Boosting farm productivity
Improved soils and reduced greenhouse gas emissions

Research findings from the Carbon Farming Futures programme, 2012 to 2016
Foreword

Australia has a proud history as a producer and exporter of high-quality, safe and sustainable food and fibre. Most of the fresh food consumed in Australia—around 90 per cent—is produced here, as are most processed foods.

The Department of Agriculture and Water Resources assists Australian agriculture, food and fibre industries to be more sustainable, productive, internationally competitive and profitable. It does this through policies and initiatives that promote better resource management practices, innovation, self-reliance and improved access to international markets.

Australian farmers have always faced and adapted well to the challenges of a highly variable environment. According to scientific evidence and observation, Australia is becoming warmer and the majority of the country is becoming drier. This is affecting the rate of evaporation and soil moisture levels, which are crucial to crop and pasture success. Australia also has an international obligation to reduce greenhouse gas emissions. The Carbon Farming Futures programme was designed to assist farmers to address these challenges.

This publication summarises the findings from research under the Carbon Farming Futures programme, which ran from 2012 to 2017. The publication also identifies some key growth opportunities and constraints farmers will face over the coming decades. This work showed real ways that farmers could boost productivity and profitability while improving soils and reducing greenhouse gas emissions.

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Highlights

Under the Carbon Farming Futures programme, which began in 2012 and ran through to 2017, the Australian Government invested more than $139 million in 200 projects, involving more than 530 farmers and 350 organisations. The programme examined ways to improve farmer productivity and profitability while adapting farmer practices to deal with a more variable climate and assisting Australia to meet its international obligations to reduce greenhouse gas emissions.

This publication gives an overview of the key research achievements of the programme that show how farmers, working with industry, rural research and development corporations and universities, can improve profit and productivity when introducing practices or technologies to:

• reduce greenhouse gas emissions (mitigation)
• increase the amount of carbon in agricultural soils (sequestration)
• deal with a more variable climate (adaptation).

The work also improved some of the tools and management practices that farmers rely on to participate in the Australian Government’s Emissions Reduction Fund.

The programme, managed by the Department of Agriculture and Water Resources, was delivered through a series of competitive grants programmes.

Some highlights from the Carbon Farming Futures research are set out in this chapter.

Reducing emissions from ruminants

• Research identified treatments that reduce emissions, including supplements, forages, breeding and genetics.
• Inhibiting methane production in ruminants does not affect an animal’s health and can improve the growth and productivity of an animal.
• Where improved reproductive performance and efficiency of feed use results in a higher animal carrying capacity, methane intensity (the amount emitted per unit of saleable product) will be reduced.
• New and better techniques and methods are now available to measure methane emissions. As a result, the National Greenhouse Gas Inventory estimate for the contribution of methane from dairy and beef herds has been reduced by 24 per cent.
Reducing emissions from manure

- Lower manure application rates and the incorporation of manure into soils can reduce emissions while maintaining farm productivity.
- Composting and pelletising rather than stockpiling livestock manures reduces emissions.
- The use of sorbers (insoluble materials used to recover liquids) can improve crop yield while decreasing nitrous oxide and ammonia emissions.
- Storing effluent for shorter times in ponds and covering manure stockpiles can reduce emissions by up to 88 per cent.
- A switch from raw to composted manures can greatly reduce emissions.

Reducing nitrous oxide emissions

- Nitrogen use efficiency in Australian agricultural systems is low, with consistently high losses of applied nitrogen.
- Careful nitrogen budgeting in some agricultural systems can reduce nitrogen losses by up to 80 per cent.
- The use of nitrification inhibitors to slow down or delay the conversion of nitrogen fertiliser to nitrate effectively reduces nitrous oxide emissions.
- Modest changes to fertiliser practices could increase the annual profitability of the eastern cropping regions by up to $6 million.
- The widespread use of legumes in northern grain regions could save growers up to $22 million a year in nitrogen input costs.
- Increasing soil carbon and nitrogen stores through less frequent cropping and increased legume or grass pastures reduces nitrous oxide emissions with minimal impact on productivity in the rain-fed subtropics.
- Introducing legumes in grain-based cropping systems could reduce synthetic nitrogen inputs to near zero with no yield reduction.
- Fertiliser rates in temperate regions could be reduced (even halved) with no yield reduction.
- Nitrous oxide emissions in deciduous tree crops were among the lowest recorded for Australian agriculture.
- To limit indirect nitrous oxide emissions from irrigation water, run-off needs to be reduced in furrow irrigated systems and/or the nitrogen loading of the water reduced.
- A new low emission fertiliser was developed based on slow release of ammonium from modified activated charcoal (biochar).
- Improved measurements led to reductions in the nitrous oxide emission factors used by the National Greenhouse Gas Inventory and a decrease of up to 21 per cent in the contribution attributed to nitrogen fertilisers.
- Indications that methane uptake (which potentially offsets nitrous oxide emissions) is significant in most arable soils.
Improving soil carbon

- Application of compost and biochar results in increased crop productivity and soil carbon.
- Quality data on soil carbon for a number of major agricultural systems were collected, often for the first time.
- Existing models significantly underestimate carbon sequestration in the biomass of environmental plantings.
- Reversing soil carbon decline through reforestation is a slow process and it typically takes more than 15 years for the soil carbon levels to exceed that of pasture.
- Long-term tagasaste plantations have a high potential for sequestering carbon.
- Standardised methods for analysing soil organic carbon and for estimating soil organic carbon in regrowth, reforestation and environmental plantings have been developed.

Whole-farm systems modelling

- Farm management scenarios show that emissions intensity can be reduced while maintaining farm productivity and profitability.
- A case study demonstrated that a livestock farm can be productive, profitable and carbon neutral through planting trees while increasing production on the balance of the land.
- Farmers have access to better tools to estimate soil organic carbon stocks and how these may change over time.

Adaptation

- Options for management practices to deal with a more variable climate were identified across a range of farm business types.
- Growth, yield and resource use (water and nutrients) all changed significantly under elevated carbon dioxide conditions.
- Betaine (an amino acid supplement) improved the recovery of heat-stressed dairy cows, resulting in improved milk yields.
- Feeding on cinnamon did not alleviate symptoms of heat stress in cattle.
- Significant gains can be made for heat tolerance in the Australian dairy herd through selective breeding.
- Targeted improvement of transpiration efficiency in sugarcane breeding would assist the development of varieties adapted to drier and hotter conditions.
- The incidence of sunburn damage for Royal Gala apples will increase in some of Australia’s warmer growing regions, but could be halved in some locations by installing netting.
- When applied on a rotational basis, delayed pruning can contribute to spreading harvest time with no impact on vine vigour, yields, grape or wine quality.
- Night-time irrigation with sprinklers does not significantly lower vineyard temperature but does improve yield and potential wine quality, and can reduce the instances of sunburn damage.
Carbon Farming Futures programme

Actions to reduce greenhouse gas emissions or increase carbon storage can also increase the land sector’s resilience to a more variable climate, protect Australia’s natural environment and improve long-term farm productivity. The Carbon Farming Futures programme was established with more than $139 million of funding to prepare farmers to take such actions. The programme was to examine, demonstrate and distribute knowledge about ways that farmers can improve productivity and profitability while adapting farmer practices to deal with a more variable climate. These adapted farmer practices also assist Australia to meet its international obligations to reduce greenhouse gas emissions.

Researchers additionally improved a number of the tools and methods that farmers rely on to participate in the Australian Government’s Emissions Reduction Fund. This fund is the principle tool under the Australian Government’s Direct Action Plan to source low-cost emissions reductions and improve Australia’s environment. Details are available at the Department of the Environment and Energy’s Emissions Reduction Fund web page.

This programme built on research undertaken under the previous Climate Change Research Program, described on the Department of Agriculture and Water Resources Climate Change Research Program web page.

The programme supported 200 projects across three key areas:

- **Filling the Research Gap**—$74 million to support research into new technologies and practices for farmers to reduce emissions and/or increase soil carbon, as well as adapting farm practices to address business risks from a more variable climate.

- **Action on the Ground**—$44 million to assist farmers to undertake on-farm trials of new technologies and practices. More than 530 farmers and 300 partner organisations were engaged through these projects.

- **Extension and Outreach**—$21 million to increase the knowledge of farmers on how to enhance productivity while reducing greenhouse gas emissions or increasing soil carbon. This programme also provided advice on how farmers could participate in the Emissions Reduction Fund. Events held included workshops, webinars, field days and paddock walks. Extension materials included books, fact sheets, flyers and videos, which are available on the My Carbon Farming website. Underpinning the Extension and Outreach programme was training for a network of extension providers that spanned industries and locations across Australia.
Extension providers from around Australia attended training workshops

Extension to farmers included field days
Proposals were invited in each of the programmes across several rounds as part of a competitive grants process. Projects were assessed against published criteria by an expert assessment panel made up of research and industry experts and departmental staff. Most projects under the CFF programme operated for approximately three years.

The majority of projects were delivered in partnership with research providers, industry groups, universities and state governments to ensure that:

- the best expertise and experience were gathered to develop practical advice and solutions
- commercial realities were taken into account to improve the transition from applied research, to demonstration of commercial applications, to adoption
- Australia can contribute to, and influence the work of the Global Research Alliance on Agricultural Greenhouse Gases.

More information is available on the department’s Carbon Farming Futures web page.

**Mitigation and adaptation for Australian agriculture**

Agriculture has an important role in assisting Australia to meet its international obligations to mitigate greenhouse gas emissions. Agriculture can also contribute to mitigation through the storage of carbon in agricultural soils, which reduces carbon dioxide levels in the atmosphere.

The agricultural sector accounts for approximately 14 per cent of Australia’s total greenhouse gas emissions. Agriculture’s greenhouse gas emissions comprise methane from enteric fermentation (around 73 per cent of agricultural emissions), nitrous oxide from agricultural soils (around 18 per cent), emissions from livestock manure (around 5 per cent) and emissions from field burning of agricultural residues, lime and urea application and rice cultivation (around 3 per cent combined).

Farmers will also need to prepare for the climate changes predicted for coming years. Australian farmers have always managed for, and adapted to a variable climate. These risks will grow: there will be more extreme weather, hotter heat waves and more frequent droughts. The industry will also have new opportunities, including for innovation (such as business diversity, new crop types and varieties). A farmer’s skill, flexibility and judgement, together with access to new practices, technologies and professional support, will allow farm businesses to reduce their vulnerability and maintain or improve their long-term productivity and profitability.

Mitigation and adaptation are often related. Many mitigation options lead to direct benefits for farm businesses (such as improved soils or lower input costs) that strengthen a farmer’s ability to deal with the risks of a more variable climate.
New research

The Carbon Farming Futures programme recognised that farmers require robust, reliable information before they make decisions about adopting new practices or technologies. The programme targeted research into technologies and farm practices that could help increase agricultural productivity that also:

- reduced greenhouse gas emissions (methane and nitrous oxide)
- increased the storage of carbon in agricultural soils
- improved measurement and modelling capability
- helped farmers adapt to increased climate variability.

The department took great care to ensure the credibility of the research outcomes. An Expert Advisory Panel assessed and ranked all research funding applications to ensure that research coming out of the programme would be well organised and produce relevant, high-quality results with defensible outcomes.

The panel comprised leading experts, industry representatives and government officials with expertise in agricultural research and production systems and included representatives from both an Australian and overseas independent science organisation. An independent leading scientist, Professor Snow Barlow, was appointed Chair of the panel.

This programme fostered greater collaboration among researchers and research organisations, which has enabled important questions to be addressed at a national level. The projects also supported 41 new agricultural research doctorates, helping to develop and expand Australia’s agricultural research capacity.

The key findings of the Carbon Farming Futures research are detailed in this report.
Implications for method development under the Emissions Reduction Fund

The new research has also supported development of a number of approved methods under the Emissions Reduction Fund, including beef cattle herd management and reducing greenhouse gas emissions in milking cows through feeding dietary additives.

The research outcomes may also assist the government to identify other opportunities for abatement methods. This will be assessed on a case-by-case basis in line with the requirements for Emissions Reduction Fund methods specified in the Carbon Credits (Carbon Farming Initiative) Act 2011 and in decision-making on future method development priorities.

More information

More resources about how farmers can increase productivity, reduce emissions and adapt to a variable climate are available at:

Building Farmer & Advisor Knowledge in Carbon Farming carbonfarmingknowledge.com.au
Carbon farming and your business holbrooklandcare.org.au/carbon
Carbon Farming Futures agriculture.gov.au/ag-farm-food/climatechange/carbonfarmingfutures
Greenhouse in Agriculture greenhouse.unimelb.edu.au/
Global Research Alliance on Agricultural Greenhouse Gases globalresearchalliance.org/
myCarbonFarming mycarbonfarming.com.au
Primary Industries Climate Challenges Centre piccc.org.au
Reducing emissions from ruminants

When ruminants such as cattle and sheep digest feed, up to 12 per cent of feed energy is lost in the form of methane gas, a by-product of microorganisms that live in their rumen. Methane is belched into the atmosphere and along with it feed energy that could otherwise have been used to make muscle, milk or wool.

