Final report

Literature review of biological systems in livestock grazing for capturing atmospheric methane

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Abstract

The project aim was to research biological sources and sinks of methane in livestock grazing systems. Methods identified could be included in Australia's Carbon Marketplace to incentivise producers and increase adoption to technologies and practices to reduce methane emissions or store carbon. Future R&D includes research of how various trees absorb and emit methane, an analysis of precipitation patterns in Australia and their effect on methane uptake in the soil, and research into the effects of grazing patterns on soil health.

Executive summary

Background

The project aim was to research biological sources and sinks of methane in livestock grazing systems. The results of the research will be used to inform producers on different agricultural practices that farmers could adopt to improve soil and grassland health and increase methane (CH_4) uptake.

Objectives

The objective of the project was to research biological sources and sinks of methane in livestock grazing systems, to determine sustainable alternatives for reducing methane emissions from livestock in Australia.

Methodology

Research comprised a literature review of various topics related to achieving the milestones. Infographics on the global methane budget (Figs. 9 and 10) were created based on data derived from Ciais, Sabine et al. (2013); Kirschke, Bousquet et al. (2013); (Saunois, Bousquet et al. 2016).

Results/key findings

The largest methane sinks available to grazing systems include the atmosphere, soils, and trees. The largest anthropogenic sources of methane are emissions from ruminants and landfill sites. In Australia, the troposphere removes approximately 12 teragrams per year (Tg/yr) of methane from the atmosphere, and soils are estimated to remove another 2 Tg/yr. Certain species of trees also have the potential to absorb methane from the atmosphere. The largest anthropogenic source of methane in Australia is agriculture, releasing 3-5 Tg of methane per year. Thus, increasing methane sinks by increasing the amount of methane taken up by soils, as well as the amount taken up by plants, could help reduce or store methane emissions from livestock grazing systems.

Because the production and consumption methane from soils occurs as a result of different microbial processes, controlling the factors that influence the growth of microorganisms may help to increase CH_4 uptake from the soil. Numerous factors can affect the growth of methanotrophs and methanogens, including precipitation, soil moisture, soil temperature, soil pH, nutrient availability, and fertilizer. Extremes in any of these cases (acidic soil, poor drainage or nutrient availability, or excessive use of fertilizer) are known to reduce methane uptake in soils.

Benefits to industry

Practical applications to the red meat industry include considering how additions to the soil, such as precipitation and fertilizers, affect the ability of methanogens to uptake CH_4, as well as altering timing of grazing patterns to take into account soil microbes. Tree planting of certain native species, as well as engaging in grazing management practices could also help to increase absorption of CH_4 and CO_2 from the atmosphere and soil.

These changes would have numerous economic and sustainability benefits, as a reduction of any amount of CH_4 emissions or increase in CH_4 capture is considered incredibly beneficial to reducing global warming. There are also added financial incentives in the form of carbon offsets, which are currently being implemented in numerous countries around the world.

Future research and recommendations

Development and adoption activities could include the addition of these practices to Australia's Carbon marketplace, to incentivise farmers to engage in methane-reducing practices.
Future R&D is necessary to fully understand the most effective biological-based methods and models for methane capture. Given our findings, we suggest the following research:

- Conducting a "Genius of Place" report on healthy grasslands in Australia and similar biomes. A Genius of Place considers a healthy ecosystem as a whole, looking into the ecology and organisms of a particular place to provide guidance for sustainable design or management.

- An analysis of the benefits of circularizing waste streams, either by identifying how farm waste could benefit other industrial and agricultural streams, or how waste from other industries could benefit the red meat industry.

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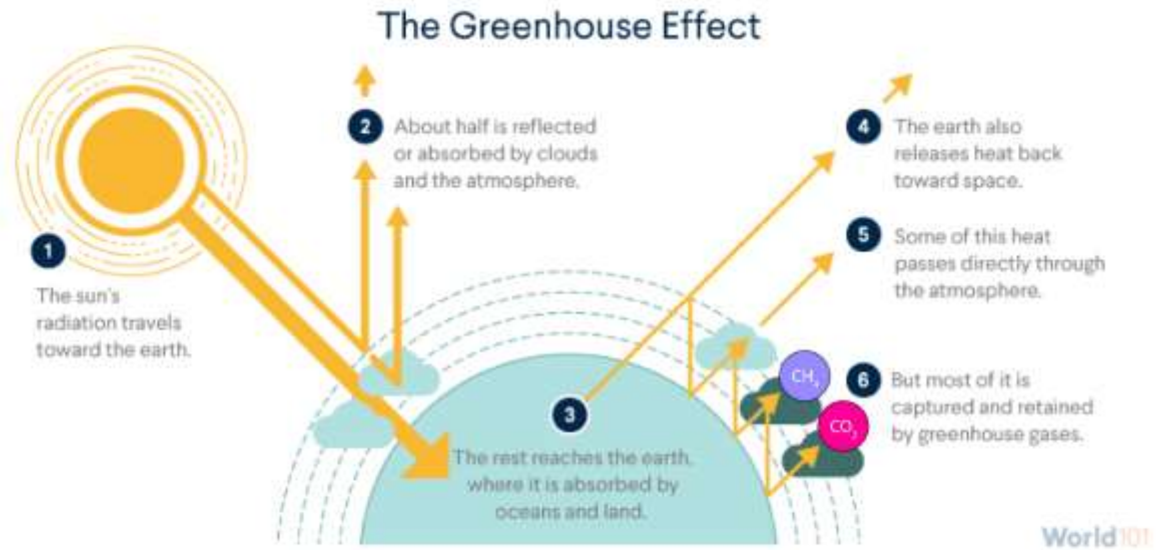
1. Background

1.1 Role of methane in the atmosphere

1.1.1 The greenhouse effect

Earth absorbs heat from the sun, but this heat is insufficient on its own to warm the Earth because most of it passes through the atmosphere and back out into space. However, certain molecules in the atmosphere, known as greenhouse gases (GHGs), including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are able to absorb and retain heat and warm the Earth, a phenomenon known as the 'greenhouse effect' (Fig. 1). Without these molecules, temperatures on Earth would be below freezing. Only a small concentration of these molecules is necessary to absorb enough heat to warm the Earth. However, as the concentration of these gases increases, the amount of global warming also increases (Bolin and Doos 1989).

Figure 1: The greenhouse effect warms the Earth*



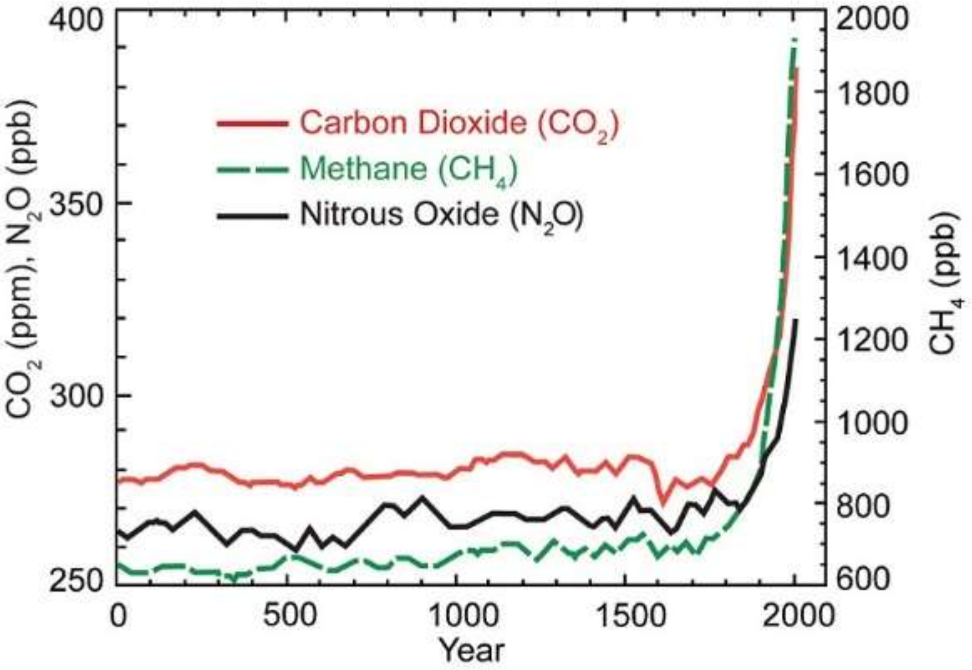
* Modified from: (Council on Foreign Relations, 2019)

Fig.1 shows heat from the sun is insufficient on its own to warm the Earth, because most of the heat would escape back into space. Greenhouse gases such as CO_2 and CH_4 help to trap heat in the atmosphere, warming the Earth to liveable temperatures.

