Abstract 1 – Methane, air quality, and climate change

Methane (CH_4) is a greenhouse gas (GHG) with an effect stronger than CO_2 [1]. It has a lifetime of less than 10 years in the atmosphere because it reacts with hydroxyl radicals (OH) in a series of interactions that creates ozone (O_3); however, increasing atmospheric methane increases the lifetime of the methane by taking up more of the OH, which causes there to be less OH available to oxidize the methane[1]. This means that methane remains in the atmosphere longer, amplifying its greenhouse effect. The resulting ozone, though beneficial in the stratosphere, is a pollutant with detrimental health effects when it is created by CH_4 in the troposphere. The current atmospheric methane concentration is 156% of pre-industrial levels[2].

Methane emissions, which have been increasing significantly in the 2010s[3] , are from both anthropogenic and natural sources. In many of the below sources, methane is created by decomposition in anoxic (anaerobic) conditions, as opposed to the carbon dioxide mainly produced in aerobic decomposition[4]. Human sources, which account for 60% of methane emissions, include agriculture, waste, fossil fuel use, and biomass burning[5]. Agriculture emits methane mostly through ruminant animals like cows which have methanogens (methane-producing microbes) in their gut and the management of their manure in concentrated conditions which leads to anaerobic decomposition. Organic waste, similarly, when held in anaerobic conditions emits methane, which is why landfills and sewage are large sources. Fossils fuels are another large anthropogenic source (methane is a main component of natural gas) via leaks in distribution pipes and drilling fields and incomplete burning. Finally, biomass burning also releases methane when it incompletely combusts[5]. In the natural world, wetlands are the single largest emitter; due to waterlogged conditions, organic matter decomposes anaerobically releasing methane (but also storing carbon because it is decomposing more slowly than in aerobic conditions) which can vary based on the local environmental conditions such as pH, temperature, and salinity[4]. This makes wetland emissions the largest source of uncertainty in the methane budget[6]. On the sink side of the budget, the two main avenues are the reaction in air with OH mentioned above which destroys the methane[5] and uptake by soil microbes in the presence of oxygen[2]. The sources and sinks are summarized in Figure 1. The majority of methane is emitted in the northern hemisphere[2].

The current methane concentration in the atmosphere is contributing to effective radiative forcing (ERF) mostly through direct effects as a GHG but also through indirect effects. Methane oxidation eventually produces tropospheric ozone and water vapor, which are GHGs as well. It also, through a chain of reactions in the atmosphere, affects aerosol-cloud interactions by changing the aerosol size distribution. The aerosol-cloud interactions are the largest source of uncertainty in the ERF of methane[7]. One study quantified the methane climate response as 0.21 ± 0.04 °C per effective $PgCH_4$, where “effective” accounts for the short lifetime of methane[8].

The high levels of methane are also worsening air quality. Methane emissions have an approximately linear relationship to increases in tropospheric ozone, and the effects are globally mixed[9]. One estimate is that the effect of methane on ozone is 1.0 ± 0.2 ppb of ozone per effective $PgCH_4$[8]. This is detrimental to humans, plants, and animals. Ozone exposure leads to increased risk of respiratory disease in humans[10] causing over one million deaths every year[11]. Crops exposed to higher ozone levels are less productive; for example, four major crops were estimated to have yield losses ranging from 3% to 16% at mid-2000s-level ozone (7-12% for wheat, 6-16% for soy, 3-4% for rice, 3-5% for corn)[12].