Methane has a global warming potential 25 times that of carbon dioxide. In Australia, methane accounts for about 20 per cent of all national emissions. More than 90 per cent of agricultural methane emissions is produced by ruminants.

Researchers identified a range of treatments that can lift productivity while lowering methane emissions. They found:

• feeding leucaena in conjunction with pasture, rather than pasture alone, in northern cattle systems could lift productivity by up to 22 per cent and lower methane emissions by up to 20 per cent
• feeding nine kilograms of wheat per day to dairy cows can lift milk production by up to 20 per cent while lowering methane emissions by up to 40 per cent
• feeding red macroalgae to cattle has the potential to maintain or increase productivity while reducing methane emissions by up to 60 per cent.

The results from this work has given a better understanding of how methane is produced in livestock, as well as practical and accurate means of measurement. Researchers have also identified opportunities for manipulating rumen function directly through genetic selection and targeting specific biochemical pathways of microbial fermentation.

Ruminant methane research projects funded under Round 1 of the programme were grouped together as the National Livestock Methane Program, coordinated by Meat & Livestock Australia. Much of the Round 2 ruminant methane research was coordinated through the University of Western Australia as part of Australia’s contribution to an international collaborative effort, the Ruminant Pangenome Program. This program is investigating and developing the potential for genetic control of livestock to reduce methane emissions while maintaining productivity and profitability. The national and international facilitation activities arising from this collaborative effort have led to improvements in Australia’s ability to report on abatement of land sector methane emissions.
Improved reproductive performance and feed utilisation

Research has allowed development of farm practices to improve reproductive performance and reduce the amount of feed needed for maintaining an animal (over its whole lifetime). Building on this work, scientists confirmed that improved reproductive performance, which increases the proportion of animals available for sale (rather than needing to keep a high number of reproducing animals in a herd or flock), will reduce the total lifetime amount of feed needed by the herd or flock. Researchers confirmed that, where this improved efficiency of feed use results in a higher animal carrying capacity, methane intensity (or the amount emitted per unit of saleable product) will be reduced.

This work has assisted the implementation of an emissions reduction method, the Beef Cattle Herd Management Determination 2015, detailed on the Department of the Environment and Energy’s Beef cattle herd management web page.
Implications for animal health and productivity

A key concern with work to inhibit methane production in ruminants is whether this has negative implications for the health and productivity of an animal. Researchers investigated the efficiency of rumen digestion in response to efforts to inhibit methane production. They found that rumen microorganisms will successfully, and safely adapt to such inhibition and confirmed that methane inhibition does not affect an animal’s health and can actually improve the growth and productivity of an animal.

Direct rumen manipulation

Researchers found that manipulating rumen function directly can improve the capture of energy from feed. For example, enhancing the activity of microbes—called acetogens—will take up excess hydrogen and convert this to a new energy source for the animal (acetic acid) instead of creating methane.

Researchers have identified a new species of microorganism that is responsible for a previously unknown biochemical pathway that produces methane in the rumen. The efficiency of this pathway is four times greater than other methane-producing pathways. This means that the potential for reducing methane is significantly greater if this biochemical pathway can be manipulated, or even blocked. One way to do this may be to develop a vaccine against the methane-producing organisms in the rumen.
Genetics and breeding

One option to mitigate methane emissions from livestock is selective breeding of animals for lower methane emissions. A selective breeding strategy requires that the low methane trait is heritable and is not associated with poor animal production outcomes. The trait also has to be measurable in many animals. Researchers confirmed that methane production is heritable.

Breeding low methane dairy cattle

Researchers investigated the practicality of including methane emission intensity (emissions per litre of milk) as part of the breeding goals for dairy cattle. The work confirmed a strong correlation between dry matter feed intake and emission levels.

Researchers concluded that reductions in emissions could be achieved by selecting for reduced dry matter intake, while maintaining production. The work also developed genomic breeding values for methane emission levels, which will allow farmers to select dairy cattle with reduced methane emissions.

Host control of microbial fermentation in sheep

A sheep affects the microbial populations in its rumen, and hence its methane production, through how much feed (and what type) it eats and the functional variation in its forestomach. Evidence shows that elements of these contributing factors are heritable.

Researchers have demonstrated that traits of the animal likely to influence methane production are variation in fermentation rate, rumen volume, distribution of digesta in the rumen, and the time feed is retained in the rumen. These contribute to the genetic basis of differences in methane production between animals.

This work has provided a selection of tissues and rumen contents from animals with known methane-related observable characteristics (phenotypes) for further study. These are expected to underpin the future discovery of a dependable means of selecting animals with low or high methane-producing characteristics.
Genetics for improved reproduction and feed efficiency in sheep

The heritability of traits for feed intake, feed-intake efficiency, methane production and reproduction were measured. The findings showed that feed intake is a more important trait to improve efficiency in breeding programmes than methane production. Selecting for reduced methane will not necessarily reduce the feed intake of growing lambs on high-quality diets. Additionally, feed intake has more positive genetic correlations with growth and live weight than methane.

Measuring heritable methane emission traits in sheep

Researchers have developed a method for obtaining short-term measures of methane in sheep after brief removal from pasture. These measurements are sufficiently useful to make genetic progress towards a lower methane emitting, more efficient sheep.

Correlations between methane emissions from sheep measured using this off-pasture method and more precise laboratory methods are high and provide confidence that off-pasture measurement of methane can be useful for making genetic progress. This work has shown that indirect measurements of feed intake based on relatively easy-to-measure methane and carbon dioxide emissions from sheep may be a better, more profitable, selection method than selection against methane alone.

The work also provided information on methane production across a breeding cycle. Researchers suggested that this may have the potential to inform the Australian greenhouse gas accounting process, which at present assumes a single relationship between feed eaten and methane emissions for all sheep.
Feeds and supplements

Feeding on leucaena

The use of leucaena (a legume fodder crop that grows in tropical and subtropical environments) has been shown to improve productivity and profitability, as well as reduce methane emissions in cattle production systems in northern Australia.

Whole-farm modelling has shown an increase in gross margins by up to 37 per cent and methane emission intensity down by up to 17 per cent compared with a base farm without leucaena. This was a result of higher farm production through increased herd size and faster liveweight gain.

In Queensland trials near Rockhampton, cattle grazing on both pasture and leucaena had growth rates up to 22 per cent higher than cattle grazing on pasture only. The cattle feeding on leucaena also produced up to 20 per cent less methane.

Feeding on grape marc

Feeding grape marc—a by-product of wine making made up of skins and seeds—has been shown to reduce methane emissions in dairy cows, sheep and cattle in feedlots. In practice, the influence of feeding grape marc on both methane emissions and productivity is variable because grape marc samples differ in active tannin content and provide only a low energy feed for animals.

Researchers concluded that feeding grape marc could be effective when used as a replacement for low-quality diets, or during feed shortages.

Farmers need to be aware that grape marc can present a risk of containing residues of agricultural chemicals. This risk can be mitigated by sourcing grape marc from reputable feed companies.
Feeding dairy cows on wheat

Feeding wheat grain to dairy cows is an effective way to both reduce methane emissions and increase milk production. The research has shown that methane is reduced by 30 to 50 per cent and milk production increased by up to 20 per cent (per cow) when lactating dairy cows are fed 9 kilograms of wheat per day in conjunction with freshly cut ryegrass pasture or chopped lucerne hay.

While feeding wheat is not common practice in the dairy industry, particularly for pasture-based systems, it would be a simple process on Australian farms where cows are already fed mixed rations. However, producers would need to ensure they do not feed cows too much wheat, as this can increase the risk of ruminal acidosis.

Feeding on nitrate instead of urea

Many cattle producers, particularly in northern Australia, feed non-protein nitrogen to cattle (in the form of urea) during the dry season to improve animal productivity. Substituting nitrate for urea has been shown to have the added benefit of reducing methane emissions. An abatement method for the use of nitrates has been approved under the Emissions Reduction Fund. This method is best suited to cattle in northern Australia that typically consume a high fibre low nutrition diet over summer.

Feeding nitrates has the downside that, if too much is consumed too quickly, it is potentially toxic to cattle. A set of best management practice guidelines has been developed and released through Meat & Livestock Australia’s website to help producers decide how to feed nitrates to their herd safely.

Feeding on nitrate and sulphate rich shrubs

Diets rich in nitrate and sulphate are known to reduce methane emissions from sheep and cattle. Several Australian native shrub species used by livestock farmers in the low to medium rainfall zone produce significant concentrations of these compounds. These species include *Atriplex nummularia* (old man saltbush), *Maireana brevifolia* (small-leaf bluebush), *Rhagodia preissii* (Mallee saltbush) and *Enchylaena tomentosa* (ruby saltbush).

Regardless of the methane implications, these plants offer farmers significant opportunities to broaden the feed base to cope with climate variability and capitalise on unseasonal summer rainfall. As well as providing nutrients that are limited during summer and autumn, the shrubs improve the resilience of the farm enterprise by buffering risk across seasons.

An additional advantage of using plants naturally high in nitrates and sulphur in grazing systems, rather than relying on formulated supplements, is the opportunity for diet selection and learned grazing behaviours by animals to avoid nitrite toxicity.
Reduction emissions from ruminants

Feeding on Australian native shrubs

Introducing Australian native shrubs with methane-reducing properties alongside pasture species is an effective method for reducing emissions from sheep in south-west Australia, while increasing productivity and profitability.

The autumn feed-gap period is a major limitation to sheep productivity in the region as pasture is generally poor quality. Traditionally, sheep are offered supplementary grain during this period, which is expensive to supply and labour-intensive to handle. Studies have shown that strip-grazing sheep on rows of native shrubs with preserved inter-row pasture for six to eight weeks in autumn substantially improves growth rates and condition. It also eliminates the need for supplementary feeding. Because the species used are known to have methane-reducing properties, this grazing system can also reduce methane emissions intensity by up to 26 per cent for the period—or a 4 per cent reduction across the year.

Supplementing with bioactive compounds from native plants

Extracts from a number of Australian native plants have the potential to reduce methane emissions.

Laboratory studies show that tar bush (*Eremophila glabra*) contained some of the most potent methane-reducing compounds. Feeding this plant to sheep in the animal house at 15 per cent of their diet reduced their methane production by about 12 per cent.
Two bioactive compounds (extracted from native Australian leptospermum and melaleuca plants) can reduce methane emissions by up to 97 per cent in the laboratory. When provided as supplements in commercial conditions, these compounds have been estimated to reduce methane emissions by around 25 per cent. The cost of the compounds is difficult to estimate. Both compounds can probably be manufactured, either as supplements or lick-blocks, and readily fed to cattle or sheep anywhere in Australia because the amounts needed are very low.

**Feeding on red macroalgae**

One of the most effective supplements for reducing methane emissions in livestock is marine red macroalgae. Experiments in cattle and sheep have shown that feeding dried and ground preparations of the species *Asparagopsis taxiformis* reduced emissions by up to 80 per cent. Total feed intake was not significantly affected and in some cases actually increased.

The red algae appear to change the concentration of short-chain fatty acids in the rumen, which provides an alternative sink for hydrogen—a key element in methane production. Red algae has the potential to have a major role in reducing methane emissions across all Australian livestock industries. At present, production costs are high and availability is limited.

Researchers are looking at the potential to develop commercially viable production systems, such as in conjunction with marine aquaculture operations.
Feeding on modified pastures

Cattle and sheep that graze on legumes often produce less methane compared with those grazing on grasses. However, methane production varies considerably between different legume species and even between cultivars within the same species.

*Biserrula pelecinus* is consistently the most anti-methanogenic pasture legume identified in laboratory studies, but field trial results were more variable. Researchers did confirm that the main driver of methane production was feed quality.

Ruminants feeding on pasture with a higher digestibility produced less methane per unit of dry matter intake than those feeding on pasture with a lower digestibility. This has positive implications for animal production; pastures with higher digestibility are also associated with increased productivity, pasture utilisation and farm profitability.

New tools to measure emissions

Being able to measure methane emissions accurately is a critical part of assessing which reduction practices work best. Researchers have developed a number of new techniques and methods to improve measurements.

Among these is a revolutionary new membrane that makes it possible to use wireless sensors in the rumen that can detect the concentration of various gases, including methane and carbon dioxide. The sensors have the advantage of being able to measure methane emissions from cattle under any production system.
Researchers have also tested a new paddock-based system developed in the United States for measuring emissions from cattle, the GreenFeed Emission Monitoring (GEM) unit. They have confirmed the accuracy of the unit and ensured it is suitable for Australian conditions, including long-term use in remote grazing environments. They have also designed and developed a GEM unit specifically for measuring emissions from sheep.

