Australia's National Science Agency

Australia's carbon sequestration potential

Summary report

Introduction – setting the scene

See section 1 of *Australia's carbon sequestration potential: Technical report* for further details.

Why carbon sequestration is needed

Permanently removing significant amounts of Greenhouse Gases (GHG) from the atmosphere, combined with ambitious emissions reductions, is the only realistic path for the world to reach the goals of the Paris Agreement (UNFCCC, 2015) and limit the worst impacts of climate change. It is estimated globally that beyond deep decarbonisation, up to 10 gigatonnes of carbon dioxide equivalent (CO_2-e) annually will need to be permanently removed from the atmosphere by 2050, and up to 20 gigatonnes annually of CO_2-e reductions by 2100 (NASEM, 2019).

As part of this global effort Australia has committed to a net GHG emissions reduction target of 43% below 2005 levels by 2030 and net zero emissions by 2050 delivered through decarbonisation and permanent atmospheric carbon dioxide removal. Carbon sequestration is a key component of achieving this target.

Aerial view of rural properties on the Murrumbidgee River, south of Murrumbateman, NSW

This report

This report summarises the findings of a review of current technology options for carbon sequestration. The review is compiled from existing knowledge, literature sources and consultation with subject matter experts. This report presents the overall conclusions of the assessment and summarises the technology assessments. More detail and the assumptions that underpin the estimates can be found in the full technical report.

Key definitions

Emissions types

- **Avoided emissions** refer to deliberate activities that **prevent** carbon from being released into the atmosphere. This reduces the amount of greenhouse gas being added to current levels.
- **Negative emissions** refer to deliberate activities that **remove (and store)** CO_2 from the atmosphere. This directly reduces levels of atmospheric GHGs.

Technical vs economic potential and realisable sequestration

Both technical and economic potential sequestration levels need to be considered when assessing the various technologies:

- **Technical potential sequestration** is the maximum level that is biophysically or technically possible. In general, technical potential is limited only by current climatic and other biophysical capacity or system storage capacity at the current level of technology efficacy.
- **Economic potential sequestration** is the level attainable given current efforts to implement technical and management changes. Economic potential is considered within the context of technological, policy, regulation and social limitations that define the sequestration possibilities.
- **Realisable sequestration** is potentially available once shared resource limitations, availability and other inter-dependencies are considered.