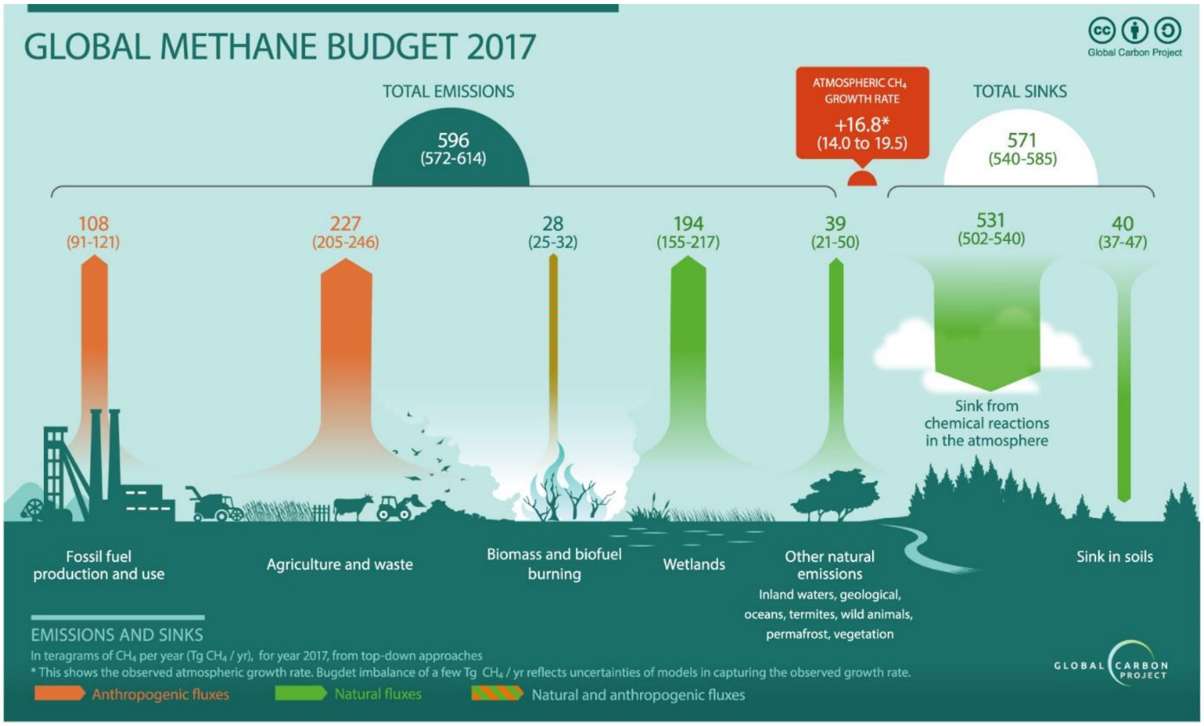

Figure 1: Methane sources and sinks[5]

There are several methane-related environmental feedbacks that can act to amplify or reduce the effects of climate change (Figure 2). Wetlands could release much more methane as temperature increases depending on the water, vegetation, and microbial conditions: a drier wetland could become aerobic and release CO2, while a warmer and wetter one could remain anaerobic and release CH_4 at a higher rate[13]. This could greatly accelerate climate warming[14]. Boreal permafrost, which also stores a great deal of organic carbon in its frozen soil, could also reach a tipping point as soon as 1.5°C global temperature increases and become a source of methane as it thaws, increasing climate change and further accelerating its melting[15]. The most prominent methane-related feedbacks in the short term are expected to be wetlands, but beyond that permafrost melt and aquatic systems will play a major role[13]; however, local environmental conditions are crucial to determining climate feedbacks which contributes to uncertainty[16].

Methane mitigation has the potential to greatly reduce climate change in the short term. If all anthropogenic methane emissions ceased now, by 2050 the climate could be about 1°C cooler than it otherwise would (Figure 3), and warming would be much slower even in high CO_2 scenarios[8,17]. Cutting methane could allow for a higher CO_2 budget[18]. This is due to the higher short term global warming potential of methane (the long-term peak warming will still be determined by CO_2)[8]. Reducing methane also benefits health and crop yields by reducing ozone[19].