Australian scientists have also played a leading role in the development of international guidelines for more accurate and effective use of a chemical tracer (sulphur hexafluoride), which is a popular method globally for measuring methane emissions in ruminants.

More information

More information on the research to reduce methane from ruminants is available at:

- Livestock Methane Database [livestockmethane.info](livestockmethane.info)
Reducing manure emissions

Large quantities of manure are an inevitable consequence of intensive livestock production. Manure is a source of methane and nitrous oxide emissions, particularly when broken down under anaerobic conditions such as in settlement ponds or when stockpiled.

Agricultural manure management accounts for about 5 per cent of all agricultural emissions in Australia, with intensive livestock production (such as grain-fed beef cattle, piggeries, dairy and poultry) accounting for 95 per cent of these emissions.

Manure emissions research funded under the programme was grouped together as the National Agriculture Manure Management Program (NAMMP). The NAMMP was managed by Australian Pork Limited and coordinated national research to estimate the agricultural greenhouse gas emissions abatement potential for various manure management systems across the manure supply chain for Australian intensive livestock industries. Major findings include:

- confirmation that lower manure application rates, application under dry conditions, incorporation into sandy soils and composting and pelletising can all reduce emissions
- development of a processing technology to stabilise solid manure by anaerobic digestion to prevent methane emissions
- better understanding of how to reduce emissions by composting rather than stockpiling manures and by using composted rather than raw manures in horticultural production
- identification of emission reducing storage options for solid and liquid effluent and manures.

Land application practices

Researchers measured emissions from sandy and clay loam soils following applications of different types of manures from the pork, feedlot cattle and poultry industries. These manures include digested pond sludges as well as raw, stockpiled, composted and pelleted manures. Mitigation strategies for land application of manures were then developed and evaluated in both a broadacre wheat cropping system and an intensive horticulture system.

Researchers found that environmental factors such as temperature, soil moisture, carbon to nitrogen ratio and soil permeability often have a much greater effect on emission rates from manure applied to soils than the type of manure or amount applied.
Case study: broadacre wheat cropping

- Lower application rates of manures to soils have the potential to reduce greenhouse gas emissions (regardless of soil type). This worked for most manures, especially piggery sludge and stockpiled manures.

- Low manure application rates were also found to increase the abundance of methane oxidising bacteria in soils. This means that, while microbial communities in manure-amended soils are a potential source of nitrous oxide, they can also be a sink for methane.

- In sandy soils, directly incorporating manure into the soil led to reductions in emissions in many piggery and chicken meat manures (although this was not observed in beef feedlot and hen layer manure samples).

- In clayey soils, incorporating manure directly into soil actually increased the emissions compared with the standard practice of applying manure to the surface of the land.

- The release of nitrous oxide emissions from manure-applied soils was greatest after a winter rainfall event. Dry seeding shows the potential to reduce emissions by up to 25 per cent.

- Composting and pelletising rather than stockpiling livestock manures (particularly piggery and feedlot manures) showed a potential reduction of greenhouse gas emissions by up to 70 per cent and 80 per cent, respectively. Composting poultry manures before land application had little impact on emissions.

The results of the field trials also showed, irrespective of the source of manure, a trend for higher grain and biomass yields in field plots receiving livestock manure, particularly the stockpiled manures in the sandy soils and composted manures in the clayey soils. These improvements in grain yield with the livestock manure treatments are likely to increase if manure application is continued in subsequent years. Long-term field trials have shown it usually takes three to five years of repeated manure or compost application before significant gains in crop yields are reported.
Case study: intensive horticulture

Researchers studied the repeated use of raw and composted manure from layer chickens and beef feedlots in intensive horticulture in cracking clay soils (vertosol). The work found that:

• composted manure reduced nitrous oxide emissions by up to 45 per cent compared with raw manures when applied at rates designed to match plant demand
• application of synthetic fertiliser could be reduced by up to 38 per cent without a yield penalty
• the supply chain reduction in emissions associated with composting and use of composted manure was 68 to 97 per cent, most of which was from the use of composted manures.

Composting is a long-established, flexible and low-cost manure management technology that can deliver a wide range of benefits. Expansion of manure composting and use of composted animal manures together with reduced mineral fertiliser use could be achieved relatively easily, delivering marked emission reductions. Added benefits include improved nutrient use efficiency and reduced environmental pollution.
Modifying manures

Researchers examined a number of practices for modifying manures with the potential to reduce emissions.

Sorbers

Sorbers (insoluble materials or mixtures of materials used to recover liquids), when incorporated into livestock manures for application to soils, have the potential to reduce emissions. Researchers examined several promising sorbers, including vermiculite and bentonite, and found that:

- vermiculite tended to be the most efficient sorber
- sorbers can substantially decrease emissions (notably, nitrous oxide and ammonia) by up to 60 per cent and potentially reduce the need for conventional fertiliser
- in sodosol soils, both vermiculite and bentonite are very effective (up to 80 per cent) in decreasing nitrous oxide and ammonia emissions
- reductions in nitrous oxide emissions from manure applied to vertosol soils approached 60 per cent
- sorbers can potentially improve plant growth (up to 20 per cent) and boost carbon retention in the soil by about 50 per cent.

The research concluded that a sorber-based approach has the potential to be developed into a technology to mitigate manure emissions. In addition, significant productivity gains and a reduction in the use of conventional fertilisers are possible when sorbers are incorporated into livestock manures as they are being applied to soils. This is because significant amounts of the nitrogen derived from nitrous oxide is retained and used for plant growth.
Composting

Researchers investigated the potential to reduce emissions by composting rather than stockpiling animal manures, and by using composted rather than raw manures. The work examined manure from the intensive dairy, feedlot (beef), pork and layer chicken industries. It was found that:

- composted manure reduced nitrous oxide emissions by up to 45 per cent (when applied at rates designed to match plant demand)
- application of synthetic fertiliser could be reduced by up to 38 per cent without a yield penalty
- composting of feedlot manure reduced emissions 20-fold compared with stockpiling, though composting emissions were higher in the chicken, pork and dairy manures
- aerated composting can result in higher emissions than passive (windrow) composting
- while composting of manures does not consistently reduce emissions compared with stockpiling, applying composted instead of raw manures to the field did reduce emissions.

Blending chicken manure and sawdust for composting trials

Anaerobic treatment

Researchers extended earlier findings to develop new practices to prevent emissions during collection, storage and land application of manure products. This work allowed scientists to develop an anaerobic processing and nutrient recovery technology for chicken layer manure and spent piggery litter manure—a viable technology option for processing solid manure into clean biogas energy and renewable fertiliser.
Manure management in pork production

Conventional piggeries manage waste by collecting and storing manure in uncovered ponds. For these systems, the vast majority of emissions are methane (from the anaerobic decomposition of organic matter).

Researchers compared conventional piggeries using a long (greater than 200 days) retention time treatment pond (the main system in Australia) with short (less than 30 days) pond systems or deep litter housing. It was found that:

- use of the short treatment pond system reduced total emissions by up to 87 per cent
- use of a deep litter system reduced emissions by up to 85 per cent.

These investigations provided substantial new data that could be used to refine the National Accounts Inventory and the modelling used in the Emissions Reduction Fund method for the destruction of methane from covered anaerobic ponds. More refined modelling could provide confidence that some baseline data can be modelled rather than measured, which could reduce the compliance costs for participating in the Emissions Reduction Fund.

Manure management in egg and chicken meat production

Researchers examined ways to estimate emissions from the chicken meat and layer hen industries based on changed feeding or manure management. The research found:

- emissions for Australian chicken meat production were eight times lower than the values currently estimated by the Australian National Greenhouse Accounts
- for both meat chicken and layer hens, baseline emissions were low, supporting the possibility of revising the Australian inventory factors
- in layer hen systems, there is the potential to reduce emissions by up to 88 per cent by covering stockpiled manure removed from the sheds (particularly during the early period after the establishment of the stockpile)

The results justified the further development and validation of the current predictive models available to the Australian poultry industries.

More information

More information on the research to reduce emissions from manure is available at:

Reducing nitrous oxide emissions

Nitrogen is a critical element for plant growth and reproduction. Australian soils are often nitrogen deficient. As a result, nitrogen is increasingly added through fertiliser. While the complex nitrogen cycle (Figure 1) converts nitrogen fertiliser to provide ammonium and nitrate for plant consumption, the cycle also leads to gaseous losses of nitrous oxide and di-nitrogen gas (not a greenhouse gas).

The biochemistry of nitrogen transformation

Nitrous oxide is produced naturally in soils through the microbiological processes of nitrification and denitrification (Figure 1).

**Nitrification** – Aerobic oxidation of nitrogen by soil microbes that leak nitrous oxide ($\text{N}_2\text{O}$) into the soil and to the atmosphere during the mineralisation process that produces nitrate:

- organic nitrogen $\rightarrow$ ammonium ($\text{NH}_4^+$) $\rightarrow$ nitrite $\rightarrow$ nitrate ($\text{NO}_3^-$)

**Denitrification** – Anaerobic reduction of nitrate to di-nitrogen ($\text{N}_2$) gas by soil microbes, which produces $\text{N}_2\text{O}$ gas as a by-product: nitrate $\rightarrow$ nitrite $\rightarrow$ nitric oxide $\rightarrow$ nitrous oxide $\rightarrow$ di-nitrogen

Denitrification is normally the dominant process (compared with nitrification) in terms of the amount of $\text{N}_2\text{O}$ lost to the atmosphere from agricultural soils. The main factors controlling denitrification are:

- the availability of inorganic N in the soil;
- the availability of soil carbon as an energy source for microbes; and
- the oxygen available in soil (low when soils are saturated and pore spaces are filled by water).
Nitrous oxide is 298 times more potent than carbon dioxide at warming the atmosphere. It remains in the atmosphere for an average of 114 years before being removed or destroyed through chemical reactions. Agriculture accounts for about 57 per cent of human-induced nitrous oxide emissions.

Nitrous oxide is an important indicator of economically significant losses of nitrogen to the atmosphere. Nitrogen is a prerequisite for profitable crop and pasture productivity. Increasing the efficiency of nitrogen in agricultural production systems can provide substantial cost savings and improved profit for farmers.

Soil conditions largely determine whether high-nitrogen materials are transformed into nutrients available for plant growth or lost as nitrous oxide or di-nitrogen gas, or through deep drainage. Warm, wet soils with a relatively high organic matter content favours nitrous oxide production.

Researchers have identified treatments that can be applied to production systems to lower nitrous oxide emissions and/or increase the efficient use of nitrogen, including:

- careful matching of applied nitrogen to the actual nitrogen needs in some agricultural systems, which could reduce annual nitrogen losses by up to 80 per cent
- irrigating more frequently with smaller application amounts can increase both nitrogen and water use efficiency
- vegetable growers minimising nitrogen loss through leaching, nitrous oxide emissions and ammonia by applying an inhibitor or incorporating manure before sowing or transplanting
- making modest changes in fertiliser management practices, which are likely to increase annual profitability of winter and some summer crops in eastern Australia by up to $6 million.

Nitrous oxide research funded under Round 1 of the programme was grouped into the National Agriculture Nitrous Oxide Research Program (NANORP), coordinated by the Grains Research and Development Corporation. NANORP has substantially improved the understanding of soil nitrogen processes under Australian conditions.

**Nitrification inhibitors**

Nitrification inhibitors (or stabilised fertiliser treatments) are chemicals which slow down or delay the biological conversion of applied nitrogen fertiliser compounds to nitrate. Delaying this conversion ensures that more nitrogen remains available to the crop for longer, without the risk of losses through leaching or denitrification.

A caveat on the inhibitor research is that the impact of an inhibitor on nitrogen losses was measured only as a change in nitrous oxide emissions. In reality, large amounts of soil nitrogen can be lost as di-nitrogen gas when conditions are right. This could mean that the inhibitors tested were more effective than the results might suggest, and that the lack of effects on residual soil nitrogen, crop yield and the amount of nitrogen fertiliser required to achieve a given yield were due to non-nitrous oxide losses.
Dimethylpyrazole phosphate (DMPP)

The inhibitor DMPP reduced nitrous oxide emissions in all examined production systems. For example, in intensive dairy production systems in southern Victoria, DMPP-coated urea reduced nitrous oxide emissions by up to 50 per cent. Fertiliser cost savings for intensive dairy production was estimated to be more than $150 per hectare per year. This indicates potential savings in nitrogen fertiliser for the dairy industry (500 farms with average pasture area of 60 hectares) of $4.5 million per year.

DMPP had more variable impacts on ammonia loss from manures and urea in testing at different dairy pasture and vegetable production sites. Productivity benefits were only seen in a subtropical dairy pasture, most likely due to the low background mineral nitrogen levels. In vegetable systems, the high background mineral nitrogen levels and inputs masked any potential nitrogen savings from using DMPP. This highlights that many intensive vegetable production systems are operating with nitrogen input levels well in excess of what is required by the crop. Practices that reduce excessive nitrogen inputs in these systems will have significant economic and environmental benefits.

n-Butyl thiophosphoric triamide (NBPT)

Researchers found that the inhibitor NBPT effectively reduced ammonia loss from dairy pastures in both temperate (by 45 to 56 per cent) and subtropical (40 per cent) regions.