1.1.2 Anthropogenic contributions to greenhouse gas concentrations

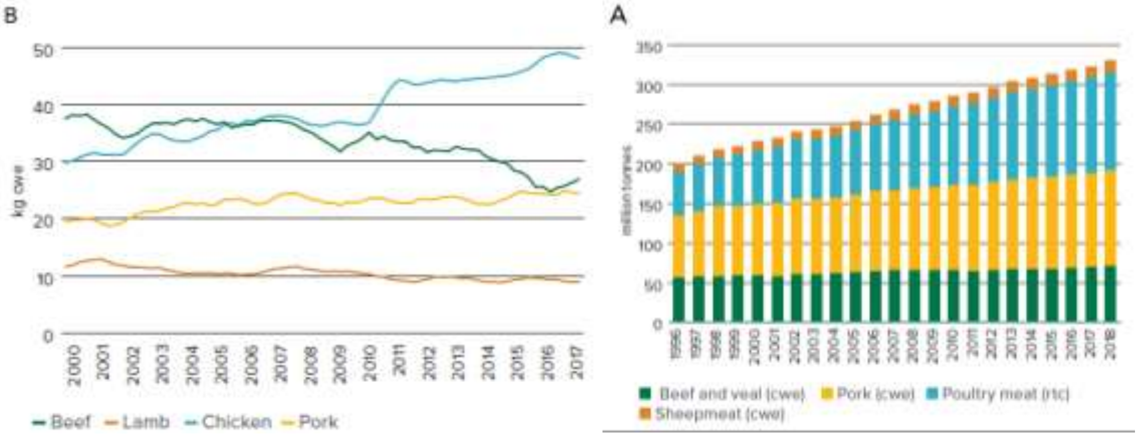
The increase in industrialization has significantly increased the amount of greenhouse gases present in the atmosphere, most notably CO_2 and CH_4. The concentrations of CO_2 and CH_4 have steadily increased over the past 150 years (Fig. 2) (Stocker, Qin et al. 2013). Global meat consumption has also increased over the past several decades (Fig. 3A). Although beef consumption in Australia has steadily decreased in recent years (Fig. 3B), Australia was still the third largest beef and veal exporter in the world in 2018 (Meat & Livestock Australia 2019). Release of methane by ruminants through enteric fermentation has led to a significant increase in the amount of CH_4 released into the atmosphere (Fig. 4A, B). Other causes, such as natural gas fracking, rice paddies, and landfills, significantly contribute to the amount of methane in the atmosphere (Saunois, Jackson et al. 2016).

Figure 2: Concentrations of greenhouse gases in the atmosphere over a 2000-year period*



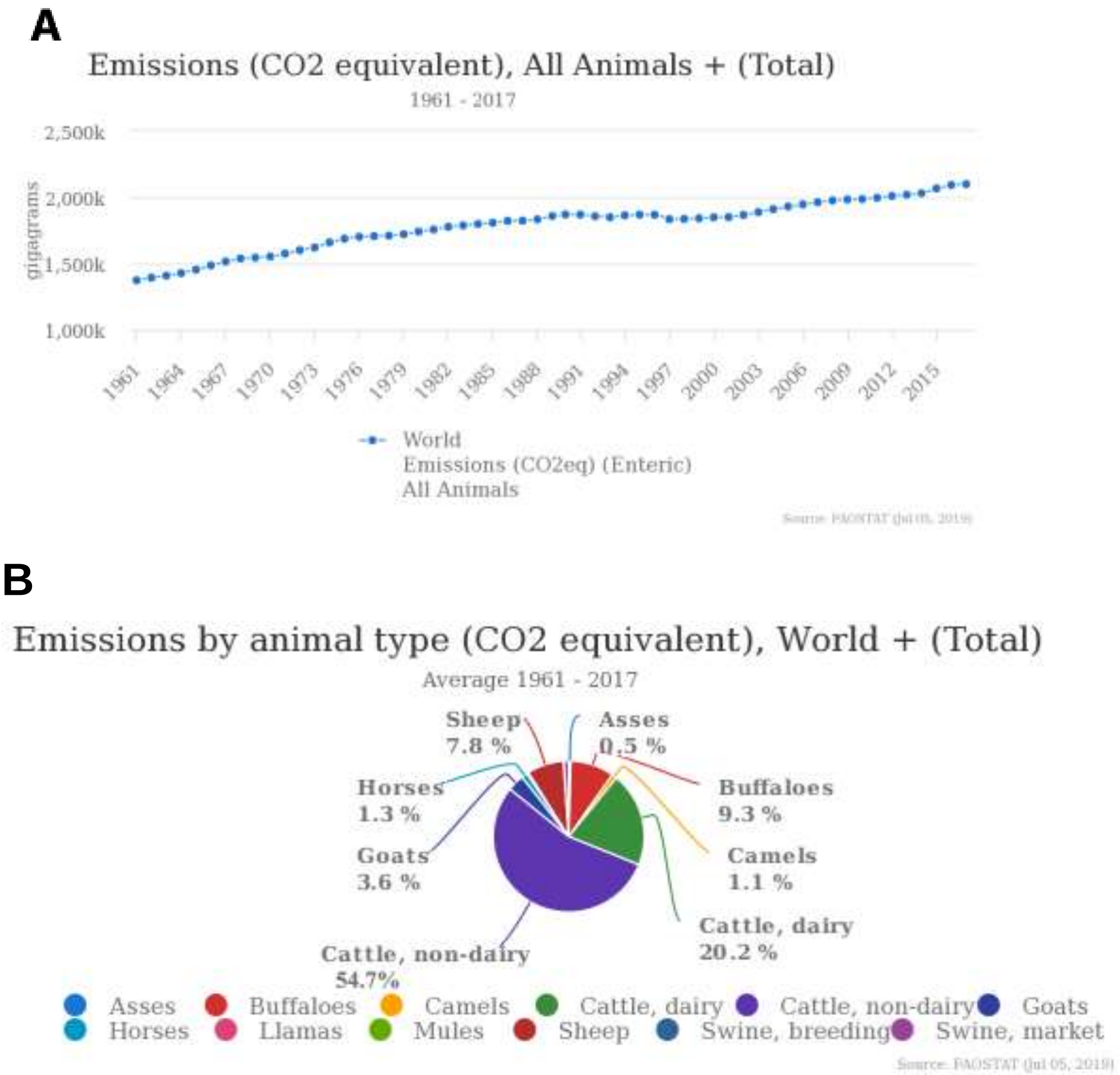
* Levels have increased rapidly in the past 150 years. Source: World Meteorological Association (WMO). http://www.wmo.int/pages/prog/arep/gaw/ghg/ghgbull06_en.html

Figure 3: Meat consumption has steadily increase over the past several decades*



*A) Total global meat consumption from 1966-2018.; B) Australian per capita meat consumption-fresh and processed. Source: MLA State of the Industry Report (2019).

Figure 4: CH_4 emissions produced by digestive systems of livestock (enteric fermentation)*

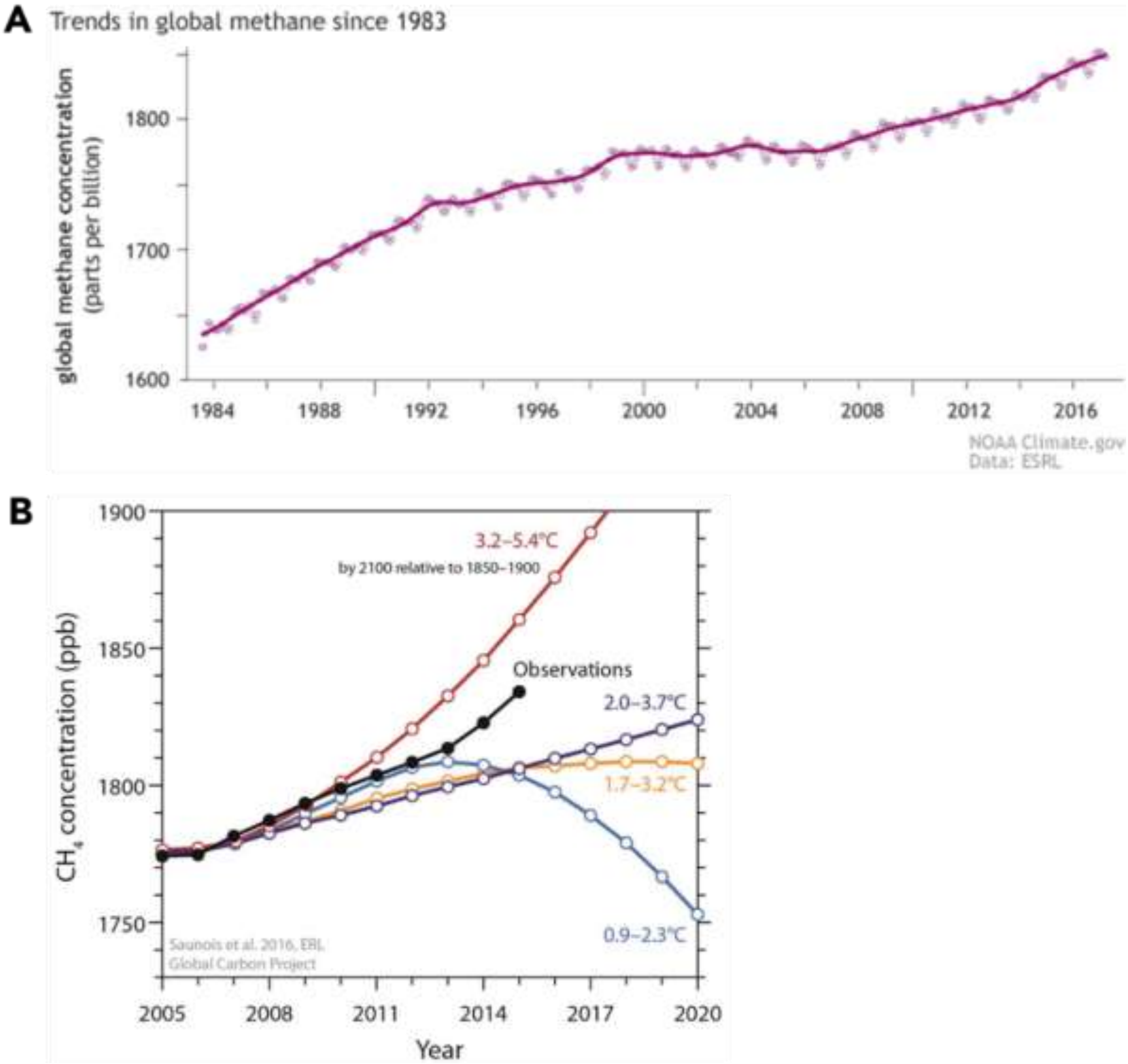


* Numbers represent CH_4 as its CO_2 equivalent (1 tonne of CH_4 degrades to ~2.75 tonnes of CO_2). A) World emissions of all livestock from 1961-2015. B) World CH_4 emissions by type of animal. Source: UN Food and Agriculture Organization (FAO), http://www.fao.org/faostat/en/?#data/GE