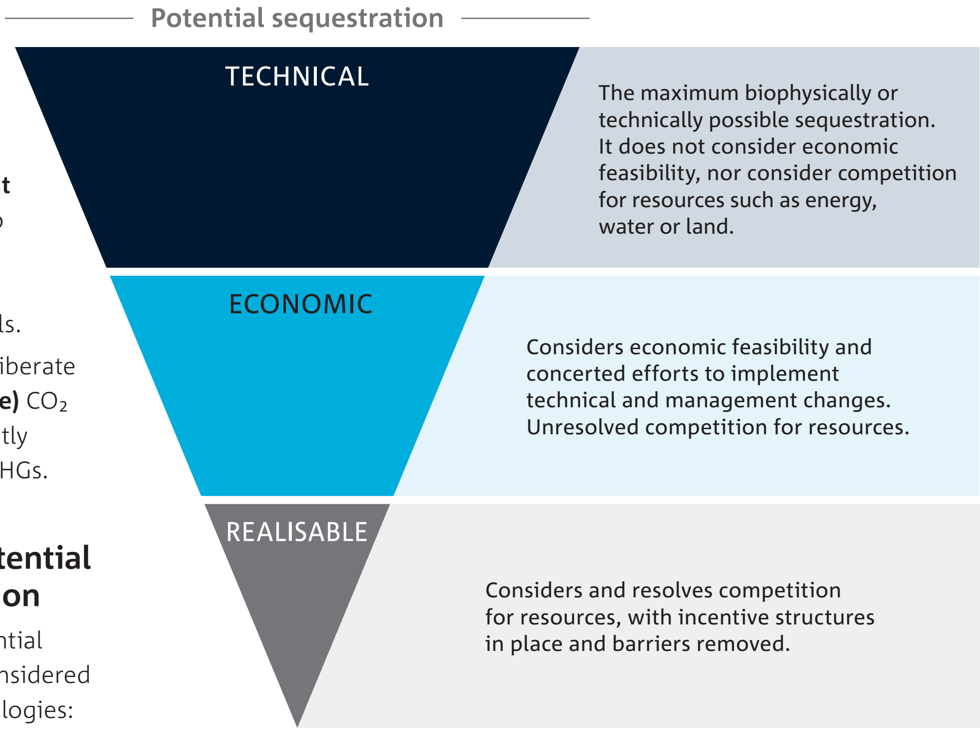


Figure 1. Types of sequestration

Types of sequestration technology

There are 3 approaches to sequestration considered in this report (following Minx et al. 2018):

- **Biological solutions** take advantage of natural biological systems to take up and store atmospheric CO_2 (also known as natural, nature-based or natural-climate solutions). Examples include permanent planting and soil carbon.
- **Engineered solutions** rely on chemistry to capture and store atmospheric CO_2. Examples include mineral carbonation and direct air capture.
- **Hybrid solutions** combine aspects of biological and engineered solutions. Examples include bioenergy carbon capture and storage, which uses biomass to capture carbon and produce energy, and then captures the carbon released and sequesters it in geological stores.

Key findings – results and the way forward

See section 2 of *Australia's carbon sequestration potential: Technical report* for further details.

Technology assessment findings

This review assessed each technology against common criteria, where possible, to explore the technical potential of the technology to contribute to carbon sequestration in Australia. Estimates in this report have been prepared by reviewing the latest literature, consulting experts and synthesising into key findings; these are relevant at the time of the publication of this report.

Cliffs along the coast of the Great Australian Bight

TECHNOLOGY TYPE	EMISSION TYPE	TECHNOLOGY		ECONOMIC POTENTIAL	LENGTH OF STORAGE	COST PER TONNE	RESOURCE COMPETITION	TECHNOLOGY AND COMMERCIAL READINESS LEVELS
		CAPTURE	STORAGE					
Permanent plantings	negative	woody vegetation	woody vegetation, soil	1–30 Mt/year	25–100 years	$$	land use, water	●●● / ●●○
Plantation and farm forestry	negative	woody vegetation	woody vegetation, soil	31–100 Mt/year	25–100 years	$$	land use, water	●●● / ●●○
Human induced regeneration of native forest	negative	woody vegetation	woody vegetation, soil	31–100 Mt/year	25–100 years	$	land use	●●● / ●●○
Avoided clearing	avoided		woody vegetation	1–30 Mt/year	25–100 years	$	land use	●●● / ○○○
Savanna fire management	avoided, negative	woody vegetation, vegetation	soil	1–30 Mt/year	25–100 years	$		●●● / ●●○
Soil carbon	avoided, negative	vegetation, crops	soil	1–30 Mt/year	25–100 years	$$	land use	●●● / ●◐○
Blue and teal carbon	avoided, negative	woody vegetation	woody vegetation, soil	No estimate	25–100 years	$$		●●● / ●◐○
Pyrolysis biochar	negative	woody vegetation	woody vegetation, soil	No estimate	100–1000 years	$$$–$$$$	land use, biomass	●●● / ◐○○
Geological storage			engineered	31–100 Mt/year	1000+ years	$$–$$$	geological storage, energy	●●● / ●●○
Bioenergy with carbon capture and storage	negative	woody vegetation, vegetation	engineered	31–100 Mt/year	1000+ years	$$$$	biomass, water, geological storage	●●● / ○○○
Direct air capture		engineered		No estimate	Depends on storage type	$$$$$	water, energy, land use	●●○ / ○○○
Mineral carbonation and enhanced weathering	negative	engineered	engineered	No estimate	1000+ years	$$–$$$$$	water, energy	●●○ / ○○○

Emission type

- = negative
- = avoided

Capture and storage technology

- = woody vegetation
- = vegetation
- = crops
- = soil
- = engineered

Economic potential

- (one gear) = 1–30 Mt/year
- (two gears) = 31–100 Mt/year
- (three gears) = >100 Mt/year

Length of storage (years)

- (one clock) = 25–100 years
- (two clocks) = 100–1000 years
- (three clocks) = 1000+ years

Cost per tonne of CO_2 sequestered

- **$** = $5–10
- **$$** = $10–30
- **$$$** = $30–90
- **$$$$** = $90–180
- **$$$$$** = $180+

Resource competition

- = land use
- = biomass
- = water
- = energy
- = geological storage

Technology **and commercial readiness levels**

- ○○○ = low 1–3
- ●●○ = medium 4–7
- ●●● = high 8–9

Figure 1. Technology summary

Technical and economic sequestration potential

The level of technical, economic and realisable sequestration of different technologies is a critical measure to inform Australia's planning.