In separate work comparing DMPP with NBTP researchers found that, while DMPP-coated urea applied to pasture showed a 50 to 55 per cent reduction in nitrous oxide emissions, NBTP-coated urea did not reduce nitrous oxide emissions (nor did the use of an alternative nitrogen fertiliser, urea ammonium nitrate).

Nitrapyrin

Researchers evaluated nitrapyrin in high-rainfall dairy sites in south-western Victoria for nitrous oxide mitigation options for urine, dung deposition and nitrogen fertiliser use. The work confirmed that nitrapyrin was effective at reducing nitrous oxide emissions from urine by up to 25 per cent.

Inhibitor performance against a range of soils

A variety of nitrification inhibitors were tested against 30 soils from across Australia in a laboratory study. An average 39 per cent reduction in nitrification and 60 per cent reduction in net nitrous oxide emissions were observed.

The organic carbon content and temperature of the soil had a significant impact on the nitrification inhibitors’ effectiveness, with generally less inhibition in soils with higher organic carbon content or temperatures.
Case study: the Australian vegetable industry

Demonstration vegetable production sites across three states were used to trial nitrous oxide emissions reduction techniques using nitrification inhibitors. Researchers determined that nitrous oxide mitigation strategies need to target post-harvest emissions (the highest emissions were measured in the post-harvest fallow period). The work showed that by improving timing of manure application and by using inhibitors on manures, growers can reduce nitrous oxide emissions by up to 70 per cent without any loss in productivity in vegetable crop production.

In some cases the results also demonstrated that at least one fertiliser application could be dropped due to improved nitrogen efficiency. This would save fertiliser costs, fuel costs and labour costs estimated at more than $500 per hectare.

The research also determined new nitrous oxide emission factors for the Australian vegetable industry under a number of different cropping practices and regions.

 Trials used manual and automated chambers to collect emissions data
Ian Porter
Efficient use of fertilisers

Fertiliser use typically represents a large portion of the crop’s variable costs, which can be a major determinant of a farm’s profitability and productivity.

Researchers confirmed that annual nitrous oxide emissions of Australian agricultural soils are highly variable. Nitrogen isotope studies also confirmed that nitrogen use efficiency in Australian agricultural systems is low, with consistently high losses of applied nitrogen including:

- 20 to 50 per cent lost in the cracking clay soils (vertosols) of the northern grains region
- 20 to 40 per cent lost in the high-rainfall zone grains region of southern Victoria
- 20 to 40 per cent lost in the Wimmera region of the southern grains zone
- 12 to 45 per cent lost from grain sorghum in New South Wales
- 40 per cent lost from subtropical dairy systems.

The findings also indicated that the fertiliser-induced emission factors (the proportion of added nitrogen lost as nitrous oxide) could range from 0.1 per cent to 7 per cent.

Case study: grain growing soils

Researchers confirmed that total nitrous oxide emissions for grain growing continues to be at the low end of the scale in the western grains region and is modest relative to values reported for other cropping systems in Australia and overseas.

The greatest risk of nitrogen loss from nitrous oxide emissions occurred in response to summer/autumn rainfall events between crop growing seasons when the soils were fallow and in response to soil wetting following summer/autumn rainfall.

The work also suggested that modest changes to the current nitrogen fertiliser regime for winter crops in the high-rainfall zone of southern Victoria and the Wimmera and summer crops in the northern grains region (by reducing some treatments to better match the actual nitrogen needs of the crops) could increase profitability in the eastern grains zone by $6.2 million per year.

Free draining sandy soils

Researchers found that increasing soil carbon marginally increases nitrous oxide emissions. This is counterbalanced by a reduction in the amount of fertiliser required to meet crop needs and a potential reduction in total nitrous oxide emissions. The fertilising effect of organic matter resulted in increased grain yield in two successive years by up to 40 per cent, even when rainfall was below average.
Coarse textured semi-arid soils

Nitrous oxide emissions from grain cropping are low and may be negated by soil methane uptake (methane is a potent greenhouse gas). Similar observations are evident in the semi-arid southern grains region of New South Wales.

Cracking clay and well-drained clay-loam soils

Alkaline cracking clay soils (vertosols) have a higher potential for gaseous nitrogen loss (40 to 50 per cent) than free-draining clay-loam soils (ferrosols). Even though both these soil types have similar amounts of clay (about 55 per cent), the shrink/swell characteristics of vertosols restrict water movement compared with the ferrosols, which promotes significant losses of nitrogen (as nitrous oxide and di-nitrogen gas) following surface sealing and saturation.

Researchers also confirmed that increasing soil carbon and nitrogen stores by decreasing the frequency of cropping and increasing the frequency of legume or grass pastures is an effective nitrous oxide reduction strategy that has minimal impact on productivity in the rain-fed subtropics.

Case study: perennial tree crops (apples and cherries)

Nitrous oxide emissions were investigated from intensive cherry and apple production in two key growing regions (Huon Valley, Tasmania and central western New South Wales).

Researchers found that nitrous oxide emissions in deciduous tree crops were among the lowest recorded for Australian agriculture. This was likely due to the low rates of nitrogen fertiliser, cool temperature growing conditions and highly efficient drip irrigation systems. This means there is little scope for the use of nitrification inhibitors in orchard production systems. Optimising nutrient use efficiency with improved drainage and a reduction in soil compaction in the inter-row will facilitate further mitigation of nitrous oxide emissions.

The work also demonstrated that existing practices for orchards (at the sites trialled) is sufficient to achieve good fruit quality outcomes while keeping nitrous oxide emissions to a minimum. Improvements can likely still be made in nitrogen uptake efficiency through more effective delivery of nitrogen (matching the nitrogen fertiliser rate to the removed nitrogen from cropping). Timing of nitrogen application should coincide with greatest root growth, which commences around four weeks after bud burst. To avoid leaching of applied nitrogen, fertigation should be staggered with a break of up to one week between fertigation events.
Emission reduction through use of weather forecasts

Farmers have long been advised to avoid applying nitrogen fertiliser on moist soils before heavy rain. However, farmers in dryland agriculture (and often in irrigated situations) are eager for some rain after topdressing crops and pasture with nitrogen fertiliser.

Researchers examined the use of weather forecasts to adjust the timing, and in some cases the rate, of fertiliser application. This focused on management of fertiliser based on the water content of the top 15 centimetres of soil. Scientists worked with farmers and farmer groups at five sites, representing a range of industries, soils, nitrogen fertiliser rates and climates.

The work developed a framework for using climate forecasts out to 6 weeks to guide nitrogen fertiliser decisions in farming systems.

Emissions from irrigation water

Irrigation water can contain significant concentrations of nitrate and dissolved nitrous oxide. The irrigation water itself, as well as the sediments deposited in the channels and canals of the irrigation system, may be sources of nitrous oxide emissions.

Researchers confirmed that the key cause of these indirect emissions is the loading of tail water with nitrogen sourced from the fields. To limit emissions, run-off needs to be reduced in furrow irrigated systems and/or the nitrogen loading should be eliminated. Researchers also confirmed that rapid reuse of nitrogen-rich tail water (reducing nitrogen loss through run-off) and improving water and nitrogen use efficiency are potential methods to reduce nitrogen losses.

The work has also developed a more comprehensive and accurate understanding of the nitrous oxide emissions from irrigated cotton farms and more generally flood irrigated agricultural systems in the semi-arid zone. Estimates of nitrous oxide emissions from the surface waters of a cotton irrigation network are now possible.

Modified biochar—a new low emission fertiliser

Researchers have developed a nitrogen fertiliser based on slow release of ammonium from modified activated charcoal (biochar). This slow release fertiliser not only produces low emissions of nitrous oxide, it is also a soil remediation agent and a means of increasing soil carbon.

Researchers prepared a range of biochar samples in the presence of clay, a source of iron and a source of nitrogen from a range of different biomass starting materials. These studies allowed scientists to optimise the conditions (including temperature and timing of the addition of the nitrogen source) to ensure a significant uptake of the nitrogen onto the biochar surface.

Researchers confirmed that this material provides nitrogen to plants while lowering nitrous oxide and ammonia emissions from the soil. The work also clarified the mechanism by which nitrogen modified biochar inhibits nitrous oxide emissions.

Steps have been taken to establish a commercial venture based on the production of these materials, with the intent of using them as a fertiliser as well as an environmental remediation agent.
New measurement tools

Successfully reducing nitrous oxide emissions from agricultural soils often depends on identifying soils that will respond to an emissions reduction strategy. A method to rapidly and easily identify such soils was needed.

Researchers confirmed that it is now possible to rapidly and inexpensively measure the active carbon fraction in a field using a handheld colorimeter. The work also confirmed that the active carbon fraction of a soil is an indicator of its nitrous oxide loss potential. This provides a rapid test for measuring field scale emissions of nitrous oxide.

Other innovations include:

- micrometeorological techniques to measure ammonia gas being released from soils
- tracking the fate of nitrogen added as fertiliser using nitrogen isotopes.

The improved measurements also led to reductions in the emission factors used by the National Greenhouse Gas Inventory for most land use categories (except sugar cane), with a consequent decrease of up to 21 per cent in the contribution of nitrogen fertilisers to Australia’s nitrous oxide emissions account.

The potential also exists in cotton and the non-irrigated high-rainfall cropping to use more tailored emission factors that recognise that outputs are not always directly proportional to the inputs. An abatement method for reducing nitrous oxide emissions in cotton has been developed, which is detailed on the Clean Energy Regulator’s website.

New datasets

Novel automated technology was used to continuously measure key soil emissions—nitrous oxide, carbon dioxide and methane—at field sites focused on reducing nitrous oxide emissions. This technology provided essential new data for industries, farmers and farm advisers seeking practical ways to improve nitrogen management.

Sixty-six complete datasets of total nitrous oxide-nitrogen emissions and ancillary productivity data were assembled. This represents a unique database, derived from automated, continuous recording systems located in a wide diversity of climates, industries, land uses, management options and soils. Final datasets were uploaded into a repository on the N2O Network website.

The automated chamber data from various nitrous oxide study sites also suggested that methane uptake (which potentially offsets nitrous oxide emissions) is significant in most arable soils. This observation is particularly significant in the low-rainfall, non-irrigated cropping environment. These observations may have international significance because of the contribution of the semi-arid cropping regions globally to greenhouse gas emissions and climate change.
Modelling

Researchers tested a number of assumptions needed to simulate and model nitrogen to correct shortfalls in existing modelling capacity. These included:

- the proportion of nitrogen in nitrites and nitrates (from the bacterial conversion of ammonium compounds) emitted as nitrous oxide—researchers confirmed that this proportion is not constant as assumed in many models; rather, it changes significantly at high temperatures

- understanding the non-biological processes that influence the ratio of di-nitrogen gas to nitrous oxide, a critical parameter in all simulation models—researchers found that di-nitrogen losses from saturated subsoils may be a significant component of the total nitrogen lost from agricultural systems. After a single soil saturation event at three subtropical dairy sites, 76 to 97 per cent of the total gaseous losses of nitrogen over 21 days were attributed to di-nitrogen rather than nitrous oxide

- confirming nitrification rates for soils—the amount of nitrous oxide lost via the nitrification pathway under aerobic conditions needed to be quantified. Researchers demonstrated that the contribution of nitrification to nitrous oxide emissions under aerobic conditions is likely to be small.

The scientists also made advances in the simulation of nitrous oxide emissions in crop production. This has the potential to increase the accuracy of the models used in Australia.

More information

More information on research to reduce nitrous oxide emissions is available at:


National Agricultural Nitrous Oxide Emissions Research in Australia

N2O Network [n2o.net.au](http://n2o.net.au)
Case study: grain modelling

Researchers used models to simulate yields and nitrous oxide emissions for a broad range of crops and treatments at diverse sites in the northern and southern grains regions. The simulations demonstrated the value of a legume phase in a cereal-based crop rotation for both productivity and nitrous oxide reductions. Researchers concluded that introducing legumes in grain-based cropping systems could reduce synthetic nitrogen inputs to near zero without having a negative impact on cereal yield and greatly reducing nitrous oxide emissions.

Case study: sugarcane modelling

Simulations were used to explore the sensitivity of nitrous oxide emissions, yield, emissions intensity and nitrogen use efficiency in six sugarcane-growing regions. In all cases yields, nitrous oxide emissions and emissions intensity increased with increasing nitrogen fertiliser inputs. Growing a legume break crop in the fallow increased yields at lower nitrogen rates. Legume fallow also increased nitrous oxide emissions (and intensities) compared with bare fallows because legume crop residues contributed to soil nitrogen stores.