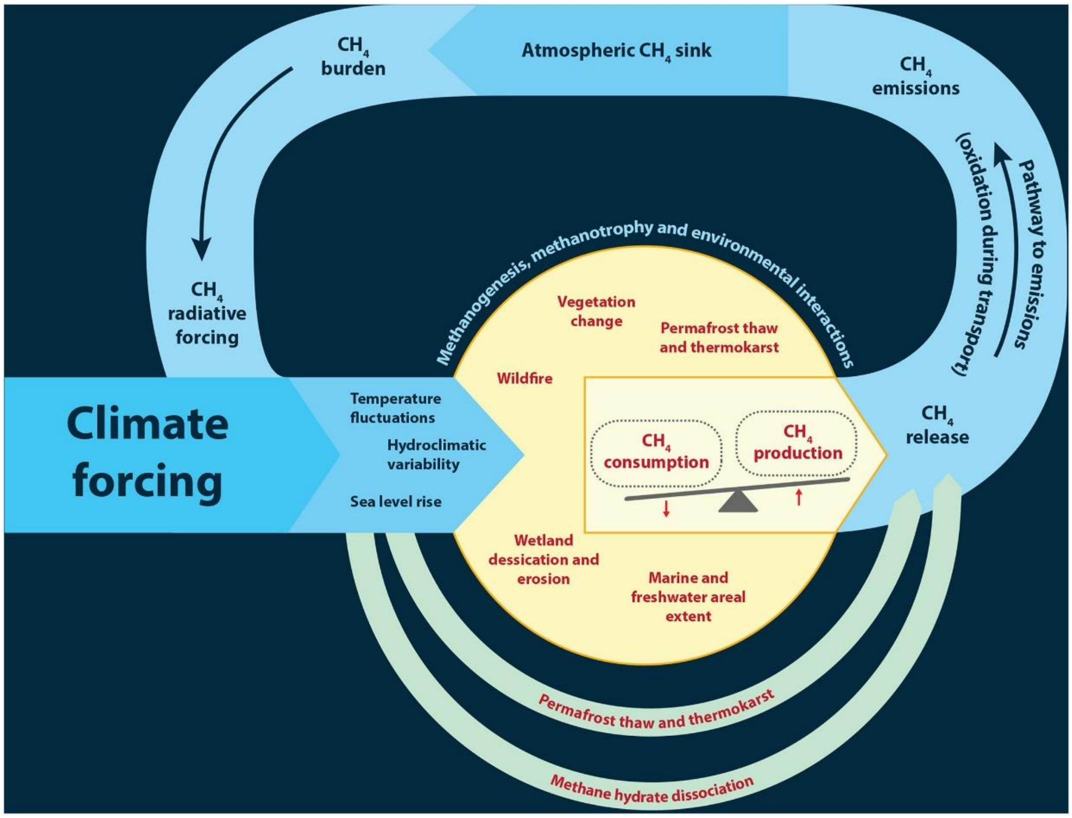

Figure 2: Climate feedbacks with methane[13]

Direct methane removal has not been researched to the same extent as carbon removal, but there are some feasible methods such as soil microbe management, photocatalysts, and metal catalysts[6]. There are many methane sources that could be reduced or eliminated without the need for technological capture. Gas leaks should be repaired from gas fields and pipelines. Domestic use of gas for heating and cooking which also leaks methane through incomplete combustion should be replaced with electric appliances. Better management of sewage, landfills, and manure could better contain or capture and burn methane as fuel. Separating organic waste for composting also prevents methane production because it decomposes aerobically. Finally, reducing cattle (and other ruminant) farming (likely via reduced meat consumption) would greatly reduce methane production from both the cows and manure management[20]. In conclusion, methane is a powerful GHG, and reducing anthropogenic CH_4 emissions would have impactful short- and long- term climate and health benefits.

