from sugar-crops was based on their sugar mass (13% for sugarcane and 16% for sugar-beet). This yields a total global crop production of 3.21×10^{12} kg of cereal equivalent, 75% of which is cereals. Rice production is 0.72×10^{12} kg of rice. Thus we estimate 1.5 g N_2O–N kg^{-1} of grain and 12 g CH_4–C $kg^{-}1$ of rice. To get the emissions per PWh we use a range of efficiency estimates. As our central estimate we use 11 kWh per kg of microbial biomass production from Sillman *et al* [16]. For upper bound we combine the lowest estimated efficiency of bacilliculture from Alvarado *et al* [36] of 15% combined with a estimated caloric value for a kg of dried bacterial biomass of 3500 kcal kg^{-1} (see supplementary information S3) to yield 28 kWh kg^{-1}. For the lower bound we use the estimated efficiency of bacilliculture from Liu *et al* [20] of 55% assuming that improvements in the process can eventually compensate for energy required to capture CO_2 from the air and separate bacterial biomass. This yields a lower bound of 7.5 kWh kg^{-1}. The estimated caloric value of bacterial biomass is similar to wheat, rice and maize but lower than soybeans (see supplementary information S3), thus we assume a 1 to 1 substitution of bacterial biomass and grain. We use 100 year Global Warming Potential of 34 for CH_4 and 298 for N_2O [6] to estimate a naive but conventional CO_2 equivalent abatement potential of bacilliculture. In other sections of this study we incorporate N_2O and CH_4 emissions directly into Earth system model simulations, a more comprehensive but rarely used approach [46].

Ecological recovery following cessation of agriculture would also have an effect on local and global climate [2]. However whether the net balance is a cooling or warming effect is site specific and hence is left aside for this estimate.

2.4. SSP simulations

To examine the potential impact of bacilliculture on future climate change we require scenarios of future agricultural land use and emissions, such that we can examine the difference between scenarios with expected future agriculture and scenarios modified to account for bacilliculture. We base our scenarios on the shared socioeconomic pathway (SSP) and the core set of scenarios used for CMIP6 [31]. Each SSP-based scenario has specified future emissions of CH_4 and N_2O, with CH_4 broken into emissions from agriculture and industry [47]. Additionally SSP scenarios provide gridded land use change data for each year of the scenario [47]. Unmodified SSP based simulations were conducted with the UVic ESCM with the model's emergent equilibrium climate sensitivity of 3.8 °C, as well as climate sensitivities of 2.0 °C and 5.0 °C. Corresponding changes to aerosol forcing scaling factor were imposed to match all climate sensitivity variants to the historical temperature trajectory. Eight of the SSPs were simulated: SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-3.4, SSP4-6.0, SSP5-3.4-Over, and SSP5-8.5 [31]. These simulations are referred to as 'standard simulations'.

For each SSP-based scenario we modify the CH_4 and N_2O emissions and land-use to account for adoption of bacilliculture as the principal pathway of primary production to feed humans and domesticated animals. Consistent with our maximalist approach the modified scenarios assume that bacilliculture-produced microbial protein will either replace animal protein directly or that the medium used to grow cultured meat [48] may in the future be produced from bacilliculture grown feedstock. An alternative scenario where bacilliculture produced biomass is used to feed livestock is left aside for now but has been noted as a potential avenue for future investigation. Additionally, we assume at maximum 90% of agriculture can be replaced. For simplicity we impose the same relative change in agriculture on all SSP scenarios. We assume that agriculture is replaced logistically, with a mid-point in year 2050 a growth rate of 0.2. Note that for a logistic function the growth rate is only reached at the time of mid-point and is lower for all other times. For CH_4 agricultural emissions are provided by the SSP database [47] until the year 2100. Thereafter we assume that agricultural emissions are constant following the method used for the SSP extensions to year 2500 [49]. For N_2O anthropogenic emissions are assumed to come from three sources: agriculture, industrial emissions, and sewage. At the point of departure in year 2010 agricultural emission are taken to be 75% of total N_2O emissions consistent with reference [45], industrial emissions are taken at 20% and sewage at 5% [50]. For the future the industrial fraction is taken to be proportional to global CO_2 emission rate in each SSP scenario, and the sewage fraction is taken to be proportional to human population in each SSP. The fraction of agricultural land use for both pastures and crops is reduced uniformly in each grid cell.