1.1.3 Role of methane in global warming

CO_2 is consistently cited as the driver of climate change. However, methane levels in the atmosphere have risen from around 715 parts per billion to nearly 1800 ppb since industrial times (1750) (Fig. 5). Methane is only around in the atmosphere for approximately 12 years before it degrades, compared to over 100 years for carbon dioxide. However, once it degrades, 1 tonne of methane produces approximately 2.75 tonnes of carbon dioxide. One molecule of methane also traps significantly more heat than one molecule of carbon dioxide. Global warming potential (GWP) is used as an estimate of how much heat a particular GHG traps in the atmosphere over a particular time period, usually 20 or 100 years. The larger the GWP, the more heat the gas absorbs and thus the more it heats the Earth compared to CO_2 (CO_2 will always have a GWP of 1 because all gases are measured relative to it). Methane has a GWP of 84 over 20 years, which means it heats the Earth 84 times more than CO_2 over 20 years. Because GWP depends on the lifetime of the molecule, and because CH_4 has a relatively short lifetime (approximately 12 years), methane has a stronger GWP over 20 years compared to 100 years (84 versus 28). Nitrous oxide (NO_2), by comparison, has an average lifetime of 121 years, and thus has a GWP of 264 over 20 years, and 265 over 100 years (Table 1).

Figure 5: Increasing methane concentrations in the atmosphere*



* A) Methane concentrations in the atmosphere have steadily increased over the years, and have now reached over 1800 parts per billion. B) Projections of the effects of increasing CH_4 concentrations in terms of global warming. Current projections estimate CH_4 concentrations are on track to increase warming by between 3.2°C–5.4°C by 2100. Sources: National Oceanic and Atmospheric Administration (NOAA), https://www.climate.gov/news-features/understanding-climate/after-2000-era-plateau-global-methane-levels-hitting-new-highs, and Saunois, Bousquet *et al.* (2016). (Saunois, Bousquet *et al.* 2016; Stocker, Qin *et al.* 2013)

Table 1: Global warming potential (GWP) of major greenhouse gases

Greenhouse Gas	Lifetime (years)	GWP 20 years	GWP 100 years
CH_4	12.4	84	28
NO_2	121	264	265
CFC-11	45	6900	4660

1.1.4 Effects of reducing CH_4 emissions

Because of its warming potential, reducing methane emissions could be 20-60 times more effective in reducing the potential warming of the Earth's atmosphere over the next century than would equivalent reductions in CO_2 emissions. Reducing methane back down to pre-industrial levels would has the potential to cool the Earth by 0.5°C over the next ten years. Carbon offsetting via Australia's Carbon Marketplace can incentivise producers to engage in methane-reducing practices. Carbon offsets are predicted to steadily rise in price over the coming decades (Fig. 6) (Stiglitz, Stern *et al.* 2017), and could be worth more for methane compared to carbon dioxide on a tonne-for-tonne basis. Table 2 shows a comparison of global carbon pricing in Australia, the United States, Europe, and Canada. Table 3 shows a conversion of USD to AUD based on a historical conversion rate on January 1st, 2015.

Table 2: Global carbon pricing as of August 1, 2019*

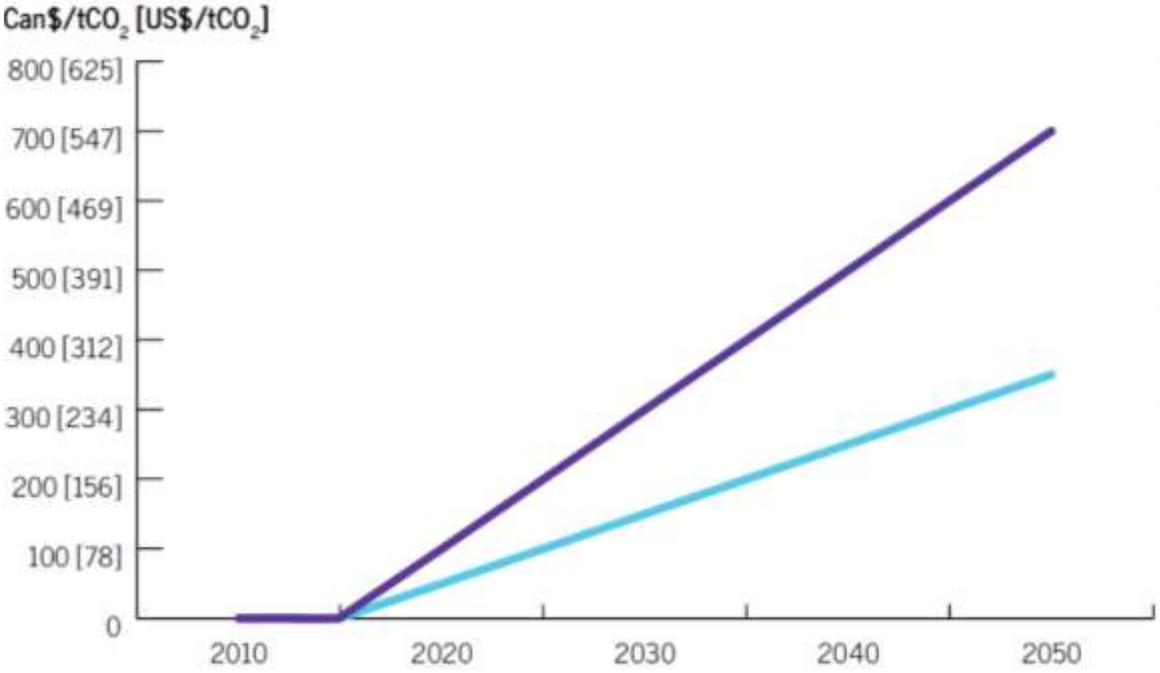
Country	Carbon Pricing
Australia	16.30
USA (California)	25.28
Europe (EU)	47.83
Canada (Quebec)	25.28

* Amount reflects price per tonne of CO_2. All amounts have been converted to Australian dollars based on the average exchange for the month of October, 2019. Source: Xe.com. The table includes data from Australia (ACCU, Australian Carbon Credit Unit), Source: CommTrade Carbon (https://accus.com.au/), the state of California Cap-and-Trade program in the United States, the EU ETS (European Union Emissions Trading System), and the province of Quebec in Canada. Source: World Bank Carbon Pricing Dashboard, https://carbonpricingdashboard.worldbank.org/map_data

Table 3: USD (United States Dollar) conversion to AUD (Australian Dollar) based on the conversion rate on January 1st, 2015. AUD numbers have been rounded to the nearest whole number. Source: Xe.com

USD	AUD
625	765
547	670
469	574
391	479
312	382
234	286
156	191
78	95

Figure 6: Projected pricing of carbon offsets*



* Projections show the carbon-price level needed to reach a level lower than 2 tonnes of carbon dioxide (tCO_2) per capita by 2050. Prices are given in Canadian dollars (Can$) and United States dollars [US$], based on the average exchange rate for 2015. The blue line depicts the scenario if the tCO_2 goal is met, while the purple line depicts the scenario if the goal is not met. Source: Stiglitz, Stern et al. (2017).

2. Objectives

The objective of the project was to research biological methods for methane capture, to determine sustainable alternatives for reducing methane emissions from livestock production in Australia.

The project contained two milestones: 1) review the biological organisms that utilize methane, 2) determine how these organisms utilize methane, and to what effect.

Both milestones were met, with a review of the biological organisms, how the utilize methane, and the factors that influence this utilization described in sections **Error! Reference source not found.**-**Error! Reference source not found.**.

3. Methodology

3.1 Literature review

Research comprised a literature review of various topics related to achieving the milestones. Infographics on the global methane budget (Figs. 9 and 10) were created based on data derived from Ciais, Sabine et al. (2013); Kirschke, Bousquet et al. (2013); (Saunois, Bousquet et al. 2016). All cited literature can be found in the References.