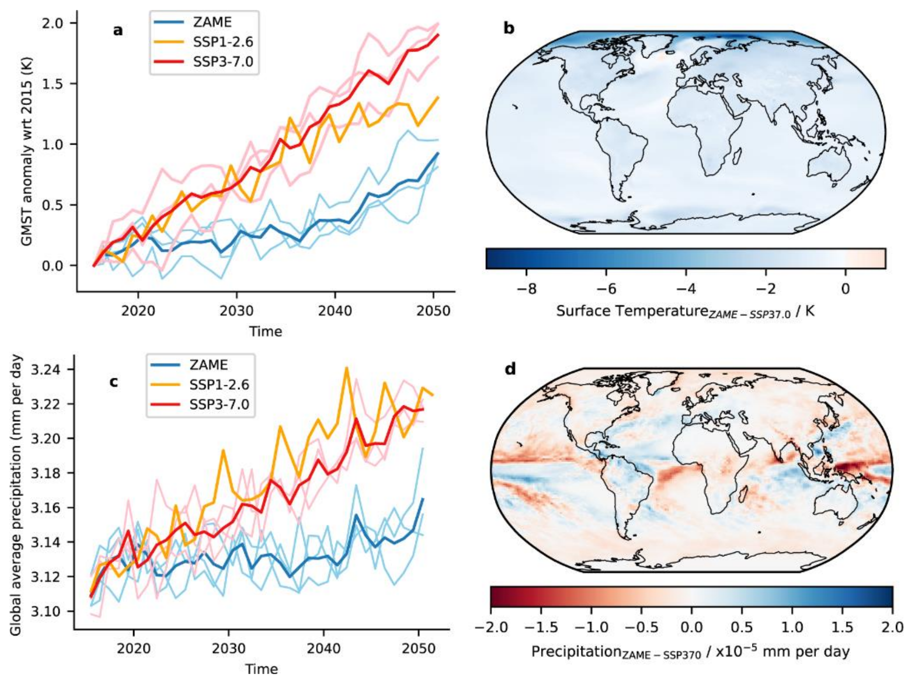

Figure 3: Effect of Zero Anthropogenic Methane Emissions (ZAME) on global mean surface temperature (GMST) and global average precipitation versus SSP1-2.6 (Sustainability scenario) and SSP3-7.0 (High emission scenario), showing that anthropogenic methane elimination would significantly reduce global temperatures and precipitation[17]

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Abstract 2 – Land-based climate mitigations

Land use has large impacts on climate change (CC) because of interactions through multiple physical channels (Figure 4). First, land use affects the surface albedo which determines how much solar radiation is absorbed versus reflected, influencing warming. Croplands or snow-covered fields have a high albedo, while forests have a lower albedo, thus land use change can affect large-scale warming or cooling through albedo[1]. Second, land use influences the moisture in soil which affects both the water and energy cycle. Soil moisture cools land through evaporation and plant transpiration (evapotranspiration) which is more efficient at cooling than dry heat convection. The vegetation cover, or lack thereof, affects the soil moisture and how much is evapotranspired, which can heat or cool the land and affect precipitation[2]. Third, land use alters biogeochemical cycles like the carbon cycle. Plants store carbon in biomass by removing CO_2 from the air with photosynthesis. Forests store more carbon than other ecosystem types with tropical forests being the most productive, followed by temperate and then boreal forests[3]. In total, 31% of human carbon emissions are absorbed by photosynthesis[4] (Figure 5).