Two sets of experiments were conducted to examine the effect of bacilliculture on the scenarios, one set with the modified CH_4, N_2O and land-use forcings and the UVic ESCM set-up to track the temperature from the standard SSP simulations. To compensate for the lower CH_4 and N_2O forcing and the altered land-use the model will diagnose higher CO_2 emissions to maintain the temperature trajectory of the standard baseline simulation. Thus these simulations assess how the adoption of bacilliculture could effect the cumulative CO_2 emissions consistent with each SSP. The second set of experiments again uses the modified CH_4, N_2O and land use forcings as well as being forced with the diagnosed CO_2 emissions from the standard SSP (standard SSP simulations are forced with CO_2 concentrations). These simulations have identical cumulative CO_2 emissions as the standard SSP simulations but will have different global temperatures. Thus these simulations assess how the adoption of bacilliculture could effect global temperature change.

2.4.1. SSPs without negative emissions

A third set of SSP experiments were conducted to examine the potential for bacilliculture to replace active measures to remove CO_2 from the atmosphere under temperature overshoot scenarios. In this set of simulations the UVic ESCM is forced with the modified CH_4, N_2O and land use forcings in addition to modified CO_2 emissions diagnosed from SSP1-1.9, SSP1-2.6, SSP4-4.3, and SSP5-3.4-Over. The CO_2 emissions pathways follow those from the standard simulations until net zero CO_2 emissions are reached. Thereafter CO_2 emissions are held at zero instead of becoming net negative. To keep the forcings consistent for each SSP scenario, CO_2 emissions pathways were only constructed from the scenario simulations with an ECSs of 3.8 °C. Thus new baseline simulations were conducted for ECS of 2.0 °C and 5.0 °C forced with CO_2 emissions diagnosed from the standard scenarios conducted with ECSs of 3.8 °C.

3. Results

3.1. Illustrative energy transition model

To explore the effect of devoting renewable energy to bacilliculture an illustrative model was devised, wherein renewable energy grows logistically [51] until enough energy is available to replace fossil fuels and agriculture. Figure 2 shows the effect of devoting a given percentage of renewable energy to bacilliculture. The model suggests that devoting 25% of all new renewable energy to bacilliculture would cause 193 $GtCO_2$ emissions in excess of the cumulative emissions consistent with keeping warming to 1.75 °C. Devoting 50% or 100% to bacilliculture would cause this excess to increase to 587 $GtCO_2$ and 850 $GtCO_2$, respectively. Devoting very little renewable energy to bacilliculture until decarbonization is complete would minimize CO_2 emissions and thus based on the results shown in figure 1 minimize the irreversible component of climate warming.

3.2. Abatement potential of bacilliculture

Replacing agricultural primary production with bacilliculture would reduce emissions of N_2O from croplands and CH_4 from rice paddies and hence reduce their warming contributions (figure 1), potentially offsetting the CO_2 warming caused by diverting resources from decarbonization. Using the frequently misinterpreted [46] but widely used [6] Global Warming Potential CO_2 equivalence metric over an 100 year time horizon (GWP-100), we estimate that devoting a PWh of electricity to bacilliculture would reduce annual emissions by a maximum of 0.12 (0.05–0.18) $GtCO_2$eq/PWh (bacilliculture energy requirement 11 (28–7.5) kWh kg^{-1}) if replacing non-rice grains and 0.36 (0.14–0.52) $GtCO_2$eq/PWh if replacing rice. This compares to a reduction in CO_2 emissions of 0.20 $GtCO_2$/PWh from abatement of CO_2 emissions from electricity production with natural gas and 0.34 $GtCO_2$/PWh from electricity production with coal [39]. The effect of bacilliculture would be enhanced if the targeted agricultural lands would be replaced by high carbon density tropical ecosystem where the biophysical CO_2-sequestration balance of ecosystem recovery would favor a net cooling effect [2].