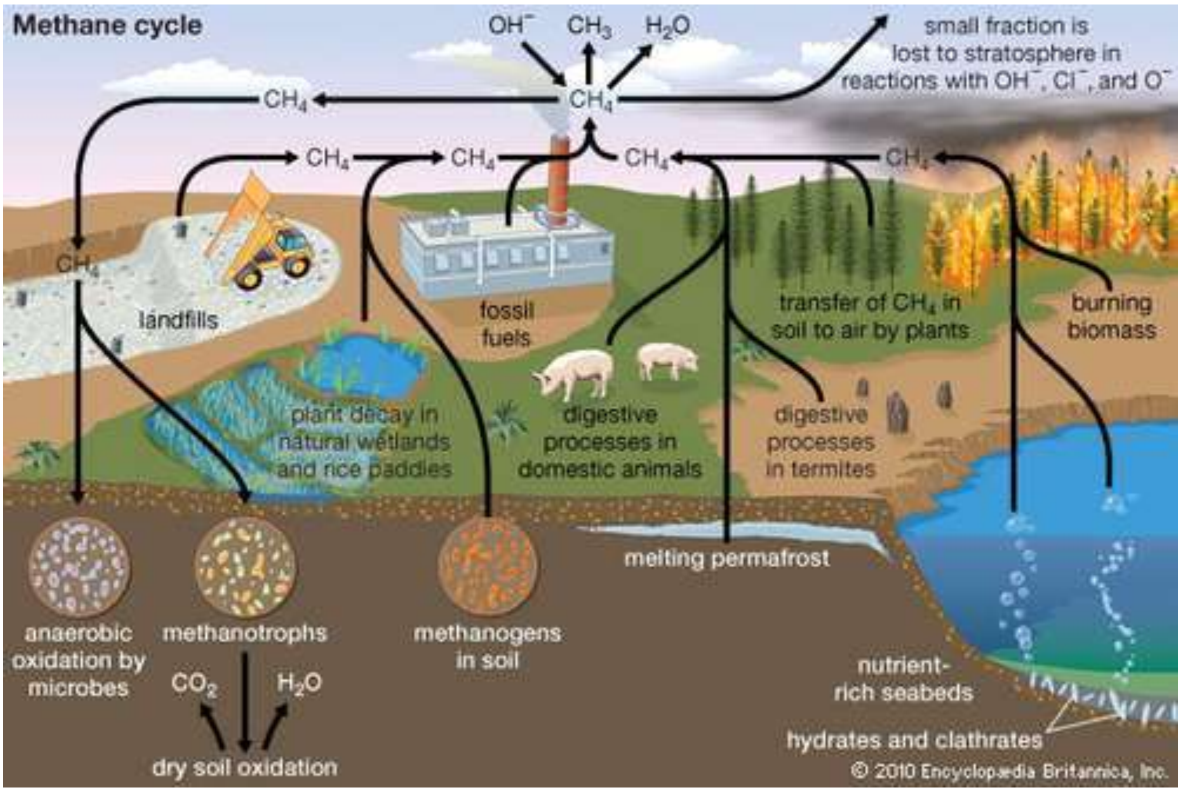
4. Results

4.1 Review biological organisms that utilise methane

4.1.1 The methane cycle

The methane cycle (Fig. 7) illustrates the different sources and sinks of methane on Earth. A methane source is any process or activity that releases methane into the atmosphere. Both natural processes and human activities release methane. The largest methane sources are wetlands, rice paddies, ruminants, and fossil fuels. A methane sink takes up methane, either storing it where it may be released later, or removing it entirely. The largest methane sink is the troposphere, which removes methane. Soils are a sink that store methane where it may be released later.

Figure 7: The methane cycle.
Source: Encyclopaedia Britannica https://www.britannica.com/science/methane-cycle

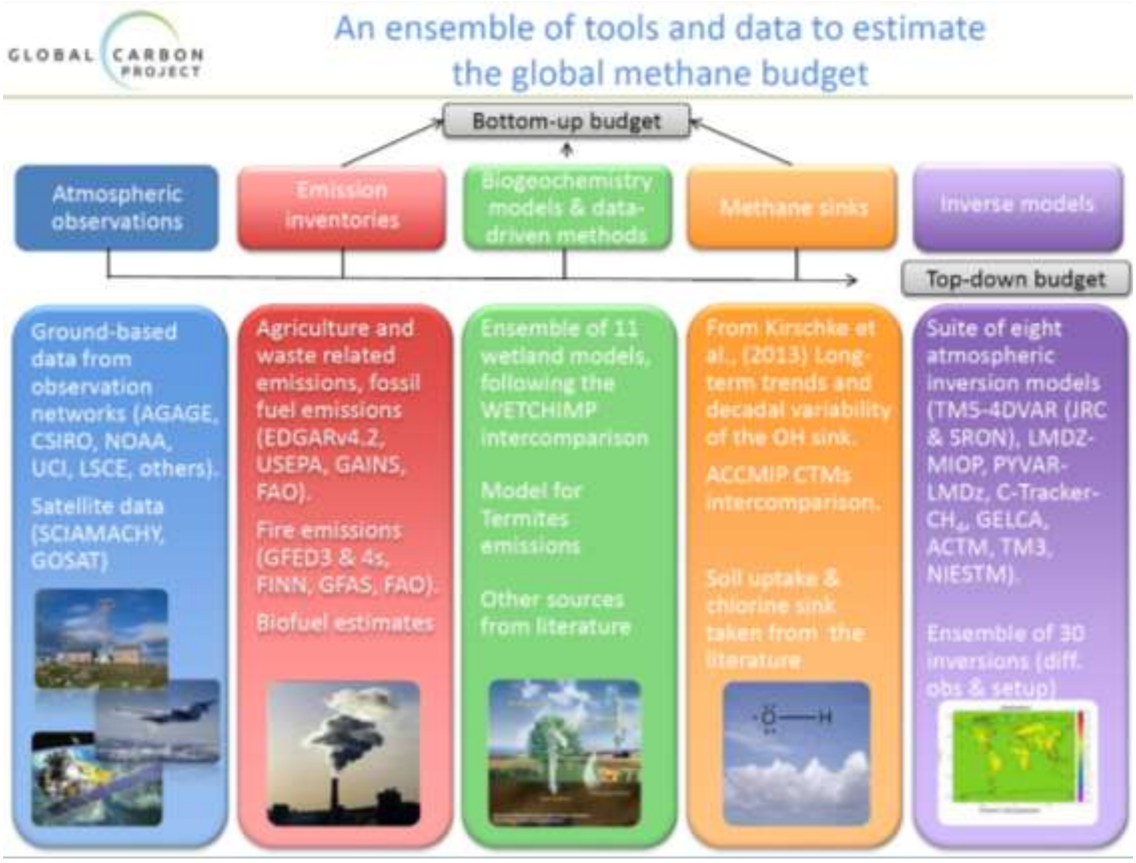


4.1.2 Sources and sinks of methane globally

Methane levels of sources and sinks are usually measured in teragrams (Tg) per year (Tg/yr). 1 Tg = 1 trillion grams = 1 million tonnes (Saunois, Bousquet et al. 2016). The total values of all methane sources and sinks make up the global methane budget. The difference in values between sources and sinks is referred to as a methane imbalance. It can be either a positive value (more source methane is released than can be absorbed by sinks) or a negative value (more methane is absorbed by sinks than is released by sources). A negative value is possible because the methane values are not exact, and are instead represented as a median within a range of values. For example, tropospheric OH is estimated to remove 535 Tg of methane per year, with a range of 450 – 620 Tg. Confidence may also be represented as a percentage of uncertainty. For example, wetlands are estimated to release 185 Tg of methane per year, with 40% uncertainty, or 60% confidence. Values for natural sources and sinks usually have a higher uncertainty or value range than anthropogenic methane sources, as they usually comprise a smaller area and are easier to measure (Saunois, Bousquet et al. 2016).

The values for the global methane budget consist of data from 2000–2012 that were published in 2016 (Saunois, Bousquet et al. 2016), as well as data gathered from 1980–2010 that were published in 2013 (Kirschke, Bousquet et al. 2013), and data gathered from 2000–2009 that were published in 2013 (Ciais, Sabine et al. 2013). Differences between values can also occur as a result of the different methodologies used, referred to as either “bottom-up” (B-U) or “top-down” (T-D). Bottom-up methodologies comprise data from agriculture and waste related emissions, fossil fuel emissions, fire emissions, and biofuel estimates, as well as models on wetland and termite emissions, and data from literature. Top-down methodologies include data from observation networks and satellite data, as well as 30 different atmospheric models to calculate methane emissions. Values for sinks were obtained from Kirschke, Bousquet et al. (2013) using top-down methodologies. All source values except for “other sources” were obtained from Saunois, Bousquet et al. (2016). “Other source” values are represented as “bottom-up” numbers from Ciais, Sabine et al. (2013). The specific modelling efforts and datasets are described in more detail in Fig. 8 (Saunois, Bousquet et al. 2016).