Biological solutions provide high economic sequestration potential

The biological technologies are well developed and have good economic sequestration potential, particularly plantation and farm forestry (32 Mt/year), permanent plantings (16 Mt/year), and soil carbon (5–29 Mt/year by 2050). Uptake has been high in these methods because of their technology maturity and the policy support provided through the carbon farming initiative and the Emissions Reduction Fund. Biological options that could offer increased sequestration levels in the future include blue and teal carbon.

Biological solutions in most cases have a shorter length of storage (less than 100 years) than geological options (hundreds to millions of years).

In addition, climate change and variability may affect sequestration potential and length of storage for biological solutions. Nonetheless at present, they provide the majority of the low-cost, readily scalable sequestration solutions.

Engineered (and Hybrid) solutions have high technical potential and long sequestration storage times, but are less mature

Engineered methods have high technical potential sequestration capacity, including direct air capture bioenergy carbon capture and storage, and pyrolysis biochar. The technical potential for geological storage is large, though is more uncertain.

High costs have to date, limited their uptake, and in many cases, they are less commercially mature than biological solutions. In addition, many of the engineered technologies include some form of geological storage.

Gaps between actual and economic potential sequestration levels represent opportunities for Australia

The gap between actual and economic potential sequestration levels is significant in many technologies Where the gap between these estimates is large, it points to an area of opportunity where economically feasible sequestration can be unlocked by reframing regulation, changing incentives, or leveraging co-benefits. (see Barriers and enablers). Technical potential similarly can be converted into economic potential sequestration with new research and development and innovation, to lower costs and overcome technical barriers.


Flowing water in the Hugh River

Adverse impacts and co-benefits

Sequestration levels should not be considered in isolation; the potential adverse impacts of technologies as well as potential co-benefits should be considered to provide a complete picture of the options available.

Many technologies are associated with environmental co-benefits

Many technologies, particularly biological solutions are associated with environmental benefits e.g. increased soil productivity and agricultural returns. These co-benefits available from sequestration activities can help to drive uptake. For example, increased biodiversity and reduced erosion associated with permanent plantings can encourage implementation, particularly on less productive land. On productive land, soil carbon approaches or permanent plantings used as shelterbelts can be incorporated into existing land uses.

Further research to quantify and value co-benefits, and communications efforts to reach potential users, will be important to support increased uptake of technologies.

Many of the technologies could create new sources of economic activity, particularly for regional Australia

Most of the technologies have the potential for significant economic and social benefits associated with regional development and employment. For biological solutions, this often involves strengthening and supporting existing industries, such as agriculture or forestry, by increasing productivity and diversifying income streams. For the engineered solutions, regional hubs can be developed around technologies that can create new, and reinvent existing, industries.

Competition is emerging for the resources required for sequestration

One of the key constraints in developing economic potential sequestration is competition for finite resources, either with existing industries or between sequestration technologies. A balanced approach will be needed to maximise the environmental, social and economic value from the resource use, while still achieving carbon targets (see Review conclusions).

Some of the most critical resources in competition will be:

- **land** – biological solutions can compete with existing land uses such as agriculture
- **water** – both biological and engineered solutions can consume additional water, and biological solutions such as permanent plantings, can alter catchment flows
- **feedstocks** – several of the technologies have feedstocks (input materials) that are a shared resource (e.g. woody biomass can be used for permanent plantings, biochar or bioenergy).
- **energy** – many of the engineered solutions have significant energy demand.

Barriers and enablers

Identifying the barriers to the uptake of technologies can enable the strategic design of methods to remove them and increase the uptake. Current enablers can be supported to encourage further uptake, and new enablers can be put into place to remove barriers.