3.3. SSP simulations

To examine the potential for bacilliculture to alleviate climate change we modified eight scenarios that are based on the shared SSPs used for future climate projections [31]. Figure 3 shows the results of these bacilliculture-SSP simulations for year 2300. For the emission tracking simulations the reduction in global warming from phasing out agriculture range from −0.22 [−0.29 to −0.04] °C (ECS of 3.8 [5.0–2.0] °C) for SSP1-1.9 to −0.85 (−0.99 to −0.39) °C for SSP4-6.0 for the years 2250–2300. The magnitude of warming reduction follows the climate sensitivity with a higher reduction under an ECS of 5.0 °C, and smaller reduction under ECS of 2.0 °C. The maximum warming reduction is found under the two SSP4 scenarios, which anticipate high growth in industrial agricultural production [52] and thus have the highest agricultural emissions of all the SSPs [47]. For the temperature tracking simulations the increase in fossil fuel cumulative CO_2 emissions from bacilliculture by year 2300 ranges from 467 $GtCO_2$ (128 PgC) under SSP1-1.9 ECS 2.0 °C to 1974 $GtCO_2$ (538 PgC) under SSP5-8.5 ECS 3.8 °C. The change in the carbon budget does not vary substantially with ECS. Intriguingly and fully coincidentally the reduction in emission for the four temperature overshoot scenarios (SSP1-1.9, SSP1-2.6, SSP4-3.4, and SSP5-3.4-Over) are similar to the total net negative CO_2 emissions assumed in those scenarios.

3.3.1. SSPs without negative emissions

Figure 4 shows the results of the SSP simulations carried out without negative emissions. For SSP1-2.6 and SSP4-3.4 the bacilliculture with no net negative emissions simulations follow the standard simulations closely for each ECS, and by the 24th century are slightly cooler than the baseline SSPs. Except for SSP1-1.9 atmospheric CO_2 concentrations are also very close by year 2300, with difference from the standard baseline simulations at −16 (−15 to −19) ppm for SSP1-2.6 and −2 (0 to −5) ppm for SSP4-3.4 (figure S2). For SSP1-1.9 and SSP5-3.4-Over

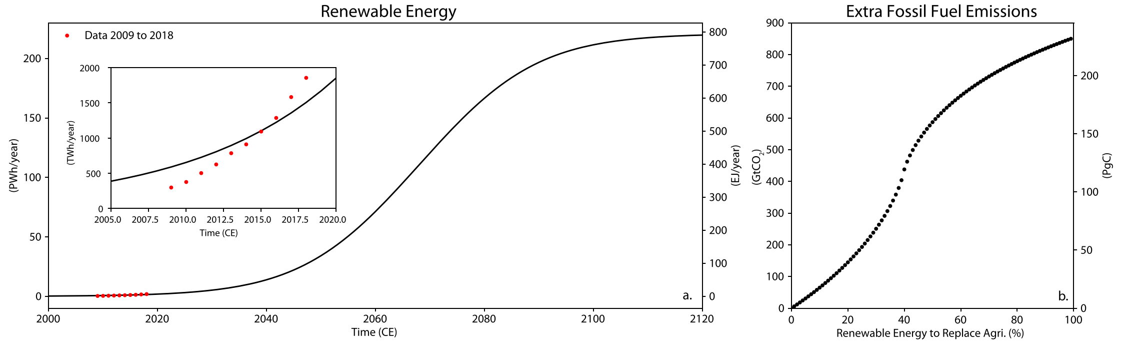

Figure 2. (a) Idealized model of renewable energy deployment. Inset zooms in on data to model comparison, showing that observed renewable energy installation rate (slope of the curve) is higher than that required by the model. Data is from International Renewable Energy Agency [40]. Electricity generation is shown (not system capacity). (b) Additional cumulative emissions of CO_2 from diverting renewable energy to bacilliculture.