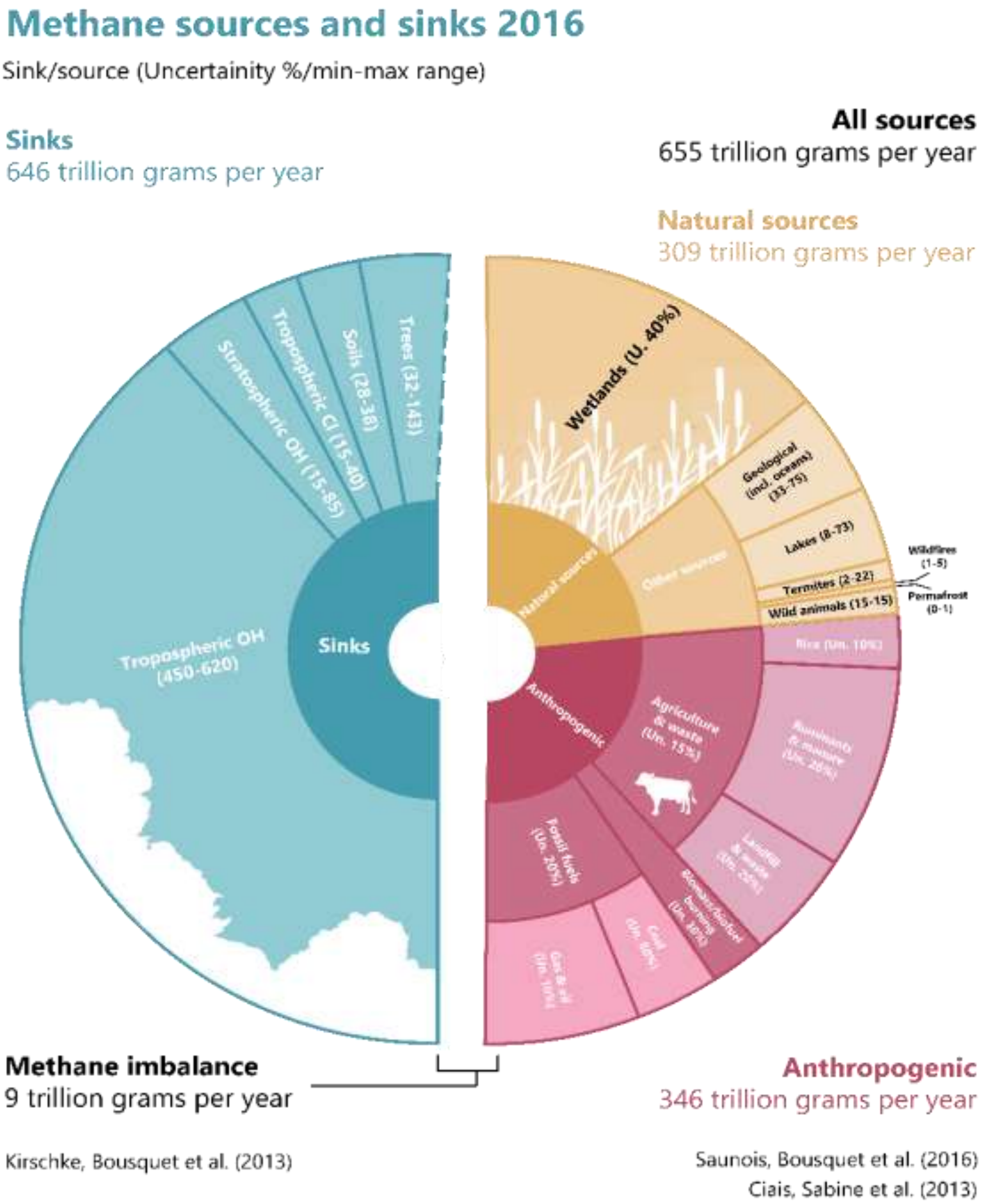
Figure 8: An overview of the bottom-up and top-down methodologies for determining the global methane budget. Taken from Saunois, Bousquet *et al.* (2016)



The methane sources and sinks that comprise the global methane budget is given in Fig. 9. The largest methane sink is the atmosphere, more specifically the troposphere, which removes over 80% of all methane in the atmosphere (Kirschke, Bousquet *et al.* 2013; Saunois, Jackson *et al.* 2016). The troposphere is the lowest layer of the Earth's atmosphere, extending from the Earth's surface up to 10 km (6.2 miles or 33,000 feet) above sea level. The troposphere comprises about 75-80% of the mass of the entire atmosphere. In the troposphere, hydroxyl radicals (OH) react with methane to eventually form CO_2. OH is formed by the reaction of ozone and water vapour. Since its reaction is water-dependent, the concentration of OH tends to decrease with increasing altitude as the air becomes cooler and drier. However, concentrations of OH are not highest closest to the ground because plants emit isoprene gas which reacts with OH and removes it from the atmosphere. Other atmospheric reactions, including free radical reactions in the stratosphere and the reaction of chlorine (Cl) with methane in the troposphere, also serve as methane sinks, but these are less common. Soils also serve as a methane sink due to the presence of methanotrophic bacteria in the soil (Saunois, Jackson et al. 2016). Methanotrophs convert methane to carbon dioxide and will be discussed in further detail in section **Error! Reference source not found.**. Trees are also hypothesized to serve as a methane sink due to their ability to absorb and store the gas (Covey and Megonigal 2019; Sundqvist, Crill et al. 2012), although the exact numbers are currently unknown. The relationship between trees and methane gas will be discussed in more detail in section **Error! Reference source not found.**.

Methane sources are divided into “natural” (i.e. not man-made) and “anthropogenic” (man-made) sources. The largest natural methane source is wetlands, which emit methane due to the presence of methanogens. This will be discussed in further detail in section **Error! Reference source not found.**. The largest anthropogenic sources of methane are emissions from ruminants and landfills. Methane from ruminants is produced as a by-product of enteric fermentation owing to the presence of methanogens in the ruminant gut. Methane emissions from landfills and waste is also due to the presence of methanogens in the soil (Gibbs and Leng 1993).

Figure 9: Methane sources and sinks comprise the global methane budget*



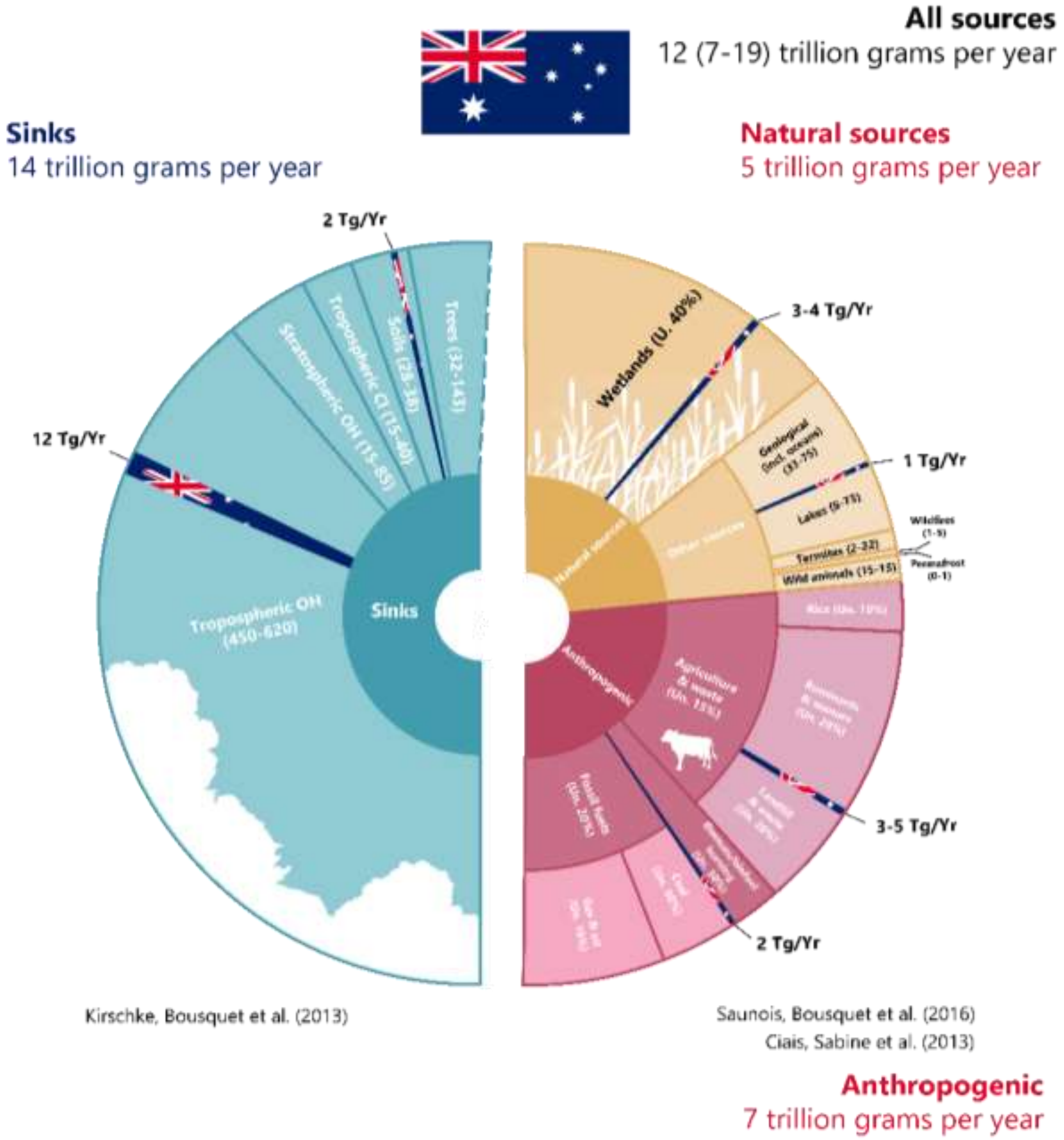
* Total values are given in trillion grams (Tg) per year. Confidence interval is given as either a min-max range of values or a percentage. Values for sinks were obtained from Kirschke, Bousquet *et al.* (2013) using top-down methodologies. All source values except for “other sources” were obtained

from Saunois, Bousquet *et al.* (2016). “Other source” values are represented as “bottom-up” numbers from Ciais, Sabine *et al.* (2013). Figure adapted from “Global methane budget for 2000-2009” from The Carbon Brief, https://www.carbonbrief.org/what-do-squirrels-beavers-and-reindeer-have-to-do-with-methane-emissions/methane1

4.1.3 Sources and sinks of methane in Australia

Data on sources and sinks of methane in Australia were derived from Saunois, Jackson *et al.* (2016) (Fig. 10). Values for wetlands, biomass burning, fossil fuels and agriculture were obtained from bottom-up methodologies. Values for “other sources”, soils, and tropospheric OH were obtained from top-down methodologies. All values for Australian data have the same confidence interval as global data. The largest methane sink is tropospheric OH reactions, which remove approximately 12 Tg/yr of methane from the atmosphere. Soils are estimated to remove another 2 Tg/yr, bringing the total for methane sinks in Australia to 14 Tg/yr. The largest sources of methane in Australia and wetlands and agriculture, releasing 3-4 Tg and 3-5 Tg, respectively, of methane per year. Other natural sources, as well as biomass burning and fossil fuel emissions comprise an additional 3 Tg/yr of emissions, bringing the total sources to between 9-12 trillion Tg/yr, although the min-max range for all source estimates is between 7-19 Tg/yr.