Managing barriers and enablers will be critical to Australia's carbon sequestration strategy. Early-stage engagement with proponents, regulators and communities may expose risks that may lead to quicker resolution of barriers. Ongoing research will also be needed to continue exploring the issues, as scaling up some technologies may reveal new barriers and competition for resources.

Research to reduce the cost per unit could improve uptake for some technologies

There is a strong relationship between cost per tonne of sequestration and the commercial readiness level of the technology. Where costs are high, projects development is limited despite the sequestration potential. This is particularly the case for many engineered solutions (e.g. direct air carbon capture and storage (DACCS) has significant sequestration potential but high costs).

Technologies with high sequestration levels and high costs would benefit from investment into research to bring down the unit cost associated with capture and storage. This could increase the national economic sequestration potential.

The same applies to barriers imposed by the high costs of carbon measurement, reporting and verification. Innovative approaches to measurement and verification could reduce costs and improve the economics of scaling both biological and engineered technologies.

Co-benefits could be leveraged and communicated to assist uptake and scaling

Measuring value and rewarding delivery of co-benefits could improve the economics of scaling some of the sequestration technologies, and efficiently meet multiple societal needs. Allowing market mechanisms that encourage benefit stacking (where multiple income sources for the same activity are delivering a range of positive outcomes) will improve the overall value proposition of technology implementation.

Providing supporting information to potential users on the environmental, social and economic benefits of technologies may also assist uptake. For most of the biological solutions, further assessment and quantification of the benefits, co-benefits and costs as well as better understanding of the land use trade-offs could support scaling.

Aligning early-stage projects to other areas of co-benefit may help to create co-funding opportunities (e.g. biochar projects can be used to support afforestation and produce products that could be used in downstream industries).

Many of the opportunities for sequestration are in regional areas. Understanding the regional benefits, including first nations values and benefits, will be critical to maximise social benefit, sustain social license to operate, as well as drive uptake and scaling. Further, regional opportunities will require suitable supply chains and logistics at a low cost to enable and support sequestration activities.

A national foresighting capability to support an increase in negative emissions

See section 3.1 of *Australia's carbon sequestration potential: Technical report* for further details.

In this report, the current state of a range of sequestration options has been produced. This has generated a series of technical and economic potential sequestration estimates for 2050. This report is based on current knowledge and estimates. Advances in technology and research development mean that these fields are rapidly evolving, which may impact both the technical and economic sequestration potential.

A new national capability will be required to provide improved and updated estimates, to identify and assess and develop optimised portfolios of options, and to guide investment and the design of incentives that unlock emerging opportunities. These decisions must be informed by data on each technology's environmental, social and economic value.

Decision making must also be informed by analyses of the implications, trade-offs and opportunities for different technologies and regions. Adverse impacts and co-benefits should be accounted for, as well as costs, and resource use and competition. Competition and dependencies exist between some technologies, with some needing a common shared finite resource such as water or biomass. A purposeful allocation of resources between competing demands will be needed to achieve best use.

Finally, to ensure technologies are ready for deployment in the time frames needed, we must identify the key success factors for scaled implementation and incorporate these factors into an accelerated research and development process. The ability to carefully design for these factors will determine the rate at which technologies can be successfully scaled and the extent to which their scaling maximises opportunities for co-benefits.

Building analytic capacity to resolve these matters should be a priority for Australia. Developing the national capability requires a modelling capability underpinned by innovations in emerging technologies. This will allow us to explore and quantify national and regional trade-offs and feedbacks of different portfolios of sequestration technologies and quantify the efficacy, benefits, co-benefits, and risk over time. It also provides the capacity to explore the efficacy of new policy levers and incentives to deliver their intended outcomes. It also allows risks and potential risks to be identified as implications for the broader economy, such as on food systems and prices.

Analyses should be ongoing because technologies are at different levels of technical maturity and are evolving with investment and scale. As the technologies and uptake trajectories change, a process of both monitoring, reporting and evaluation of outcomes, and an ability to recalibrate sequestration technology strategy in the light of changing circumstances and evidence will be required.

Roadmap for a national foresighting capability

See section 3 of *Australia's carbon sequestration potential: Technical report* for further details.