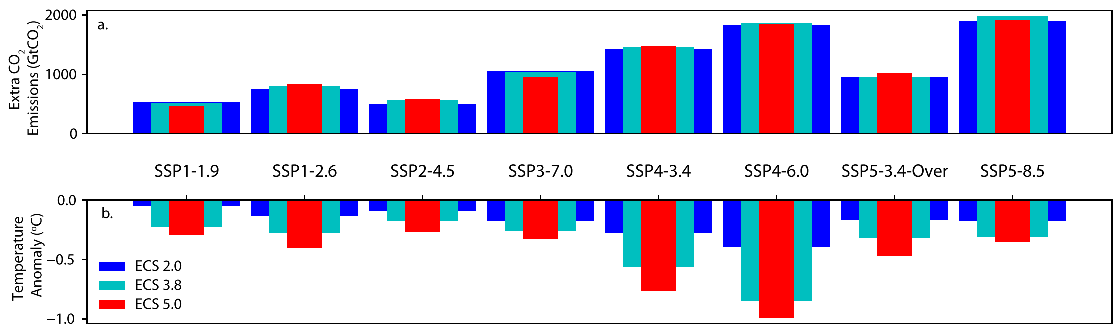

Figure 3. Change in cumulative CO_2 emissions while achieving the same temperature outcome (top row), or change in global mean temperature (bottom row) from implementing bacilliculture for each of eight SSPs based scenarios. The cumulative CO_2 emission changes are computed from simulations where the temperature trajectory of the standard SSP scenarios is followed and hence the reduction in warming from the phase-out of agricultural CH_4, N_2O and land use is replaced with additional CO_2 emissions. The temperature changes are computed from simulations where the fossil fuel CO_2 emissions from the standard SSPs based simulations is followed and hence the reduction in warming from the phase-out of agriculture is allowed to manifest. All anomalies are bacilliculture-SSPs scenarios minus standard-SSPs scenarios. Temperature difference is calculated for the mean of the year 2250–2300 period. Changes in cumulative CO_2 emissions are computed from today until year 2300.

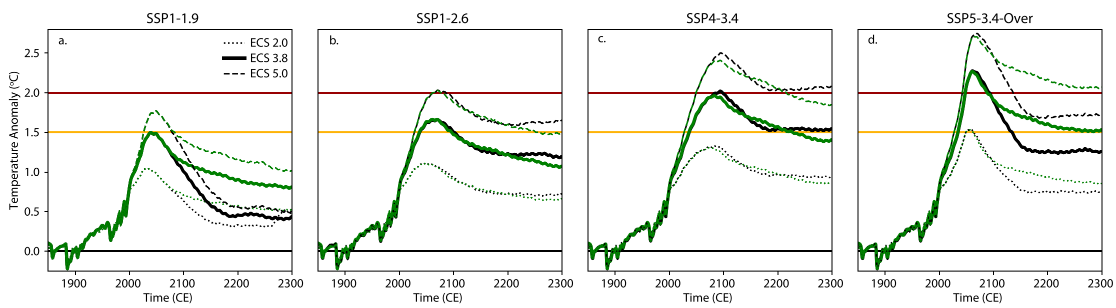

Figure 4. Results for standard simulations (black lines) and bacilliculture with no negative emissions simulations (green lines) for four SSP-based temperature overshoot scenarios. Global mean temperature anomalies relative to pre-industrial (1850–1900 mean). Amber horizontal line is the 1.5 °C guardrail and crimson line is the 2.0 °C guardrail [34]. ECS is equilibrium climate sensitivity.

the bacilliculture with no negative emissions simulations are warmer than the standard SSP. However, under SSP1-1.9 the simulations remain below the Paris guardrail of 1.5 °C [34] for all ECSs, while SSP5-3.4-Over overshoots the guardrail for about three centuries for ECS of 3.8 °C or higher. SSP5-3.4-Over overshoots the 2.0 °C [34] guardrail by only 0.07 °C under an ECS of 5.0 °C. Thus these simulations suggest that fully replacing agricultural primary production with bacilliculture primary production would allow achieving some temperature overshoot pathways without having to actively remove more CO_2 from the atmosphere than is emitted by residual anthropogenic sources.