Figure 10: Methane sources and sinks in Australia 2016 compared against global data*. Sink/source (uncertainty %/min-max range)



Kirschke, Bousquet et al. (2013)

Saunois, Bousquet et al. (2016)
Ciais, Sabine et al. (2013)

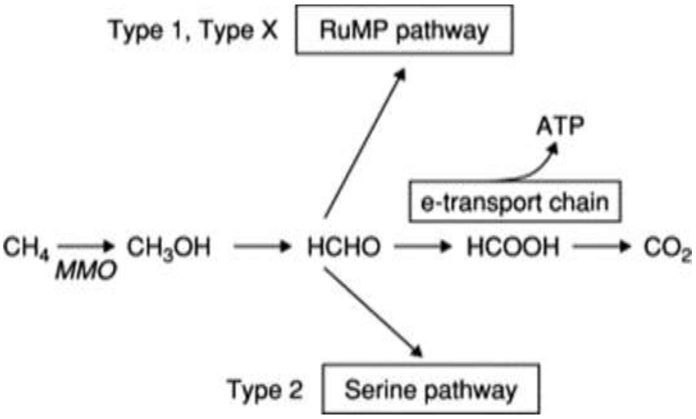
*Total values are given in trillion grams (Tg) per year. Confidence interval is given as either a min-max range of values or a percentage. Values for sinks were obtained from Kirschke, Bousquet *et al.* (2013) using top-down methodologies. All source values except for values for "other sources" were obtained from Saunois, Bousquet *et al.* (2016). "Other source" numbers are represented as "bottom-up" values from Ciais, Sabine *et al.* (2013). All values for Australian data were obtained from Saunois, Bousquet *et al.* (2016) and are consistent with data from Kirschke, Bousquet *et al.* (2013). Values for wetlands, biomass burning, fossil fuels and agriculture were obtained from bottom-up methodologies. Values for "other sources", soils, and tropospheric OH were obtained from top-down methodologies. Figure adapted from "Global methane budget for 2000-2009" from The Carbon Brief, https://www.carbonbrief.org/what-do-squirrels-beavers-and-reindeer-have-to-do-with-methane-emissions/methane1

4.1.4 Methanotrophs

Types of methanotrophs

Methanotrophs are bacteria that metabolize methane and act as a methane sink. There are three main types, Type I, Type II, and Type X, which differ depending on the type of pathway used to metabolize methane (Fig. 11). Type I and Type X methanotrophs use a ribulose monophosphate (RuMP) pathway, while Type II methanotrophs use a serine pathway. There are over 50 different species of methanotrophs, but all of them consume methane and convert it into CO_2 (Smith and Murrell 2009). Concentrations of methane, oxygen, and nitrogen are the primary determinants of the type of methanotrophs present in an environment. Soils rich in organic matter and copper and low in oxygen usually favour the growth of type II methanotrophs. Type I methanotrophs prefer lower methane concentrations whereas type II methanotrophs prefer higher concentrations of methane (Hanson and Hanson 1996).

Figure 11: Types of methanotrophs*



* Type I and Type X methanotrophs utilize a ribulose monophosphate (RuMP) pathway, while Type II methanotrophs use a serine pathway. All methanotrophs consume methane and convert it into CO_2.

Aerobic methanotrophs

Methanotrophs also differ depending on the environment. Certain types can only survive in oxygen rich (aerobic) environments, such as well aerated soils. These are known as aerobic methanotrophs (Hanson and Hanson 1996; Murrell 2010; Smith and Murrell 2009).

Anaerobic methanotrophs

Other types of methanotrophs can only survive oxygen poor (anaerobic) environments, and these are known as anaerobic methanotrophs (ANME). When methane is converted to CO_2 in low oxygen environments, it is known as the anaerobic oxidation of methane (AOM). ANME have an obligate relationship with a group of bacteria known as sulfate-reducing bacteria (SRB) that help them to convert the methane into a more useable form. These methanotrophs are most commonly found in rice paddies, deep soils, and anoxic (very low oxygen) marine and freshwater sediments (Hinrichs and Boetius 2003; Knittel and Boetius 2009; Smith and Murrell 2009). It is estimated that ANME consume almost 80% of all the methane in marine sediments (Reeburgh 2007).

4.1.5 Methanogens

Methanogens are organisms that produce methane in hypoxic (little to no oxygen) conditions. This process is known as methanogenesis. They most commonly use carbon and hydrogen to make methane and water, although they can use other sources. They are most commonly found in wetlands, landfills, rice paddies, and in the stomachs of ruminants.

4.1.6 Cattle

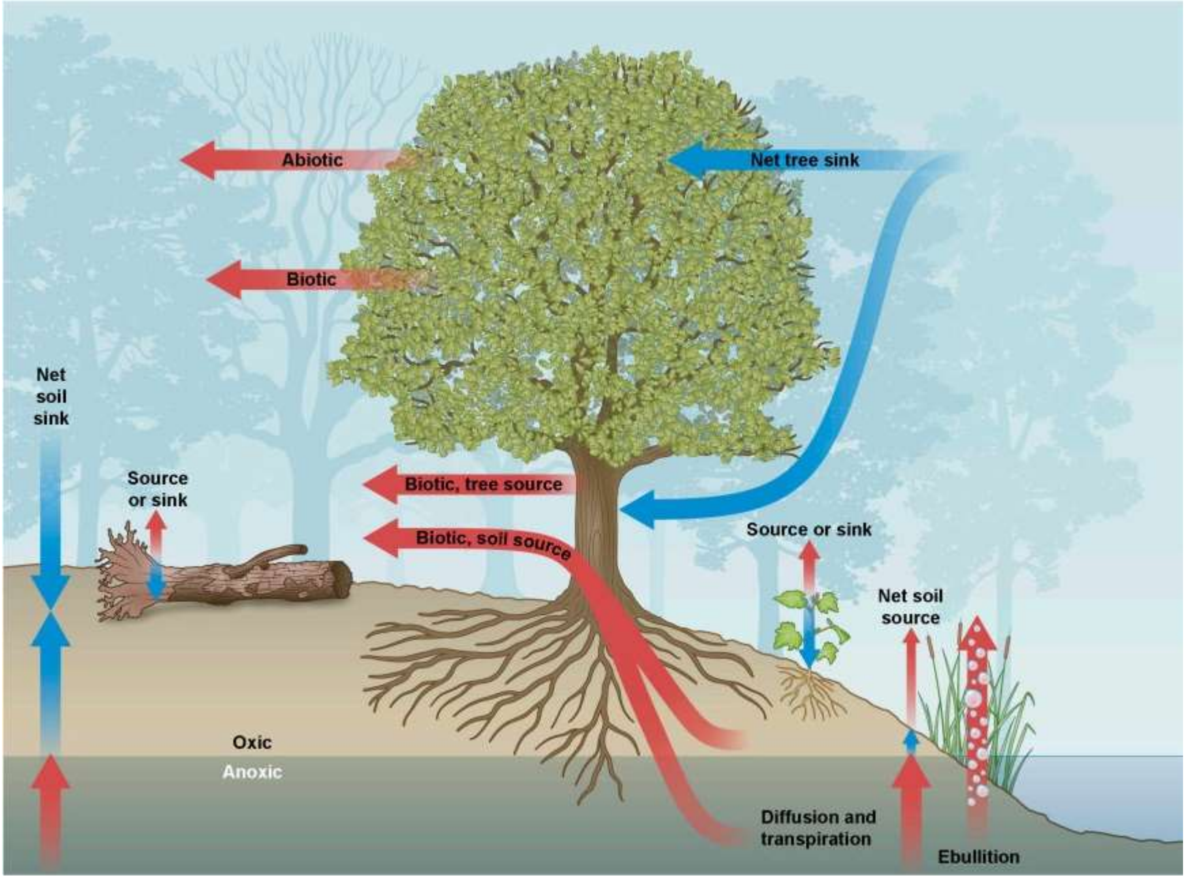
Cattle emit methane either through belching or flatulence as a by-product of enteric fermentation. Enteric fermentation takes place in the digestive systems of animals, in particular, ruminant animals (cattle, buffalo, sheep, goats, etc.), which have a large "fore-stomach," or rumen, within which microbial fermentation helps to digest coarse plant material. Methane is produced in the rumen by methanogens as a by-product of the fermentation process. This methane is exhaled or belched by the animal and accounts for the majority of emissions from ruminants. Recent research found that the methanogens that cause these emissions are similar in rumen around the world, despite differences in species and diet (Henderson, Cox *et al.* 2015). Methane production is animals has therefore come under scrutiny in recent years, not only because methane is a potent GHG, but because it also represents a loss of energy from feed that could have been used by the animal (Gibbs and Leng 1993).