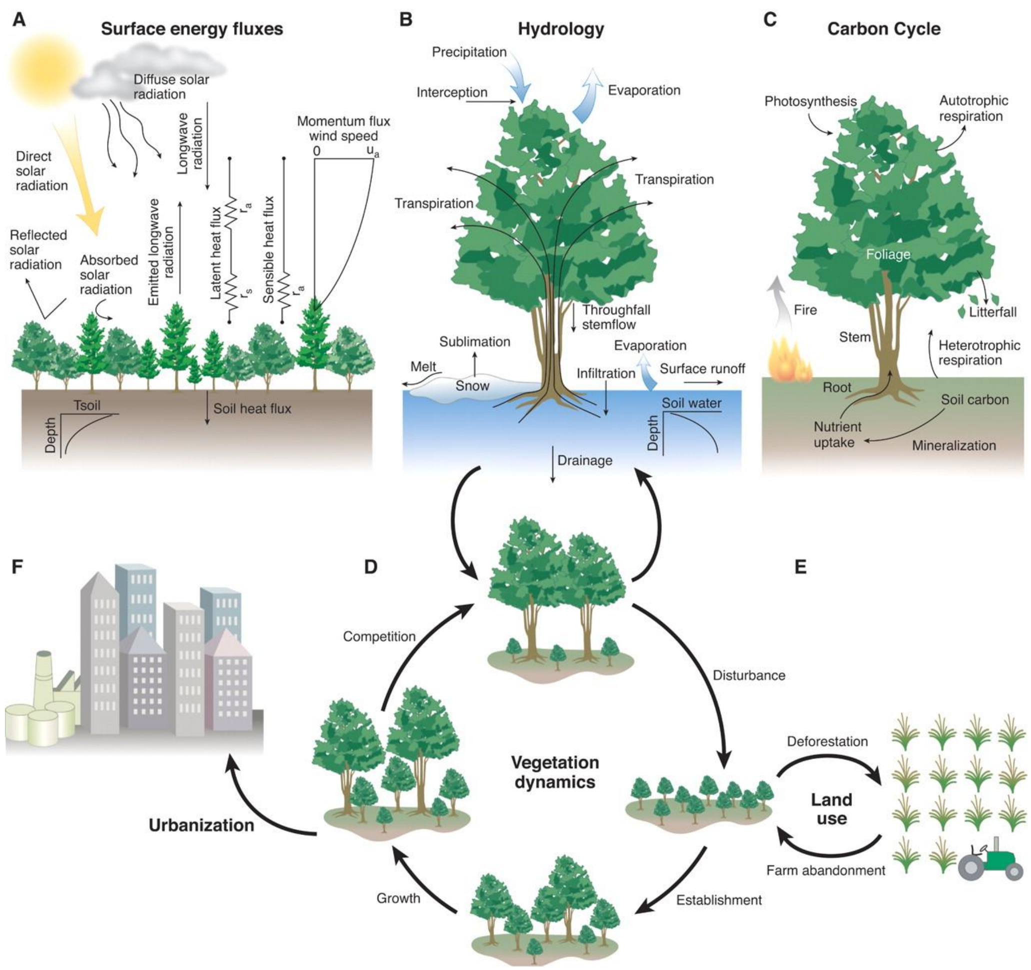

Figure 4: Vegetation and land use affect surface energy flux, the water cycle, and the carbon cycle[3].