Simulations also showed that splitting nitrogen fertiliser applications generally reduced nitrous oxide emissions (by an average of 18 per cent) and emission intensities (17 per cent) compared with a single nitrogen application.

Modelling confirmed that, on a seasonal basis, when elevated rainfall events are forecast immediately after the fertilisation period, applying urea coated with a nitrification inhibitor can lead to substantial nitrous oxide emission reductions and yield gain.

Modelling also indicated that including a soybean fallow in the crop rotation is the most successful nitrogen management strategy to reduce the fertiliser nitrogen requirement of a cane crop and limit nitrous oxide emissions without compromising yields.
Case study: dairy modelling

Simulations showed that dairy pastures in the hot temperate climate zone have the highest nitrous oxide emission potential of the three dairy systems modelled. This is because substantial nitrous oxide losses due to denitrification can occur all year round and are not limited to the wet periods of the year as in subtropical (summer-dominant rainfall) or temperate (winter-dominant rainfall) environments.

The simulations also indicated that current fertiliser nitrogen rates in temperate regions could be reduced or even halved without resulting in substantial yield penalties. In the long term this nitrogen management strategy would provide substantial cost reductions for farmers.

The dairy systems modelling confirmed that applying nitrification inhibitors in dairy pasture soils is not likely to be an effective practice.
Improved carbon storage

Soil organic carbon is the basis of soil fertility. It releases nutrients for plant growth, promotes the structure, biological and physical health of soil, and is a buffer against harmful substances. Temperature, rainfall, land management, soil nutrition and soil type all influence soil organic carbon levels. If more carbon is stored in the soil as organic carbon, it will reduce the amount present in the atmosphere. The process of storing carbon in soil is often referred to as carbon sequestration.

In Australia, soil carbon levels have dropped by up to half of pre-agricultural levels because of activities such as land clearing, fallowing, cultivation, stubble burning and overgrazing.

Some of the practices that increase soil organic carbon include conservation farming (reducing or eliminating tillage and retaining stubble from previous crops), crop management, maintaining and improving tree/forestry management, grazing management and adding organic materials such as composts and manures. Many management practices that increase soil organic carbon also improve crop and pasture yields.

Researchers have found:

- estimates of soil carbon for regrowth, reforestation and environmental and tagasaste plantings that could potentially expand the existing Emissions Fund Reduction carbon offsets
- increases in crop productivity can result from the application of compost and biochar
- increased understanding of how cropping history affects the extent of soil organic carbon increase when shifting to pasture and reforestation
- enhanced understanding of carbon (and nitrogen) as a component of soil organic matter
- standardised methods for analysing soil organic carbon
- new techniques for field estimation of soil organic carbon that have the potential to reduce sampling and analysis costs.

Soil organic carbon research funded under Round 1 of Filling the Research Gap was part of the National Soil Carbon Program (NSCP), coordinated by the Queensland Department of Science, Information Technology, Innovation and the Arts. The NSCP provided high-level coordination and scientific leadership of the research projects.
Native forest regrowth

Researchers looked at the potential to increase soil carbon through native forest regrowth. The stocks and turnover of soil organic carbon were assessed in regrowth up to 58 years old in previously cleared Queensland rangelands.

Properties that shared similar soil and vegetation, but were managed differently, were sampled for soil carbon. Models explored how climate and management at these properties interacted to influence the rate of carbon turnover. The work found that management effects on soil carbon depended on the local climate and variation in soil type. Factors such as air temperature, soil phosphorus and use of fire had strong effects on soil carbon stocks and turnover.

Findings also indicated that forest clearing and replacement with pasture reduced soil organic carbon stocks by a minimum of 5 tonnes per hectare and up to more than 12 tonnes per hectare on moderately alkaline soil.

The research provided quantified soil organic carbon information that had the potential to inform Emission Reduction Fund determinations, particularly the different ways to compare the directly measured and modelled estimations within a 25-year time frame and a 100-year time frame.
Environmental plantings

Environmental plantings are planted or seeded areas where the vegetation consists of native trees and understorey species that occur naturally in the area.

Researchers sampled above-ground and below-ground biomass and soil carbon at more than 120 environmental planting sites across a number of regions. Although most sequestration is in biomass, soil carbon contributed, on average, 8 per cent of that sequestered and was particularly high in ex-cropping sites.

In addition to improved understanding of soil carbon sequestration following reforestation, the work found that existing models significantly underestimated carbon sequestration in the biomass of environmental plantings. This was particularly prevalent in the below-ground or root components of these plantings, and in plantations established in riparian zones for erosion control or water quality improvement. As a result, predictions of carbon sequestration by environmental plantings will increase in many situations, particularly in riparian zones.
Reforestation

Researchers compared pasture with reforested areas to quantify changes in soil carbon with land use. They found that soil carbon levels had declined when livestock browsed on remnant native vegetation, and that cultivation caused further declines.

The work confirmed that reversing soil carbon decline through reforestation is a slow process; it typically takes more than 15 years for the soil carbon levels to exceed that of pasture. It also confirmed that substantially more carbon is stored in above-ground biomass with tree plantings, compared with pasture or cultivated land uses. Soil sampling techniques for reforestation were also refined.

An economic analysis of the profitability of reforestation projects was also undertaken. The species examined included African mahogany, spotted gum, building material timbers such as pine, and mixed-species environmental plants. This analysis showed borderline returns for growing hardwood species for the building industry, although high-value species such as African mahogany were likely to provide economic returns to the grower. Additional income through carbon credits or alternative sources (such as tourism, as found in north Queensland) was required to provide viable returns for hardwood plantations and amenity plantings.

Other drivers for reforestation include rehabilitation of degraded land, windbreaks for crops, livestock shelterbelts, buffer zones for watercourses and wildlife corridors.
Perennial species in cropping soils

Perennial pastures are important in mixed crop–livestock systems and are valued for providing fodder for livestock, stabilising production particularly in drier or more variable climates, reducing soil erosion, reducing groundwater recharge and for providing benefits to soil biological functioning. Perennial-based systems have a greater carbon sequestration potential associated with root mass.

Researchers identified the most feasible perennial plant options in a range of environments, including the northern Western Australian wheat belt, the South Australian Mallee, and the medium-rainfall cropping zone of south-eastern Australia. Forage shrub species, tagasaste and saltbush, tropical perennial grasses and a small range of temperate herbaceous perennial species including lucerne were examined.

The highest potential for sequestering carbon was found in long-term tagasaste plantations. Tagasaste is a legume with roots that contain nitrogen fixing rhizobium bacteria. Other shrub options such as saltbush may offer opportunities to sequester carbon, mainly in biomass rather than in soil. Perennial pasture options are less effective for sequestering carbon due in part to their faster decomposition rates. Economic analysis, which included the impact of carbon sequestration, also showed that tagasaste could be a viable component of farming systems, particularly on soils of low fertility. This analysis is detailed in the case study: an economic analysis of tagasaste.

The researchers also developed a protocol for identifying carbon contamination in soil samples attributable to coring tube lubricants. This will increase the confidence in using archived soil samples to establish benchmarks to account for changes in soil organic carbon.
Case study: an economic analysis of tagasaste

Tagasaste is commonly grown on deep sands in southern Australia where its large root system can explore the soil volume and access water at depths well below the rooting zone of other agricultural plants. Tagasaste can thrive on soils that are marginal for annual crop and pasture production. Tagasaste also shows the potential to sequester substantial amounts of carbon.

Researchers suggested that if farmers on such landscapes could realise an additional income from emissions abatement by planting their marginal cropping land to a shrub like tagasaste, it would not only be of financial benefit to them (as the economic analysis suggest), but it would also likely lead to better environmental outcomes on more marginal soil types. Researchers investigated the economics of including emissions abatement as a new enterprise within systems where tagasaste is grown on deep sands and grazed by cattle.

The work showed that receiving payments for emissions abatement improved the financial viability of tagasaste plantations for existing cattle-grazing enterprises and provided a new option for farmers without livestock to derive an income from tagasaste. A sensitivity analysis on the carbon price found that, if the carbon price was above $9, both block and wide alley scenarios would receive enough abatement income to pay for the upfront establishment costs of the tagasaste.

Organic soil amendments

Data were collected and analysed from more than 120 organic amendments. These amendments were incubated in a sand matrix with microbes sourced from 200 diverse Australian agricultural soils. This allowed researchers to assess the biological and chemical stability of the organic amendments by measuring their decomposition and carbon dioxide production.

This work provided landholders and agronomists with an extra tool to assess how stable an organic amendment may be when applied to their soil. While the stability of the carbon in organic amendments is of interest to farmers from a carbon sequestration and potential greenhouse gas mitigation perspective, it also provides an idea of how rapidly nutrients contained within organic amendments may be released. This allows farmers to better manage their fertiliser requirements after application of organic amendments, potentially improving nitrogen use efficiency and reducing fertiliser costs.
Case study: organic soil amendments in tropical soils

Researchers assessed how organic soil amendments affected tropical agricultural systems, in particular the use of biochar composted with organic matter. Biochar is the carbon rich product from the high-temperature heating of biomass in the absence of oxygen. It is similar to charcoal, but is produced with the specific purpose of carbon sequestration and as an agricultural amendment.

The work found that:

- soil water content was significantly improved at most sites under most organic amendments
- clay-rich soils showed significant improvement in soil nutrient status and crop yields improved by up to 30 per cent on clay-rich, basalt-derived soils with potential for further improvement over time
- both the short-term and long-term application of biochar/compost improved the resilience of soils, including greater retention of nutrients and water holding capacity
- the organic amendments had comparatively little impact on leaf chemistry at any site
- all amendments containing biochar increased soil carbon, with little evidence of an increase in soil carbon due to compost, except where native carbon stocks were lowest.

The work also showed that carbon dioxide emissions were elevated in organic-amended treatments due to the additional source of easily decomposable carbon in compost. However, this initial pulse only lasted for four to six weeks and was offset by the long-term carbon sequestration in biochar-containing treatments. All organic amendments reduced total nitrous oxide emissions. The highest reductions were seen in the biochar-only treatments.
Region-specific soil management

Western Australia

Researchers examined the influence of farm management and environment in Western Australia on mechanisms driving carbon turnover. When soil clay content is low, critical limitations for accumulation of soil organic carbon exist when average annual temperature is greater than 17.2 °C and rainfall is less than 450 millimetres. As a result, enhanced management of soil organic carbon to mitigate or decrease emissions is challenging for low rainfall dryland farming systems. While restricted in magnitude, there is potential to increase productivity and subsequent accumulation of soil organic carbon (given sufficient time), but short-term responses to any productivity gains are unlikely.

Work was also done to assess the potential to increase soil carbon through practices such as claying, liming and soil inversion. Researchers found that:
- lime application, while important for managing soil acidity and productivity, did not lead to increased soil organic carbon levels even after relatively long time frames
- increasing clay content did increase soil carbon; however, if clay content rose above 30 per cent, the key functional ability of the microbial community to decompose organic matter (such as crop residues) was impeded
- soil inversion (to bury surface organic matter residue) can be used to achieve immediate productivity improvements and redistribution of soil organic carbon, but total soil organic carbon levels in the medium term were unchanged.

Researchers concluded that increasing soil organic carbon levels in the sandy soils of the WA wheatbelt would remain difficult without significant changes to the input of organic materials.

Eastern Australia

Researchers obtained evidence of soil carbon under different management systems in eastern Australia, including Victoria, New South Wales and Queensland. The work found that the effect of management is very small in increasing soil organic carbon.

Conversion of cropland to pasture is the practice with the most potential to increase soil carbon sequestration. However, the consequences of this transition for emissions are uncertain. Differences in the carbon and nitrogen dynamics in cropping and pasture systems, and the introduction of livestock to pasture systems, mean that nitrous oxide and methane emissions need to be considered along with soil carbon.

Other findings included:
- long-term cropping reduced both carbon stocks and the productive capacity of the soil through fertility and soil structure decline
- stubble retention and minimum tillage did not increase soil carbon
- inclusion of legumes in rotations with grain crops reduced soil carbon losses and increased soil nitrogen in some instances but not in others
- intensification of pasture systems to raise productivity and conversion of Victorian native grassland sites to agriculture were observed to maintain or increase soil carbon levels.
Southern Australia

In the medium to low-rainfall regions of southern Australia, the productivity of crops and pastures can be constrained by the soil’s chemical properties, which may limit the ability of farming systems to accumulate and retain organic carbon. Soils in this region are predominantly alkaline, frequently sodic and many have high concentrations of carbonate salts.

Poor productivity (around 50 to 60 per cent of potential yield) on sodic alkaline soils often limits carbon inputs. The work demonstrated the feasibility of lowering alkalinity by using gypsum, and also identified threshold alkalinity values where gypsum would be most beneficial.