4.1.7 Trees

Trees have been shown to both uptake and emit methane; an overview can be found in Fig. 12. Trees become a source of methane when living trees or dead wood emit methane produced by methanogens. The amount of methane emission depends on the tree species, tissue types within living trees, and stages of trunk decay. Methanogens within the trees likely exist in a symbiotic relationship with bacteria responsible for wood decomposition, although this process is not well understood. Trees can act as a sink for methane when they passively take in methane along with other gases from the air that passes through the leaves or trunk. Methane can also reach the tree if it bypasses methanotrophs in the soil and enters through the roots (Covey and Megonigal 2019; Jensen and Olsen 1998; Keppler, Hamilton *et al.* 2006; Sundqvist, Crill *et al.* 2012). Although the exact numbers on trees as global methane sources and sinks are unknown, one paper (Carmichael, Bernhardt *et al.* 2014) estimates that vegetation may represent up to 22 % of the annual flux of methane to the atmosphere, contributing anywhere from 32–143 Tg/yr to global flux of methane, although these numbers have yet to be independently verified. It also important to note that these numbers include estimations on methane transport through herbaceous and woody plants, as well as emissions from cryptic wetlands, heartwood rot, and dead vegetation.

Certain tree species have been shown to be more effective at absorbing CH_4 than others, including spruce, pine, larch, aspen, rowan, and birch (Jensen and Olsen 1998) (Menyailo and Hungate 2003) (Sundqvist, Crill *et al.* 2012). Although the results are promising, further research is required to better determine the conditions under which trees absorb the most methane, and what the variation is between species. Further research in Australia on native species would be enormously beneficial in determining how tree planting could help to absorb excess atmospheric CH_4.

Figure 12: Sources and sinks of methane in trees in upland and wetland forests *



* Red arrows, CH_4 sources; blue arrows, sinks. Source: Covey and Megonigal (2019).

4.2 How these organisms utilise methane, and to what effect

4.2.1 Factors that influence methanotrophs, methanogens, and soil CH_4 uptake

Soil moisture and temperature

An effective form of biological methane capture may be increasing the productivity of CH_4 uptake from soils. The production and consumption methane from soils occurs as a result of different microbial processes, which in turn are controlled by factors that influence the growth of microorganisms. A variety of factors have been known to affect methanotrophs and methanogens, including soil temperature, precipitation, soil moisture, soil pH, nutrient availability, and fertilizer (Conrad 1996; Snyder, Bruulsema *et al.* 2009). All of these factors should be taken into account when considering effective methods for improving CH_4 uptake from soils. An increase in soil temperature is known to increase the growth of methanotrophs and methanogens, but it is not known if this is simply because increased temperatures increase bacterial growth (a common phenomenon), or if there are additional factors at work (Conrad 1996; Snyder, Bruulsema *et al.* 2009). Increased soil moisture, usually from precipitation or humidity, decreases the amount of methane and oxygen stored in the soil (water fills the air pockets in the soil). This decreases the methanotrophic population because there is less methane available for consumption. In other areas with large methane emissions, such as rice paddies, periodic drainage introduces oxygen and prevents methanogens from producing methane (Li, Qiu *et al.* 2002). However, in arid climates and upland soils, there is evidence that methane uptake is increased, rather than decreased after soil wetting and drainage, contrary to wet climates (Covey and Megonigal 2019; Dobbie and Smith 1996). Although the causes are unknown, it has been hypothesized by one research group to be due to a decrease in ethylene in the soil (Zhou, Dong *et al.* 2014), although this has yet to be independently verified. They hypothesize that stressed plants produce ethylene, which competes with methanotrophs for methane monooxygenase (MMO) in the soil. Rainfall reduces drought stress, decreasing ethylene and allowing methanotrophs to access MMO. MMO is necessary for methanotrophs to begin the first step of converting methane to CO_2, and is highly copper-dependent (Ross and Rosenzweig 2017; Semrau, DiSpirito *et al.* 2010).

Soil additions

Other factors, including soil pH and fertilizer, are also known to affect the growth of methanotrophs and methanogens. Soil pH has also been shown to affect soil microbes; the optimal pH-value for methanogenesis is estimated to be between pH 4–7, but that may vary between species (Hanson and Hanson 1996). Therefore, the effects agricultural practices such as liming on CH_4 uptake should be considered.

Nutrient availability

Nutrient availability is essential to microbial and plant respiratory processes. MMO is essential for methanotrophs to convert methane to CO_2. But it requires the presence of copper (Cu) to be active (Semrau, DiSpirito *et al.* 2010). Thus, Cu levels in the soil may affect CH_4 uptake. Fertilizers which include carbon and nitrogen may also affect methanotrophs and methanogens. Using fertilizer with carbon increases the amount of carbon available for methanogens, which increase CH_4 soil emissions. Studies examining the effects of N addition to the soil on CH_4 uptake have conflicting findings (Jang, Lee *et al.* 2011; Liu and Greaver 2009; Phillips and Podrebarac 2009; Yue, Li *et al.* 2016), and more research is needed.

Grazing

In considering ways to reduce CH_4 emissions from ruminant grazing animals, it is important to consider the environmental factors that are affected by cattle, in addition to direct emissions from cattle themselves. Influencing the way cattle interact with their surroundings may also help to improve CH_4 uptake from the soil. One such method may be the consideration of the effects of grazing on CH_4 uptake. A meta-analysis of 63 independent grazing studies from 1990–2016 measured soil GHG fluxes across global grasslands. They found that light and moderate grazing had no significant effect on soil CH_4 uptake and CO_2 emissions, but heavy grazing consistently reduced them. Variation was dependent on grazing duration and precipitation. In comparison with CO_2 emissions, soil CH_4 uptake was significantly reduced under heavier grazing, longer grazing duration, or less precipitation. This is likely due to the decrease in soil moisture and substrate availability. Grazing intensities (light, moderate, heavy) were based on the authors' qualitative classification and were defined as a grazing-induced percentage change in aboveground biomass. Grazing duration was categorized as <5, 5-10, or ≥10 years, and precipitation ranged from <400 - ≥400 mm (Tang, Wang *et al.* 2019). Other studies have also shown that grazing can have an effect on GHG emissions from the soil with heavy grazing and low precipitation usually having the most negative impact.

Using agricultural practices that utilize grazing management techniques has great potential to offset methane emissions from cattle, in part by restoring carbon and methane into the soil. Healthy prairies (which include grasslands and savannas) show net methane consumption (Chan and Parkin 2001), as well as providing many ecological benefits, such as superior erosion control, increased rainfall and soil infiltration, and carbon sequestration (Tallgrass Prairie Center 2019). Restoring ecosystems has also been shown to have ancillary benefits, such as improving bird and insect populations (Audubon 2017). Modelling grazing systems on healthy grasslands, and considering how overall ecosystem dynamics influence methane absorption and emissions, would be highly beneficial. This could be done by conducting a "Genius of Place" analysis, which looks to the ecology and organisms of a particular place to provide guidance, in this case, on restoring grazing lands to optimize carbon and methane management.

Plants

Plants can also influence methane concentrations in the soil by releasing oxygen or carbon from the roots, which can be used by methanotrophs or methanogens. This is turn affects how much methane will be available for uptake by the plants. It has been suggested that tree planting can act as a net carbon sink (Fig. 13) (Bastin, Finegold et al. 2019). Research indicates that farmers could benefit most by planting a specific combination of grasses and shrubs with various root structures or adding different mycorrhizae to support different plant species to enhance CH_4 uptake (Koziol, Crews et al. 2019). Tree planting on grazing lands has also been shown to have a positive impact on cattle and the surrounding environment (Anderson 1986; Austin 2014), and could therefore help to absorb methane emissions from nearby cattle, as well as CO_2 from the surrounding air.

4.3 Influence of methane on global warming

It is known that greenhouse gases such as carbon dioxide and methane help to warm the Earth by trapping heat in the atmosphere, a phenomenon known as the greenhouse effect. However, recent activities are releasing too much greenhouse gas into the atmosphere, leading to global warming. Although methane is less prevalent in the atmosphere, it traps more heat than carbon dioxide and therefore has a greater warming potential. Therefore, curbing methane emissions can have a significant impact on reducing global warming. One of the largest sources of anthropogenic methane emissions is non-dairy cattle. Given the fact that carbon offsets are predicted to consistently rise in price in coming years, and considering that methane contributes significantly to the carbon footprint, finding ways to reduce methane emissions in the cattle industry provides a significant financial incentive as well as providing an enormous benefit to the environment.

5. Conclusion

The goal of the project was to research biological methods for methane capture in Australia. The project contained two milestones: 1) review the biological organisms that utilize methane, 2) determine how these organisms utilize methane, and to what effect. Both milestones were met, with a review of the biological organisms, how the utilize methane, and the factors that influence this utilization described in sections 4.1-4.2.

5.1 Key findings

5.1.1 Sources and sinks of methane globally

The largest methane sinks are the atmosphere, soils, and trees. The largest anthropogenic sources of methane are emissions from ruminants and landfills. In Australia, the troposphere removes approximately 12 Tg/yr of methane from the atmosphere, and soils are estimated to remove another 2 Tg/yr. Certain species of trees also have the potential to absorb methane from the atmosphere. The largest anthropogenic source of methane in Australia is agriculture, releasing 3-5 Tg of methane per year. Thus, increasing methane sinks by increasing the amount of methane taken up by soils, as well as the amount taken up by plants, could help reduce or store methane emissions from livestock grazing systems.