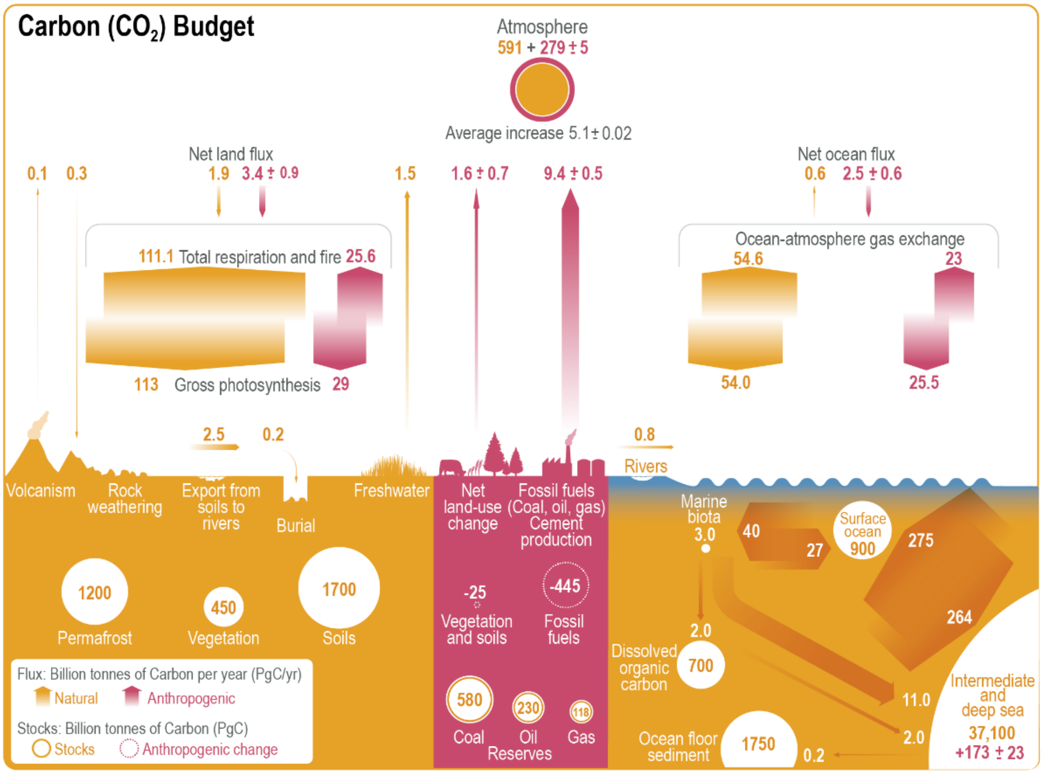

Figure 5: Global carbon budget. Approximately 31% of human emissions are stored by land-based natural processes like photosynthesis[4]

The physical channels intertwining land use and climate are subject to feedbacks that exacerbate or attenuate CC. First, increased atmospheric CO2 increases the productivity of plants so they store more carbon, creating a negative feedback[3,4]. Second, warming increases productivity by extending the growing season at high latitudes, but it decreases productivity in tropical areas. Because tropical forests sequester more carbon than boreal environments, this is a positive feedback overall [3,4]. Third, CC has increased the frequency of fire-causing weather globally [4] which risks re-releasing stored carbon back to the atmosphere by burning (positive feedback)[5]. Finally, warming increases the decomposition in soils and increases the loss of carbon from soils which is a positive feedback [4].

There are several high-profile land-based mitigations (LBMs) that remove carbon from the air. To meet 1.5 or 2°C, most integrated assessment models (e.g., 87% of AR5 models) use negative emissions technology, primarily bioenergy with carbon capture and storage (BECCS)[1]. BECCS is the process of growing biomass, burning it to produce energy, and capturing and storing the resulting CO_2. It is deemed net-negative because the carbon in the biomass was captured from the air with photosynthesis, and thus after storage is removed from the carbon cycle[6]. Though BECCS can be accomplished with crop byproducts, the scale modeled cannot be supported with residues, so bioenergy crops must be grown, requiring land use [6]. To remove 3.3 GtC yr^{-1}, between 380 and 700 Mha is needed, or 7-25% of crop land[1]. Depending on the land converted to bioenergy crops, loss of the carbon stored in the previous vegetation and the soil could take up to 100 years to recover with BECCS especially in carbon-dense systems like tropical forests[7]. Additionally, BECCS will put pressure on other planetary boundaries (PBs) such as freshwater use, nutrient flows, and biodiversity; a study by Heck *et al*. estimated remaining in the "safe" zone for all PBs would result in a net sequestration of < 0.1 GtC $yr^{-1}$with BECCS, and pushing the PBs to a riskier zone would only store 1.2-6.3 GtC yr^{-1} [8]. Success of BECCS is highly dependent on the implementation and scale[7].

Another prominent LBM is afforestation and reforestation (AR), also known as planting trees. Afforestation is planting trees in a previously unforested area, while reforestation is restoring forest to an area that was logged[9]. Trees sequester carbon, improve soil, and provide habitat for biodiversity if restored well; monocropping or industrial forestry can dramatically change the local ecosystem depending on the prior use and do not support biodiversity[10,11]. Estimates range between 1.5 and 11 GtC yr^{-1} for potential mitigation[12]. This method also requires a large amount of land: 970 Mha for 3.3 GtC yr^{-1}, or 6-20% of total agricultural land[1]. This is far more than the current abandoned or marginal land area[13].