The roadmap to develop a national foresighting capability has 4 stages:

STAGE 1	**Research current technologies and their potential.** This refers to the information delivered in this review, and further work to explore individual approaches in detail and address many of the gaps identified in this review. This stage should be repeated, ideally annually, to ensure new and emerging technologies and innovation breakthroughs are captured.
STAGE 2	**Build the modelling approach** (see Review conclusions). The integrated assessment modelling approach will be built around state-of-the-art earth system and economic models coupled together in a net zero transition framework.
STAGE 3	**Develop the portfolio** (see Review conclusions). The portfolio should be modelled and optimised based on technological, earth system, social, economic and policy considerations.
STAGE 4	**Implement across multiple pathways.** Achieving Australia's negative emission potential requires the development of pathways to implementation. Policy drivers and other levers can be designed to potentially advance technology development, reduce costs and incentivise the markets.

Figure 2. Australia's roadmap for a national foresighting capability

Review conclusions

Sequestration of GHGs through avoided and negative emissions technologies is needed in conjunction with decarbonisation for Australia to reach it's net emission reduction targets. Evidence-based strategies will enable us to meet these goals, sustain social licence and underpin credible markets, while achieving important environmental, social and economic benefits.

A portfolio of technologies will be needed to achieve Australia's carbon targets

The scale of carbon removal required for our national and global targets looks challenging when considering the biophysical limiting factors of any one technology. No single technology is sufficient to provide a pathway to Australia's emissions reduction target.

But Australia has good opportunities to sequester carbon by deploying a range of different technologies.

The technologies are at different levels of maturity, as indicated by the varying technology and commercial readiness levels. Different technologies also have different operating mechanisms and rely on different resources. Understanding the theoretical limits to the emissions reduction associated with each approach allows us to strategically plan a combination of technologies to meet our removal needs.

The portfolio of technologies will generate a range of co-benefits

There are co-benefits associated with many of the reviewed technologies, which can be leveraged to assist uptake and scaling. Many co-benefits include environmental and socio-economic benefits that flow back into local communities.

Opportunity for Australia

Australia is well positioned with abundant land-resources, significant geological storage capacity, vast marine estate and low-emission-energy resource potential (CSIRO Low Emission technology Roadmap) to translate the potential identified in this report into realisable sequestration.

Australia also has a well-developed carbon market which is a necessary institutional structure to support the scaling of these technologies.

Further, Australia has good underpinning knowledge infrastructure and a skilled, digitally-literate and digitally-enabled workforce to develop and implement a portfolio of carbon sequestration options.

While the natural resource and land base provides an opportunity to sequester carbon, the short to medium term focus should be to bring down the costs and increase the scale of delivering sequestration. This will require a combination of research, skills, delivery process building, market instrument design, and community engagement to develop social licence and to realise the co-benefits created through the scaling opportunity.

Competition for resources will require careful management

The achievable level of carbon sequestration will be limited by the resources available (see Adverse impacts and co-benefits). Taking this into account is key prioritising technologies that will have the most significant impact.

It will be important to manage use of resources to maximise the environmental, social and economic value while still achieving carbon sequestration targets.

Technologies – at a glance

See sections 4–15 of *Australia's carbon sequestration potential: Technical report* for further details.

This section summarises the technology assessments around 3 key questions:

1. What is the technology?

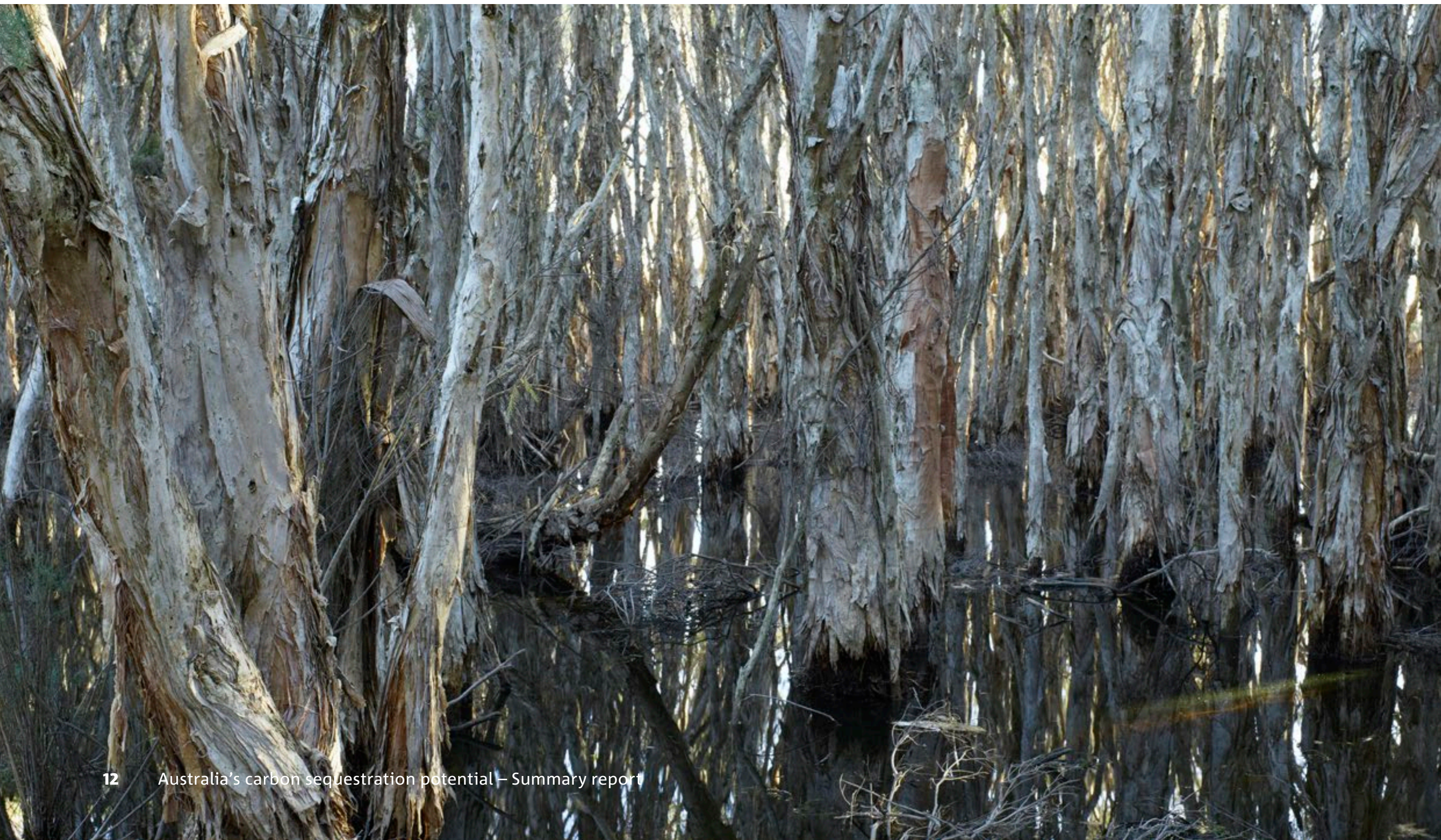
- **Description and current uptake** – how the technology acts to sequester carbon, and its current use in Australia

2. What is the sequestration potential?

- **Sequestration levels** – the actual, technical and economically feasible (economic sequestration potential) amounts of CO_2-e sequestered by the technology
- **Length of storage** – the likely duration of sequestered carbon as a balance of its turn-over rate and risks to stocks
- **Adverse social or environmental impacts** – other negative impacts that the technology may have
- **Risks to the sequestration potential** – factors that may reduce the economic sequestration level
- **Co-benefits** – other benefits (apart from carbon sequestration) that the technology may provide

3. How easily can it be further developed and implemented?

- **Readiness** – the technology readiness level and commercial readiness level (ARENA 2014), assessed on a scale of 1–9
- **Cost** – $ per tonne of carbon (CO_2-e) sequestered
- **Current barriers** – barriers to uptake and scaling; for example, financial, policy, regulatory, industry, supply chain or market blockers
- **Potential enablers** – methods to improve uptake and scaling through regulation or improvements to technology or practices.



Permanent plantings

What is the technology?