5.1.2 Methanotrophs and methanogens affect soil CH_4 uptake

Because the production and consumption methane from soils occurs as a result of different microbial processes, controlling the factors that influence the growth of microorganisms may help to increase CH_4 uptake from the soil. Numerous factors can affect the growth of methanotrophs and methanogens, including precipitation, soil moisture, soil temperature, soil pH, nutrient availability, and fertilizer. Extremes in any of these cases (acidic soil, poor drainage or nutrient availability, or excessive use of fertilizer) are known to reduce methane uptake in soils. Soil precipitation is known to reduce CH_4 uptake in wetter climates but may increase uptake (after sufficient drainage) in drier climates, although the exact causes are still not well understood. Various studies have also shown that grazing can have an effect on GHG emissions from the soil, with heavy grazing having the most negative impact.

5.1.3 Trees may serve as a methane sink

Trees have been shown to act as both sources and sinks for CH_4, although certain species are known to be better at absorbing CH_4 than others. More research is needed to gain a better understanding of which tree species are most effective at uptaking methane from the atmosphere, as well as promoting soil CH_4 uptake by methanotrophs. Because there can be extreme variation of methane emissions between individual trees, it is important to take measurements of large numbers of different species of trees in various locations.

5.1.4 Grazing management practices can improve methane uptake from soil

Utilizing grazing management practices has the potential to offset methane emissions from cattle, in part by restoring carbon and methane into the soil. Healthy grasslands and savannas show net methane consumption, as well as providing many ecological benefits, such as superior erosion control, increased rainfall and soil infiltration, and carbon sequestration (Tallgrass Prairie Center 2019). Future research through a 'Genius of Place' report would identify metrics for assessing healthy native grassland, including amount of rainfall and infiltration and amount of CH_4 and CO_2 sequestered annually, while providing suggestions for future planting and grazing management decisions that would most effectively address CH_4 reduction.

5.2 Benefits to industry

Practical applications to the red meat industry include considering how additions to the soil, such as water and fertilizers, affect the ability of methanogens to uptake CH_4 in the air (refer section 4.2.1), as well as altering/timing grazing patterns to take into account soil microbes (refer section 4.2.1.4).

Planting of certain native tree species (refer section 4.2.1.5), as well as engaging in various grazing management practices (refer section 5.3.1) could also help to increase absorption of CH_4 and CO_2 from the atmosphere and soil.

Development and adoption activities could include the addition of these practices to Australia's Carbon marketplace (refer section 1.1.4) and industry extension adoption activities, to incentivise and encourage farmers to engage in methane-reducing practices.

5.2.1 Sustainability benefits

These changes would have numerous economic and sustainability benefits, as a reduction of any amount of CH_4 emissions or increase in CH_4 capture is considered incredibly beneficial to reducing global temperature rise in the short-term. There are also added financial incentives in the form of carbon offsets (Section 1.1.5), which are currently being implemented in numerous countries around the world (Table 2).

6. Future research and recommendations

6.1 Future R&D

Future R&D is necessary to fully understand the most effective biological-based methods and models for methane capture. Given our findings, we suggest the following research:

6.1.1 Conducting a “Genius of Place” report on healthy grasslands in Australia and similar biomes.

A Genius of Place considers a healthy ecosystem as a whole, looking into the ecology and organisms of a particular place to provide guidance for sustainable design or management. The report would include the following research elements, which could also stand on their own, as well as part of a broader ecosystem assessment:

- Research into how various trees, as well as plants and shrubs, absorb and emit methane, as well as an analysis of the native tree and shrub species of Australia and their methane consumption potential. This will provide greater insight into the potential effects of tree planting in absorbing CH_4 and CO_2 from the air. Trees and plants that are shown to absorb CH_4 could then be planted by farmers and serve as a source of carbon offsets.
- An analysis of precipitation patterns in Australia and the effect of those patterns on CH_4 uptake in the soil, as well as research into the effects of grazing patterns on soil health. This would provide farmers with information on the most effective times and strategies for grazing cattle to maximize soil CH_4 uptake. Farmers engaging in these practices could then claim carbon offsets.
- A comparative analysis of native grazers and grazing patterns in Australia, native grazing patterns in similar biomes, and successful grazing management practices in similar biomes, e.g. the American plains. Several grazing practices have been shown to have a positive effect on surrounding ecosystems, including increasing bird and insect populations, as well as improving soil and grassland health. Further research into a systems-level understanding of the effects and benefits of grazing cattle may provide insight into alternative methods for improving methane capture by increasing the health and vitality of surrounding ecosystems. This could incentivize good grassland stewardship that could translate into a certification on beef products. Consumers could then directly contribute to grassland conservation by selectively purchasing beef from certified farms, as has been successfully implemented by the Audubon Society in the United States.
- Although the primary focus of the research will continue to focus on methane reduction, supporting healthy ecosystems as a whole often has ancillary benefits. For example, planting select tree species for the express purpose of greater CH_4 absorption will also lead to greater moisture retention in the soil, thereby reducing drought stress and potentially allowing greater methanotrophic activity. Other less obvious ancillary benefits are likely to be observed by supporting a healthy, biodiverse ecosystem as a whole, such as the potential to reduce pasture dieback.

6.1.2 An analysis of benefits of circulating waste streams

An analysis of the benefits of circularizing waste streams either by identifying how farm waste could benefit other industrial and agricultural streams, or how waste from other industries could benefit the red meat industry. For example, research into the benefits of using spent coffee grounds to absorb excess CH_4 from the air on farms (Kemp, Baek et al. 2015). This could help reduce waste and costs while simultaneously reducing GHG emissions across multiple industries.

Research to be done by other groups:

- An extensive analysis of the bottom-up and top-down methodologies used in Australia to measure CH_4 sources and sinks. Both methodologies still exhibit significant levels of uncertainty; a review of these methods as well as an analysis of the most effective methods used globally and the most promising future technologies could help to improve data collection and accuracy on CH_4 sources and sinks in Australia. More accurate data will improve the accuracy of carbon offset pricing, as well as provide farmers and lawmakers with more accurate targets for reducing CH_4 emissions.
- Research on different combinations of tree and cattle densities to gauge the effect on methane emission and absorption. This research could provide a framework for the creation of density models that can be used in an accounting framework to assist the Australian red meat industry to achieve carbon neutrality by 2030 (CN30).
- Measurements of methanotroph and methanogen levels in Australian soils, and how CH_4 uptake is effected following precipitation and various soil additions.

6.1.3 Development and adoption activities which would ensure the red meat industry achieves full value from the project's findings.

Development and adoption activities could include the addition of these practices to Australia's Carbon marketplace (Section 1.1.4), to incentivise farmers to engage in methane-reducing practices.

Reducing CH_4 can have a significant impact in helping to reduce global warming. Our findings suggest several different agricultural practices that farmers could adopt to improve soil and grassland health and increase CH_4 uptake. One practice is to alter cattle grazing patterns (Section 4.2.2.1). Influencing the way cattle interact with their surroundings may help to improve CH_4 uptake from the soil, and utilizing grazing management techniques has great potential to offset methane emissions from cattle, in part by restoring carbon and methane into the soil. Healthy prairies (which include grasslands and savannas) show net methane consumption, as well as providing many ecological benefits, such as superior erosion control, increased rainfall and soil infiltration, and carbon sequestration. Restoring ecosystems has also been shown to have ancillary benefits, such as improving bird and insect populations.

Producers should also be mindful of how the soil environment effects the growth of methanotrophs (which consume methane) and/or reducing the growth of methanogens (which release methane) in the soil (Sections 4.2.1.1–4.2.1.3). A variety of factors have been known to affect methanotrophs and methanogens, including soil temperature, precipitation, soil moisture, soil pH, nutrient availability, and fertilizer. In arid climates and upland soils there is evidence that methane uptake is increased, rather than decreased after soil wetting and drainage, contrary to wet climates. Other factors, including soil pH and fertilizer, are also known to affect the growth of methanotrophs and methanogens. Fertilizers which include carbon and nitrogen may also soil microbes. Using fertilizer with carbon increases the amount of carbon available for methanogens, which could increase CH_4 soil emissions. All of these factors should be taken into account when considering effective methods for improving CH_4 uptake from soils.

Planting trees and shrubs (Section 4.2.1.5) may also help to increase both methane and CO_2 uptake from the atmosphere and soils. Research suggests that tree planting can act as a net carbon sink, and that farmers could benefit most by planting a specific combination of grasses and shrubs with various root structures or adding different mycorrhizae to support different plant species to enhance CH_4 uptake. Tree planting on grazing lands has also been shown to have a positive impact on cattle and the surrounding environment, and could therefore help to absorb methane emissions from nearby cattle, as well as CO_2 from the surrounding air. Producers might also consider adding different mycorrhizae to support different plant species on grazing land, to help to enhance CH_4 and CO_2 uptake from the soil and atmosphere.

Producers can also engage in various grazing management practices (Section 5.3.1) to improve methane uptake from the soil. Utilizing grazing management practices has the potential to offset methane emissions from cattle, in part by restoring carbon and methane into the soil. Healthy grasslands and savannas show net methane consumption, as well as providing many ecological benefits, such as superior erosion control, increased rainfall and soil infiltration, and carbon sequestration.

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