A third high-profile LBM is avoiding future deforestation. Emissions from deforestation and degradation are currently 1.4 ± 0.5 PgC yr^{-1} [14] which is due to the loss of carbon in the vegetation and soil[7]. Saving forests, especially highly biodiverse and productive tropical forests, prevents emissions and allows continued carbon capture and storage through photosynthesis, potentially 1.2-5.8 GtC yr^{-1}. It also promotes biodiversity by providing habitat, and the evapotranspiration can cool the local environment[12].

The final major LBM is improved soil carbon sequestration (SCS). Managing existing agricultural land with conservation and regenerative practices can increase the carbon stored in the soil[9]. For example, in industrial forestry practices such as increased tree diversity, longer rotation periods, or lighter harvesting increase soil carbon and have co-benefits of promoting biodiversity and resilience to disease[9]. In agriculture, practices such as perennial cropping, cover cropping, reduced tillage, and nutrient management can improve SCS as well as productivity. Improved SCS generally improves retention of nutrients and water in the soil as well[10].

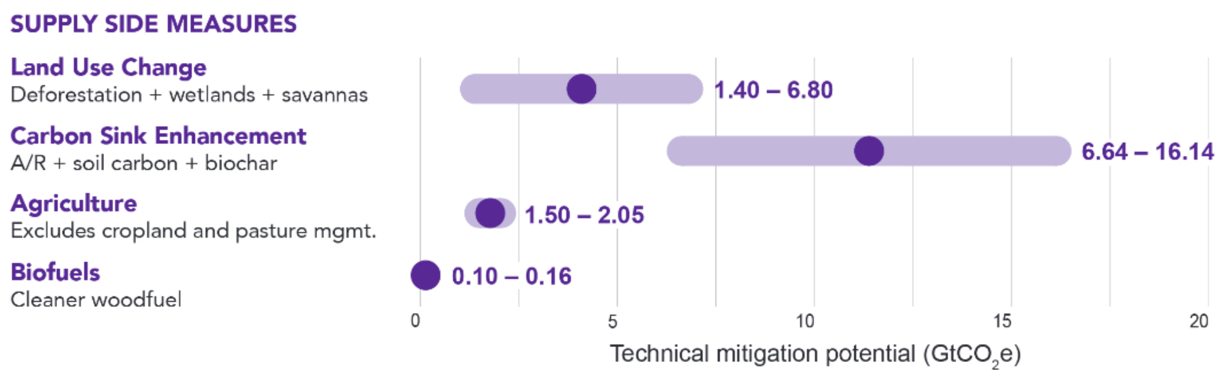

Figure 6: Potential mitigation of selected LBMs[12].

As alluded to, each LBM comes with trade-offs since land is a limited resource, and many LBMs are mutually exclusive, causing opportunity costs[9,10]. For example, deforestation is mostly driven by pressure from agriculture, such as soy, beef, and timber in South America, palm oil, timber and rubber in Southeast Asia, and sugar, palm oil, and cocoa in Africa[12]. AR and BECCS also compete with agricultural or conservation use. Additionally, effects such as changes in albedo must be considered: for instance, AR in boreal forests decreases albedo and likely has a net warming effect[15]. There are some synergies to utilize, such as SCS alongside other LBMs[10]. There are many other LBMs such as wetland restoration, enhanced weathering, and demand-side drivers such as reducing meat consumption and food waste[12] that were not reviewed for space. Overall, climate mitigation is a whole-system problem, and strategies like BECCS and AR cannot be a complete solution considering the other PB impacts. As Smith *et al*. summarize, there is no negative emissions technology that will easily meet the $< 2°C$ target[1], and thus carbon emissions must be eliminated and augmented with LBMs.

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