Researchers also confirmed that variation in soil organic carbon among different farming systems was only significant where there was frequent cultivation, or where there was intensive grazing within the system. In no-till and reduced-till systems, there was no significant difference in soil organic carbon concentration or soil carbon stocks. This suggests that a potential way to improve carbon stocks in intensive cropping systems is to simply increase overall biomass production.

The frequency of water-soluble aluminium in highly alkaline soils also suggests this may be an important soil constraint in these soils. Developing crop and pasture varieties with a greater aluminium tolerance may contribute to productivity improvements and greater inputs of carbon to these soils.
Managing grazing pressure

Total grazing pressure (TGP)—or the combination of domestic, native and feral herbivores—is a substantial risk factor for reduced ground cover and soil erosion.

Researchers examined the effects of the management of TGP in southern Australian rangelands. The work found that management involving exclusion fencing (when TGP is high) and rotational grazing had clear benefits, such as plant diversity, ground cover and soil carbon, as well as positive production outcomes. This work also suggested that, after accounting for infrastructure costs associated with fencing or water management, comparable (or even increased) stocking rates can be achieved under rotational grazing compared with conservative continuous stocking.

The results also suggest that, to avoid soil carbon losses by reducing erosion in rangelands, grazing management may be useful. Despite the small quantities of soil carbon in these areas, the extensive areas covered by rangelands represent considerable mitigation potential for altered grazing management to reduce soil loss through wind and water erosion.

The information from this work also provided a benchmark for soil organic carbon values for southern Australian rangelands.

Rotational grazing on native perennial vegetation

In low-rainfall to medium-rainfall zones, rotational grazing of perennial native grasses is often seen as a way to improve the productivity and sustainability of pasture systems by allowing vegetation to recover after short intense grazing periods. Researchers sought to assess whether soil organic carbon stocks increased under rotationally grazed paddocks relative to typical set-stocked paddocks.

Researchers found that, while a switch from continuous to rotational grazing does have production and biodiversity benefits, there does not appear to be much soil carbon benefit, at least in the short to medium term (less than 15 years).
Tillage and crop residue retention

Agricultural management practices, such as residue retention and no-till, are promoted as capable of offsetting greenhouse gas emissions because of their ability to store carbon in soils, as well as reduce soil loss through wind and water erosion and improve plant available water capacity. Researchers used isotopically labelled residues to gain insight into the contribution of above-ground carbon input to soil carbon stocks and their effect on emissions.

Researchers designed different treatments to mimic agricultural practices such as tillage and crop residue retention. This work showed that increasing carbon input on the surface (such as through residue retention) acts to prime existing soil organic matter (by increasing microbial activity and hence the decomposition rate), which may negate any intended carbon benefit. Increasing carbon input on the surface can actually lead to increases in net emissions over the first 12 months.

The work also provided a unique dataset that takes into account the effect of above-ground carbon inputs on changes in carbon stocks. It quantifies poorly understood processes (that is, the rate of movement of above-ground carbon and nitrogen and stabilisation rates in the mineral soil) and how carbon sequestration is affected by temperature, precipitation and soil type. These data also supported improvements to existing models to increase the accuracy in the way carbon/nitrogen transfers from the surface are represented. This will lead to more accurate predictions of soil carbon stock and carbon dioxide losses when changes to management practices are made.
New measurement tools

Current methods of measuring soil organic carbon levels in a specific farm’s soil are time-consuming, labour intensive and costly. They rely on repetitive sample collection and off-site lab analysis. Researchers have examined a number of new approaches to obtaining such measurements.

Improved trend sampling

Researchers investigated how soil should be sampled to optimise the measurement of soil carbon levels over time. Before this work, it was difficult to understand the basis on which people were claiming to have sequestered a particular amount of carbon in their soils. Basing carbon accounting payments on only a few measurements over time could produce results that do not reflect the true trend. Researchers confirmed that, as more measurements of soil carbon levels are taken over time, a better estimate of the trend can emerge.

Easier measurements

Researchers have developed techniques to rapidly and routinely measure numerous soil properties at a low cost. This involved a one-year, proof-of-concept study to assess the ability of visible and near infra-red (NIR) spectroscopy to measure the fraction of carbon in soil. Unlike mid infra-red spectroscopy, field portable instruments are readily available, there is less sample processing and no need to grind the samples, which are less sensitive to moisture.

An Australian soil carbon library of spectra using this technique was also established. This measured variations in soil organic carbon levels and composition under different agricultural management practices in important Australian agricultural regions.

Remote sensing

Researchers investigated a cost-efficient method to measure rangeland soil organic carbon content and composition using satellite data and field-based spectrometry. The work covered 65 000 hectares of central Australian rangeland across two properties.

The research confirmed a relationship between soil organic carbon content and reflectance of the soil in the visible near infra-red spectral range. Researchers were able to demonstrate the capacity to use on-site spectra combined with satellite data to calibrate a model for predicting soil organic carbon with reasonable accuracy. The generation of soil organic carbon spatial map data for each study area gave a promising outlook for applying remote sensing data as a proxy for soil carbon.
**Better use of existing national soil mapping**

On-farm and farm-scale quantification of soil organic carbon stocks is usually a costly and time-consuming exercise. Researchers have developed a more effective approach for landholders to derive farm-scale estimates of soil organic carbon stocks.

The work confirmed that the existing nationally calibrated model of soil carbon (as used for national accounting purposes) was not specific enough for use on an individual farm. However, scientists were able to develop a technique to downscale (to an individual farm or region) the national model, such as the mapping in Figure 2. This provided fine-scale variations of soil organic carbon from relatively coarse or generalised data. This fine-scaled information was then used as a guide to support and inform the efficient sampling of soil.

This means the density of soil sampling required can be reduced while still providing the information required to develop accurate farm-scale estimates. This is both more efficient and cost effective than has previously been possible.

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**FIGURE 2** National mapping of soil carbon stocks (a) and downscaled mapping (b)

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**More information**

More information on research to improve soil carbon is available at:


Whole-farm systems

Whole-farm systems analysis, using a range of modelling and decision support tools, allows a realistic understanding and full accounting of the complex interactions of a new technology or management practice at a farm system level.

Livestock industry modelling

Researchers conducted whole-farm systems analyses of a range of greenhouse gas emissions reduction and carbon sequestration strategies for the dairy, sheep and beef industries. The strategies included many of the strategies developed through other projects such as environmental plantings, nitrogen use efficiency, dairy, ewe and beef herd fertility, novel forages, milking frequency, soil carbon and fertiliser application technology.

Across the studies there were examples where both emissions reductions and productivity gains could be achieved (such as introducing legumes to beef and sheep systems). However, in most of the analyses conducted, reducing emissions to gain income from carbon credits was not the most profitable strategy for the farm. Better strategies were often those focused on reducing overall emissions intensity (average emissions per animal), which in turn increased productivity or profitability.

Two carbon neutral grazing systems were also modelled using real farm case studies. The results demonstrated that a livestock farm can be productive, profitable and carbon neutral by planting trees while increasing production on the balance of the land. Another case study showed that, although environmental plantings were not profitable if productive land was set aside, if these plantings could provide shade and shelter that reduced heat stress and lamb mortality this would more than cover the cost of establishment.

Some of the modelling studies undertaken include:

- carbon offset options for beef production systems in central Queensland
- early mating of dairy heifers in subtropical Australia
- carbon neutral wool growing in south-eastern Australia
- using cotton and canola by-products for mitigating emissions
- lifecycle assessment of beef cattle herds in northern Australia
- smart nitrogen technology to reduce nitrogen fertiliser inputs on dairy farms
- using leucaena to improving emissions intensities of subtropical and tropical beef systems
• soil carbon benefits in grazing systems
• feeding nitrates to beef cattle in northern Australia
• impacts of greater lifetime production on emissions and profitability in dairy and wool
• using birdsfoot trefoil (*Lotus corniculatus*) to reduce methane emissions and increase production on wool and lamb farms
• effects of ewe fertility on whole-farm productivity, profitability and emissions
• improving animal nitrogen use efficiency and reducing nitrous oxide emissions on dairy farms
• effects of flock and genetic management options on emissions, emissions intensity and farm profitability of wool
• influence of 3-in-2 milking frequency on dairy emissions
• effects of genetic and pasture-base adaptations to lamb farm production and emissions
• environmental plantings on dairy and lamb properties
• effect of earlier mating and improving fertility on emissions intensity of beef production in a northern Australian herd
• simple carbon offset scenario tool for assessing dairy and sheep farm abatement options.

A key conclusion from the work was that future mitigation research needs to include consideration of profitability impacts of the mitigation interventions. At current carbon prices the offset income alone is insufficient to incentivise the majority of graziers.
Case study: impact of abatement on livestock farmers

Researchers have determined the long-term stocking rates and productivity of livestock farming following implementation of a range of possible methane mitigation strategies. The work has also provided productivity and economic assessments of mitigation strategies to provide producers with an assessment of the economic impact on their enterprise.

Researchers have also successfully modified the existing rumen model that is used in Australia’s leading grazing animal system model (AusFARM) to reflect animal production changes resulting from mitigation strategies. The work has simulated the effects of mitigation on production across 50 years of local climate data.

Australian grain farm modelling

Australian grains farms’ potential to sequester carbon in their soils may not be achieved because practices that maximise soil carbon may either reduce farm profitability or fit poorly within the overall practicalities of farm management. Researchers have developed a comprehensive understanding of how soil carbon sequestration, abatement and farm profitability in grains farms could be affected by a range of farm management systems.

Comprehensive modelling of mitigation and profitability of a wide range of farming systems management scenarios (for example, no till, grain and graze systems, fertiliser management) was undertaken for case study farms, established with farmer groups in major grain growing regions.

More information

More information on research using whole-farm systems modelling is available at:

Carbon Farming Futures: agriculture.gov.au/ag-farm-food/climatechange/carbonfarmingfutures/

Primary Industries Climate Challenges Centre: piccc.org.au/WFSAM
What the mitigation research means for farmers

Livestock management

Over the past five years, Australian researchers have developed a better understanding of the complex relationship between greenhouse gas emissions and productivity in livestock.

Scientific research has identified options to reduce net emissions, most of which are likely to be attractive to farmers because of the associated productivity improvements. Modelling also confirmed numerous examples where emissions intensity could be reduced profitably, while meeting productivity targets.

Additional information about livestock research to raise productivity and lower emissions includes the industry Farm300 website.
Ruminants generally

On-farm practices to improve reproductive performance, reduce the proportion of reproducing animals in a herd or flock and increasing growth rate of animals for sale will reduce the total amount of feed eaten by the herd or flock that is used for animal maintenance. As improved efficiency in feed use results in a larger animal carrying capacity, methane intensity—or the amount emitted per unit of saleable product—will be reduced.

One of the most effective supplements for reducing methane emissions in livestock is marine red macroalgae. Experiments in cattle and sheep have shown that feeding dried and ground preparations of the species *Asparagopsis taxiformis* reduced emissions by up to 80 per cent. The key barrier to widespread adoption is its high production cost and low availability. If production costs of red algae can be reduced, this practice has the potential to be profitable.

Two bioactive compounds, extracted from native Australian leptospermum and melaleuca plants, have been shown to reduce methane emissions in ruminants by up to 97 per cent in laboratory experiments. The cost of the compounds is difficult to estimate. Both can probably be manufactured, either as supplement or lick-block, and readily fed to cattle or sheep anywhere in Australia because the amounts needed are very low.

Feeding grape marc has been shown to reduce methane emissions in dairy cows, sheep and cattle in feedlots. Although grape marc's potential use is limited, it could be effective and profitable when used as a replacement to low-quality diets, or during feed shortages for sheep in southern Australia.

Cattle

The efficiency of northern Australian beef production systems could be significantly improved through more intensive grazing management, breeding and genetic selection. Such improvements may also lower the emissions intensity of production by having fewer unproductive livestock on the property (that is, cows and heifers that do not have a calf) and reducing the time to achieve market weight. Increasing weaning rates, early mating and cross breeding is a highly profitable strategy for northern beef producers, though additional investment may be required in fencing or watering points to achieve this improvement in management efficiency.

The use of leucaena, a legume fodder crop that grows in tropical and subtropical environments, has been shown to improve productivity and profitability, as well as reduce methane emissions in cattle production systems in northern Australia. Leucaena increased farm production by increasing animals carried and live weight gain, which improved gross margins by up to 37 per cent.

Many cattle producers, particularly in northern Australia, feed non-protein nitrogen to cattle in the form of urea during the dry season to improve pasture consumption and animal productivity. Substituting nitrate for urea can also reduce methane emissions. An abatement method for the use of nitrates has been approved under the Emissions Reduction Fund. However, nitrate is potentially toxic to cattle if it is consumed too quickly. Best management practice guidelines are being developed to help producers feed nitrates to their herd safely.

More information about cattle research to raise productivity and lower emissions is available from the industry More beef from pastures website.
Sheep

Researchers found that the best strategies were those that both sustainably increased production and reduced emissions intensity, such as interventions that shifted the balance of the flock away from adults and towards juveniles while holding average annual stocking rates constant.