4. Discussion and conclusions

The experiments conducted here were intentionally designed to give a broad sense of the potential global climate impact of the widespread adoption of bacilliculture. Future studies can concentrate on regional and focused applications of bacilliculture, and work towards integrating the technology into scenario storylines. Of particular interest is examining whether bacilliculture can be targeted to replace the most environmentally destructive forms of crop agriculture such as replacement of the Amazon rainforest with soy crops [16] on decadal time horizons. Regions of the world rich in hydroelectric and geothermal renewable energy resources are likely to decarbonize long before other regions [53]. For such regions which are geographically isolated and unable to export surplus renewable energy, bacilliculture may become an optimal option for using surplus resources.

The simple analysis in section 3.2 would seem to suggest that replacing rice production with bacilliculture would be more of a net benefit to reducing warming than using renewables to replace natural gas fueled electricity production. However, an important limitation of the GWP-100 CO_2 equivalence metric is that it does not account for the multi-millennial lifetime of warming from CO_2 emissions [46]. Accounting for the lifetime of CO_2 it is clear that maximizing warming reduction from bacilliculture would require deploying the technology only after decarbonization has reached its limits. Another factor to consider is that agricultural soils can be altered to become carbon sinks via mixing of biochar [54] and/or basalt dust [55] into the soils. This carbon sequestration pathway would be foreclosed if agricultural lands are abandoned.

The technology of bacilliculture is in its early stages of commercialization [18] and it is plausible that production costs will remain far above that of grains during our lifetimes. Thus the technology may only be viable for its original purpose as a food source for astronauts on long-duration space missions [36]. Even if the hydrogen oxidizing pathway of producing microbial protein proves economically unfeasible, pathways which exploit agricultural wastes have a potential to increase the efficiency of agriculture and reduce the climate impact of agriculture per unit food produced [19]. The latter aspects were not explored as part of this study.

The possibility of bacilliculture feeds into the debate within the zero emissions commitment community about how to define zero emissions commitment for climate forcing agents other than CO_2 [15, 56]. The first iteration of the zero emissions commitment model intercomparison project (ZECMIP) focused solely on CO_2 despite a desire for a more comprehensive experiment accounting for all climate forcing agents [15]. An unresolved debate over how to design such an experiment centered on what to do about agricultural emissions. Two options are possible: (1) freeze agricultural emissions and land-use at some specified value; or (2) reduce agricultural emission and land-use to zero. As bacilliculture allows for the possibility of the replacement of agriculture, the potential of the technology will play a key part in designing the experiments for ZECMIP-II.

Here we have examined the potential impact of microbial biomass growth technology on climate change. Our analysis and simulations suggest that at maximum the technology could reduce warming by 1 °C compared to a continuation of current agricultural practices. However the technology also has the potential to redirect renewable energy from decarbonization efforts and indirectly lead to additional climate warming. As climate warming from agriculture is largely reservable on human time-scales, while climate change from fossil fuels emissions is not, replacing agriculture only after decarbonization is complete would maximize its potential for limiting overall global warming. Failing to account for the long lifetime of CO_2 caused warming and naively using global warming potentials may lead to false conclusions about the optimal use of renewable energy resources towards decarbonization or bacilliculture. If deployed after net zero emissions are achieved the technology under some scenarios could eliminate the need for active atmospheric CO_2 removal to achieve a peak and gradual decline in global warming.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5683/SP2/3YTMPV.

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ORCID iDs

Andrew H MacDougall https://orcid.org/0000-0001-7899-9940
Joeri Rogelj https://orcid.org/0000-0003-2056-9061

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