Introducing Australian native shrubs with methane-reducing properties alongside pasture species has been shown to be an effective method for reducing emissions from sheep in south-west Australia, while increasing productivity and profitability.

Selecting for high reproductive efficient ewe genotypes has been shown to reduce farm emissions. An economic analysis suggested that high reproducitively efficient ewes may allow producers to increase production and profit, as well as reduce emissions.

Researchers have also developed a sheep Carbon Offset Scenario Tool to explore the influence of various mitigation strategies on greenhouse gas emissions for Australian wool and prime lamb farms. This covers strategies related to diet manipulation, herd and breeding management, feed base management and waste management. This tool is available from the [Greenhouse in Agriculture website](#).

Dairy

Feeding nine kilograms of wheat daily to dairy cows is an effective way to reduce methane emissions and increase milk production. However, producers need to exercise care to ensure they do not feed too much wheat because this can increase the risk of ruminal acidosis.

While the milking cow is the single largest source of on-farm dairy emissions, non-productive cows are one of the key drivers of emissions intensity. The longer heifers take to reach first calving, the greater the emissions intensity of milk production, because they are emitting greenhouse gases without contributing to farm productivity.

Maintaining heifers on high-quality diets, via supplementary feeding during periods of low quality and/or quantity of pastures, results in increased daily live weight gain, lower methane emissions to mating live weight, and earlier calving. Together these factors reduce their lifetime emissions intensity.

Changing from an annual calving system to an extended lactation system on dairy farms was shown to produce lower total emissions and emissions intensity than annual calving and also resulted in higher operating profits.

More information about research to raise productivity and lower emissions in the dairy industry is available at the:

- [Dairying for Tomorrow website](#)
- [Future Ready Dairy Systems website](#).

Researchers have also developed a dairy Carbon Offset Scenario Tool to explore the influence of various mitigation strategies on emissions for Australian dairy farms. They cover strategies on diet manipulation, herd and breeding management, feed base management and waste management. This tool is available from the [Greenhouse in Agriculture website](#).
Nitrogen (fertiliser) and manure management

Farmers may have considerable scope to improve nitrogen management for their crops to reduce losses, increase production and profit and reduce the risk of elevated emissions.

For example, the results from comprehensive field trials suggest that the addition of low emission manures to soil could be a good management practice for increasing organic carbon, nitrogen availability, microbial diversity and resilience in soils as well as improving crop productivity. Applying lower rates of manure to land is the simplest application method for reducing emissions and is not affected by soil or manure type. This mitigation strategy is ideal for farmers who are unable to adopt more expensive and labour intensive options.

The research also confirmed that the release of nitrous oxide emissions from manured applied soils was greatest after a winter rainfall event. The research recommends dry seeding and avoiding applying manure during or shortly after a rainfall event.

In addition, there is potential for significant productivity gains and a reduction in the use of conventional fertilisers when sorbers are incorporated into manures as they are being applied to soils.

Nitrification inhibitors can also be used to mitigate nitrous oxide emissions. However, the lack of reliable productivity benefits from the inhibitors to balance their increased costs, even in predicted high-loss systems, requires improved understanding of the factors that influence their on-farm effectiveness.

Intensive livestock—pigs and poultry

The poultry layer industry has the potential to significantly reduce its emission by covering manure stockpiles.

Composting or pelletising manure is a good mitigation option for larger or mixed enterprises where multiple waste streams are freely available.

Options are being developed to allow solid manure to be processed into clean power and fertilisers to reduce emissions at a sufficiently low cost and low level of technical complexity to enable farmers to readily take it up at farm scale. When compared with alternative technologies such as composting, the anaerobic treatment technology provides incentives for adoption with the production of bioenergy (biogas) and fertiliser outputs, providing new farm income streams.

Grains

In general, soils cropped for many years in low or medium rainfall zones have a low level of organic carbon and this, together with periods of low rainfall and dry conditions in most seasons, leads to generally low levels of gaseous nitrogen losses. Losses as nitrous oxide and their emission factor (the proportion of added nitrogen lost as nitrous oxide) are low in the Australian grains industry by world standards and much lower than those in northern hemisphere grain cropping.

Nevertheless, in some situations emission risk is much higher than normal and farm management practices need to take these into account. This includes during large or prolonged rain events leading to saturation of the topsoil, or when moving from a pasture phase with high soil organic carbon back to a cropping phase with added nitrogen.
Generally, only about 30 per cent of nitrogen available to a crop can be found in the harvested grain. There is considerable scope for grain growers to improve nitrogen management to increase production and profit while also reducing the risk of gaseous losses, including nitrous oxide. Fertiliser application needs to be better matched to soil nitrogen availability and crop needs, and issues such as fertiliser type, amount, timing and placement need to be considered.

**Cotton**

Cotton growers may have considerable scope to improve nitrogen management to reduce losses, increase production and profit and reduce the risk of elevated nitrous oxide emissions.

The aim for cotton growers is to optimise nitrogen fertiliser application. Better matching of nitrogen availability and applications with crop needs, in amount, timing and location will ensure soil nitrogen is readily available when needed by the cotton crop.

Data from trials with grain crops suggest that the new generation of enhanced efficiency fertilisers, with nitrification inhibitors or slow-release coatings, may help increase nitrogen use efficiency in cotton production, especially for crops grown on cracking clay soils (vertosols).

**Horticulture/vegetables**

Intensive vegetable production systems often use a mix of inorganic fertilisers and composted manures to supply nitrogen and maintain soil organic matter under repeated cultivation. Matching nitrogen supply to the changing needs of different crops presents a significant challenge, especially given the size of the initial financial investment in planting the crop.

**Dairy pasture**

Some dairy farmers apply nitrogen at high levels that aim to maximise feed production. Together with high stocking intensities and large amounts of fodder or grain fed to cows, this results in the potential for large inputs of nitrogen per hectare in urine and dung.

Less than 30 per cent of nitrogen inputs into dairy systems are typically returned in animal products, and in some cases only 30 per cent of fertiliser nitrogen is found in pasture biomass. Dairy farmers can potentially improve nitrogen use efficiency and thereby increase production and profit. Scope exists for greater use of periodic soil testing for nitrogen to enable better matching of fertiliser application to actual pasture needs.

**Sugar**

In the sugar industry, high levels of decomposable organic carbon (following trash retention), soil acidity and high levels of nitrogen fertilisation, combined with subtropical to tropical climates and periods of intense summer rainfall, all favour nitrous oxide production.

Some growers apply high levels of nitrogen fertiliser as insurance against nitrogen losses from excessive rainfall, but overall the sugar industry could improve nitrogen management to reduce losses, increase profit, and reduce the risk of nitrous emissions. Matching nitrogen availability and applications with crop needs will ensure soil nitrogen is readily available when an actively growing crop is present to use it.
Soil carbon management

Comparisons between high and low carbon soils shows that the direct farm benefits of high soil carbon on nitrogen mineralisation and associated pasture production are substantial.

Organic amendments increase the stocks of soil carbon and many amendments such as composts and manures are a good source of plant nutrients. Applying these amendments ensures sustainable land use and increased productivity; however, availability is limited, and transport and application costs may be substantial.

Soil amendments such as biochar increase soil organic carbon sequestration significantly, and manures and composts marginally. Consistent yield increases were recorded in field trials from compost and biochar used in combination for sugarcane, banana, maize, papaya and peanut crops in northern Queensland.

In general, land use change from cropping to pasture (especially on marginal lands) improves the long-term productivity of that land. Retention of crop residues and plant matter provides ground cover, which is essential to reduce soil erosion and soil organic carbon loss by water or wind erosion, and contributes to sustainable land use.

Vegetation management for soil organic carbon provides benefits through landscape remediation. These include:

• riparian plantings to improve water quality
• plantings in saline or waterlogged paddocks
• reforestation on degraded lands
• tagasaste plantings to reduce salinity downslopes
• plantings to decrease soil loss via erosion and improve soil physical and chemical properties.

Projects on reforestation, environmental plantings and grazing lands also facilitated superior new soil sampling designs. By improving their understanding of the sampling intensities required, researchers minimised uncertainty in soil carbon estimates.
Adapting to a variable climate

Of the world’s developed nations, Australia is the most exposed to climatic extremes. Australia’s climate will change over the coming decades. Increases in the frequency or intensity of various extreme events in many parts of Australia are likely, including heat waves, droughts, storm surges, floods and bushfires.

Adaptation is the principal way for farmers to respond to a more variable climate. Adaptation presents new challenges for business and policy decision-makers—it will take time to build the skills and knowledge on how best to adapt and for implementation of decisions to make a difference. Adaptation research complements mitigation research (focused on reducing greenhouse gas emissions or sequestering carbon).

Successful adaptation to climate variability requires flexible, risk-based approaches that deal with future uncertainty and strategies that can cope with a range of possible local climate outcomes and variations. This means farmers will need the capacity, confidence, technologies and tools to make business decisions to address climate change at the producer level.

Under this programme researchers have:
• examined systemic and transformative adaptation options
• identified plant and animal traits suitable to changing conditions
• identified and assessed novel technologies and management options
• provided cost-effective tools that enable land managers to adopt practices.

Key findings of the adaptation research are described in this chapter.

Crops in high carbon dioxide conditions

Researchers studied cereal, pulse (legume) and oilseed crops for resilience to heat and drought stress under elevated carbon dioxide conditions. This provided real world, validated measurements of crop water and nitrogen use under elevated carbon dioxide conditions.

This work made use of the unique Free Air CO2 Enrichment (FACE) facilities in Horsham, Victoria, to grow crops under the atmospheric carbon dioxide concentration forecast for by 2050 (40 per cent above 2015 levels). Static heat chambers were imposed over the crops for short (3-day) periods to simulate extreme heat events.
Researchers found that growth, yield and resource use (water and nutrients) all changed significantly under elevated carbon dioxide. Yields can increase due to a carbon dioxide fertilisation effect, but crop nitrogen demand will also increase, potentially leading to nitrogen limitations (where leaf nitrogen and grain protein levels in cereals are generally reduced).

Water use efficiency is also generally increased under elevated carbon dioxide. Results indicate that the risks from water exhaustion are also greater because of the larger crop canopy. This complicates the risk/benefit consideration.

Heat stress in livestock

The occurrence of extreme weather patterns such as high heat is increasing. Extreme heat events mean an increasing incidence of heat stress in livestock. This presents a challenge, especially to intensive farming practices such as dairies and piggeries, which can result in diminished welfare and productivity outcomes.

Heat stress arises when livestock cannot adequately dissipate body heat generated from digestion and metabolism to the environment (Figure 3). Researchers investigated a number of potential adaptations to deal with heat stress.
Dietary additives to reduce heat stress in dairy cows and pigs

Researchers have extended previous work (in sheep), to examine and validate the use of dietary additives to reduce the impact of heat stress on lactating dairy cows and lactating and growing pigs. Researchers confirmed that betaine (an amino acid supplement) improved the recovery of heat stressed dairy cows, resulting in improved milk yield. This has the potential to improve dairy herd health and production during Australian summers.

The work also investigated a proposal that cinnamon could ameliorate symptoms of heat stress by improving insulin sensitivity. However, these theorised effects were not observed by researchers. This was also consistent with physiological observations—cinnamon did not alleviate symptoms of heat stress.

Breeding dairy cattle for improved heat tolerance

For dairy cattle, increased temperature and humidity levels above a certain threshold decrease production of milk and milk proteins, and this loss can be quite substantial. The adverse effect of increased heat stress on fertility, a key trait for dairying profitability, is even more dramatic. Fortunately, the production and fertility of some animals is less affected by heat stress than others, and this response is heritable.

Through widespread heat stress research (Map 1), researchers have developed and validated genomic estimated breeding values for tolerance to heat stress. These heat tolerance breeding values will be released for use by dairy farmers and bull breeding companies through the Australian Dairy Herd Improvement Scheme. This work indicates that significant gains could be made for heat tolerance through selection using these breeding values.

The researchers have also developed an online future scenarios selection tool that allows farmers to balance selection for heat tolerance with selection for other traits, in order to maximise future profits, given projected climate change on their farms through to 2035.
Case studies: sugar cane, fruit trees, viticulture and dairy

Researchers examined a number of specific industries to identify and investigate the range of adaptation practices and tools that could be appropriate.

Sugar cane

Work is underway to develop varieties of sugar cane adapted to a drier and higher carbon dioxide future. Limited water availability, whether due to seasonal, climatic or competing demands, and increasing costs can all reduce sugarcane profitability. Improving crop transpiration efficiency (growth per unit of water used) is one strategy to help address these water issues.

Researchers found that transpiration efficiency measured in a wide range of sugarcane clones varied substantially. Transpiration efficiency itself is not a single simple trait, but is a complex of several underlying mechanisms. Researchers investigated these mechanisms and identified those sub-traitsthat could be selected without negative impact on crop growth rates.

Researchers concluded that targeted improvement of transpiration efficiency in sugarcane breeding would be worthwhile. Results and experience from this work may also provide guidance for breeding other crops with high yields and water use efficiency under future climates, particularly other tropical grass crops like grain sorghum.
Fruit trees

Production of temperate perennial fruit faces unique challenges in adapting to climate change. The permanency and longevity of fruit trees means decisions implemented now will likely persist into new climates. These attributes also constrict flexibility in adaptation options with actions that seem minor, such as changing varieties, requiring substantial investment that can lock a grower into decade long commitments.

Researchers undertook field observation work on the Australian fruit tree industry (specifically apple, pear and cherry) and used this information to inform temperature-based models. The work investigated adaptation lead times to critical tipping points in the perennial fruit tree cycle (Figure 4) for winter chilling, spring frost risk, extreme heat exposure and yield potential.

Differences between growing regions were also evaluated. Physiological data on apple, pear and cherry indicated that flowering in Western Australian sites was noticeably delayed, suggesting a climate warming signal is already present in that region.

Additionally, researchers used modelling of future impacts on key fruit tree physiological processes to confirm that the future incidence of sunburn damage for Royal Gala apple will increase in some of Australia’s warmer growing regions. Simulations show that the risk of damage can be halved in some locations by installing netting.

FIGURE 4 Temperate perennial fruit tree cycle
Researchers also used observational studies to assess the temperature thresholds for sunburn damage in pears. Data showed that damage manifests when fruit surface temperatures exceed approximately 47.1 °C.

The work also sought to more accurately predict flowering timing so that climate change impacts can be forecast with more confidence. Researchers have constructed a flowering model for Pink Lady apple that better explains the observed flowering patterns. It is the first time this more dynamic modelling approach has been applied to apple in the southern hemisphere.

**Viticulture**

Hotter temperatures cause earlier and compressed ripening of grapes. This places a strain on harvesting and winery infrastructure and changes berry chemistry and resulting wine quality.

Researchers investigated the use of delayed pruning to shift grape ripening. The work found that, applied on a rotational basis, delayed pruning can contribute to spreading harvest time with no impact on vine vigour, yields, grape or wine quality. Feedback from industry has been positive, with some producers already using delayed pruning as a tool to manipulate grape ripening.

Scientists also evaluated whether lowering night-time temperature and increasing humidity (through evaporative cooling using sprinkler irrigation) around grapevines could reduce the impact of extreme heat events. The work found that night-time irrigation with sprinklers does not significantly lower vineyard temperature. However, it does improve yield and potential wine quality and reduce the instances of sunburn damage. Researchers concluded that evaporative cooling may have a role in mitigating some of the negative impacts of extreme heat events.
Dairy

Researchers have attempted to identify the impact of a variable climate on all aspects of dairy farming. They identified the vulnerabilities, thresholds and tipping points of a range of dairy farm intensification and de-intensification development scenarios against a number of possible climate futures. Key findings include:

• productivity was not necessarily correlated with profitability
• development scenarios that intensified farm production and led to the highest rate of return in wet decades could have the lowest rates of return in dry decades
• hot dry climates had the greatest negative impacts on pasture utilisation in all regions, regardless of whether farms were irrigated or not
• the detrimental impacts of climate change on profitability may be mitigated or reversed by changing to a new farming system, depending on region and extent of investment required
• intensified farm systems were inherently associated with a greater risk of return
• simplified farm systems that relied more on home-grown feed and less on purchased feeds had much more consistent returns with lower risk over the long term, suggesting that these types of farming systems would be more suited to low-production farms with risk averse managers
• farms relying more on purchased feeds with larger cows, greater herd size and more infrastructure produced more emissions (in line with productivity), but this generally did not increase emissions intensity (emissions per unit milk production) and in some cases reduced emissions intensity.

These findings will assist farmers to be more informed about the development pathways that they choose for their own business. In a more uncertain climate, farmers will be able to plan ahead using this region-specific knowledge.
Novel business structures

Traditionally farms have expanded by using bank loans to finance the purchase of a neighbouring farm. However, given the adverse future climate projected for many agricultural regions in Australia, such expansions have become riskier. Researchers examined other ways to more safely expand farm businesses (focusing on broadacre farming). Case studies of farm expansions (both family and corporate) underpinned by novel management strategies or financing methods were examined. Farm financial simulation modelling was also used to examine where and when non-traditional ways of expanding a farm may have merit.

For corporate businesses that have expanded, climate risk is found to be one of many challenges they face. Other factors often more greatly affect their business performance. Family farms that have expanded using novel financing or novel management strategies, such as using advisory boards, have often enjoyed successful expansions.

Farm financial modelling of some novel joint venture arrangements show they can deliver significant advantages. Under current and projected climates the additional wealth generated by such joint venture partnerships, compared with the traditional local expansion of the farms, was 17 per cent and 18 per cent higher, respectively. A key source of the additional wealth was the risk-spreading benefit of combining geographically distant localities with their different climates and enterprise mixes.

The researchers concluded that as farm businesses continue to expand, joint venture partnerships with other more distant expanding farm businesses should be considered.

Adaptive value chains

Climate variability has significant impacts on the market availability of food and commodities. This affects the viability and resilience of farms and their networks, as well as companies along the supply chain that produce, handle, process and market agrifood products. An adapted value chain is one where participating businesses, from farmers to retailers, are able to harness joint strategies to sustain competitive advantage in a changing climate.

Researchers found that:

• consumers do not understand the impacts of climate variability on their day-to-day lives enough to value adaptation in food so few marketing opportunities are currently possible
• whole-of-chain adaptation is possible and beneficial (as a risk mitigation strategy rather than a marketing opportunity)
• a non-adapted value chain can only continue to exist up to a certain point until climate and weather risk and threats, both direct and indirect, become insurmountable.

Researchers also developed a process which enables business to gauge the merits of an adaptation action against multiple, and potentially competing, priorities. An online adaptive value chains self-evaluation tool was produced to assist businesses apply this process.
Transformative adaptation for extensive farming

Extensive farming (as opposed to intensive farming) uses small inputs of labour, fertilisers and capital relative to the land area being farmed. Researchers investigated options for Australia’s extensive farming systems to maintain or boost profitability and improve resilience in a climate that is becoming increasingly variable. Without any adaptation, researchers observed that current management across the next 30 years could see farm profitability down by an average of 12 per cent and as much as 22 per cent.

A range of options were evaluated, focusing on land managers with grazing and mixed grazing–cropping enterprises. The work included case studies across both rangeland and mixed cropping–grazing and cropping land (Map 2).

MAP 2 Case study locations across Australia for a range of transformative adaptation options
At each case study location, a specific package of adaptation options were aggregated, based on feedback from the local farming community and in line with three broad descriptions:

- **low risk and low return farming options**—includes measures such as increasing the area used for livestock, either by changing the relative areas of existing crop-pasture sequences or the relative length of the crop/pasture phases, and incorporates long fallows, low stocking rates, lower inputs and adoption of more drought tolerant varieties.

- **medium risk and medium return farming options**—includes maintaining the cropping and livestock mix at levels close to baseline, but increasing the rate of inputs. This also incorporates the addition of slightly riskier crop varieties, running livestock at slightly higher rates with greater utilisation of pasture and short fallows introduced into the rotation. Livestock would be traded in years with high pasture supply to further increase pasture utilisation.

- **high risk and high return farming options**—measures such as increasing the area used for cropping well above that of the baseline. This relies on the selection of higher production but less climate resilient crops and greater rates of fertiliser use. This also incorporates much higher stocking and utilisation rates, with the use of short fallows and full weed control to offset soil water losses.

The results show that, generally, the high risk/high return adaptation packages result in improved farm profitability although year-to-year variation was much higher. The high risk/high return strategies are much more responsive and flexible than the other options, allowing greater responsiveness to unfolding climatic conditions. The low risk/low return adaptation options generally resulted in a slow decline in economic returns and a loss of profitability.

Greenhouse gas emissions were, for the most part, higher under all the future scenarios considered and across all farming systems regardless of adaptation options employed. This would suggest that considering an emissions intensity measure may be a more representative measure for future agricultural activities.

The effectiveness of the adaptation options showed significant geographical variation. Rural community adaptive capacity also varied considerably. In particular, the work indicates a much smaller number of effective options available for drier locations and for extensive grazing enterprises as a whole. A broader range of options are available for mixed cropping and grazing enterprises; however, grazing remains a more resilient enterprise across drier locations.

**More information**

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• South East Queensland Catchments
• Southern Cross University
• Southern Farming Systems
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## Glossary

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alley cropping</td>
<td>Planting of trees or shrubs in two or more sets of single or multiple rows with agronomic, horticultural or forage crops cultivated in the alleys between the rows of woody plants.</td>
</tr>
<tr>
<td>Biochar</td>
<td>Charcoal used for agricultural purposes, created by heating biomass in a low oxygen environment.</td>
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<tr>
<td>Denitrification</td>
<td>A natural soil microbial process where nitrate is converted to nitrogen gases (such as nitrous oxide and di-nitrogen) that are lost to the atmosphere.</td>
</tr>
<tr>
<td>Emissions intensity</td>
<td>Emissions per unit of product, such as per animal in a herd.</td>
</tr>
<tr>
<td>Extensive farming</td>
<td>An agricultural production system that uses small inputs of labour, fertilisers and capital, relative to the land area being farmed.</td>
</tr>
<tr>
<td>Ferrosol</td>
<td>A well-drained soil with red or yellow-brown colour with clay-loam to clay textures that is usually associated with previous volcanic activity and is mainly located along the Great Dividing Range.</td>
</tr>
<tr>
<td>Fertigation</td>
<td>Application of dissolved fertilisers or other water-soluble products through an irrigation system.</td>
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<tr>
<td>Forestomach</td>
<td>The first division of the stomach of a ruminant animal, in which most food collects immediately after being swallowed and from which it is later returned to the mouth as cud for thorough chewing.</td>
</tr>
<tr>
<td>Greenhouse gas</td>
<td>A gas (such as carbon dioxide) that absorbs infrared radiation, helping to trap heat in the atmosphere.</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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<tr>
<td>Methane</td>
<td>A colourless, odourless flammable gas that is released during the decomposition of plant or other organic compounds and is a greenhouse gas.</td>
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<tr>
<td>Nitrification</td>
<td>Process by which bacteria in soil and water convert ammonia or ammonium to nitrites and nitrates.</td>
</tr>
<tr>
<td>Nitrification inhibitor</td>
<td>A chemical that slows down or delays the biological conversion of applied nitrogen fertiliser compounds to nitrate.</td>
</tr>
<tr>
<td>Nitrogen cycle</td>
<td>The circulation of nitrogen in nature, consisting of a cycle of chemical reactions in which atmospheric nitrogen is compounded, dissolved in rain, and deposited in the soil, where it is assimilated and metabolised by bacteria and plants, eventually returning to the atmosphere by bacterial decomposition of organic matter.</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>A colourless gas produced naturally in the atmosphere by denitrification and is a greenhouse gas.</td>
</tr>
<tr>
<td>Perennial plant</td>
<td>A plant that lives for more than two years, as distinct from annuals and biennials—generally the top portion of the plant dies back each winter and regrows the following spring.</td>
</tr>
<tr>
<td>Riparian vegetation</td>
<td>Plant habitats along the river margins and banks.</td>
</tr>
<tr>
<td>Rumen</td>
<td>The first stomach of a ruminant from which food is returned to the mouth as cud for thorough chewing and in which cellulose is broken down by the action of microorganisms.</td>
</tr>
<tr>
<td>Ruminant</td>
<td>An animal (such as a cow, sheep or goats) that has more than one stomach and that swallows food and then brings it back up again to continue chewing it.</td>
</tr>
<tr>
<td>Soil amendment</td>
<td>Any material mixed into soil to improve soil physically or chemically, making it more suitable for plant growth.</td>
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<tr>
<td>Soil organic carbon</td>
<td>The amount of carbon stored in the soil is a component of soil organic matter—plant and animal materials in the soil that are in various stages of decay.</td>
</tr>
<tr>
<td>Spectroscopy</td>
<td>The study of the properties of matter by looking at the pattern of absorption and emission of light.</td>
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<tr>
<td>Transpiration efficiency</td>
<td>Plant biomass production per unit of water transpired.</td>
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<tr>
<td>Glossary Term</td>
<td>Definition</td>
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<td>Value chain</td>
<td>The path by which a product or service is created and marketed. In the case of agrifood products, this path might include input suppliers, growers, transport and storage, processors, wholesalers, retailers and consumers, as well as governance and support institutions. Value contribution is also a function of how relationships are managed, how information is shared and used, and how efficiently processes are handled.</td>
</tr>
<tr>
<td>Vertosol</td>
<td>A soil in which there is a high content of expansive clay that forms deep cracks in drier seasons or years.</td>
</tr>
</tbody>
</table>
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