Permanent plantings are plantings of woody vegetation on non-forested land, typically on previously cleared agricultural land. The plantings are not for harvest and are typically of native vegetation, and carbon in permanent plantings is sequestered in the living biomass, forest debris and soil.

Emission type	Capture technology	Storage technology
Negative	Biological	Biological

What is the sequestration potential?

The economic potential sequestration offered by permanent plantings is relatively high. Permanent plantings of native vegetation also offer considerable environmental benefits, and are particularly suitable in areas of low productivity. Large plantings can affect water resources.

Actual (2010–2020)	Technical potential (2050)	Economic potential (2050)	Length of storage
2.1 Mt/year	~480 Mt/year	~16 Mt/year	25–100 years

Adverse social or environmental impacts

- Change to conventional land use
- Large-scale plantings can affect catchment water flow and resources
- Increased fuel load and fire risk

Risks to the sequestration potential

- Climate change (increased temperature, altered rainfall)
- Drought, fire, pests and disease

Co-benefits

- Improved biodiversity and landscape connectivity
- Improved soil health and soil carbon
- Reduced erosion
- Improved productivity, especially in areas where plantings are mixed with other land uses (e.g. shelterbelts; see Case study)
- Diversification of farm income

How easily can it be further developed and implemented?

Permanent planting is well established, with several private companies, nongovernmental organisations and not-for-profit organisations specialising in establishing and maintaining plantings. However, the current carbon price means that alternative land uses in productive areas are more profitable than carbon farming. Methods to reduce costs and increase return could encourage uptake.

Readiness	Cost per tonne of carbon sequestered	Emissions Reduction Fund methodology
Technology readiness level: 9 Commercial readiness level: 4–5	\$20–\$30	Yes

Current barriers

- Concerns with changes to conventional land use and potential impacts on communities
- Costs/economics
- Availability of suitable land
- Limited availability of seeds or tubestock
- Cost of seeds or tubestock

Potential enablers

- Better quantification of co-benefits
- Inclusion of soil carbon in assessment methodologies
- Innovative methods for cost reduction
- Increased carbon price
- Improved supply chain for seeds or tubestock

Case study

Shelterbelt established adjacent to grazing paddock, protecting livestock from wind. Photo credit: Arthur Lyons.

Shelterbelt tree plantings

Integrating shelterbelt tree plantings within agricultural landscapes can deliver multiple benefits to both landholders and the environment. These include:

- providing habitat for flora and fauna and increasing habitat connectivity across landscapes
- providing windbreaks to protect crops and livestock, leading to reduced animal stress and increased productivity
- reducing evaporation from the soil surface, meaning increased soil water availability to support pasture growth
- reducing windspeed and slowing surface water flows to reduce soil erosion.

If the planting uses commercial plantation species, this can provide additional economic benefits.

An experimental investigation of the impacts of linear (shelterbelt) tree plantings across four sites in northern Tasmania was undertaken by CSIRO, the University of Tasmania, and Private Forests Tasmania. The aim of the study was to better understand the potential benefits of integrating commercial plantation trees *(Pinus radiata)* into existing farming systems.

The study found that, compared with unsheltered or open paddocks, tree shelters (CSIRO 2018):

- reduced average wind speeds by 20–50%
- reduced evaporation by 15–20%.

The study also found that in the shelter of the planting, the pasture produced 30% more biomass than unsheltered or open paddocks. Economic analysis of a square paddock of approximately 25 hectares showed that the returns from tree planting over 25 years was approximately $54,000, comprising tree harvest ($14,000), shelter benefits to productivity ($42,000), carbon sequestration ($3,000) and amenity/land value ($1,000). Net costs, including fencing, were approximately $6,000.

The study showed that the integration of trees into farming systems can bring benefits that are worth several times the value of the trees, and that small areas of trees can make a disproportionate impact on overall returns and environmental impacts.

Plantation and farm forestry

What is the technology?

Plantation and farm forestry can increase carbon sequestration by establishing new plantations and by changing management practices in existing plantations. This sequesters carbon in living biomass, forest debris and harvested wood products.

Emission type	Capture technology	Storage technology
Negative	Biological	Biological

What is the sequestration potential?

The economic potential sequestration for plantation and farm forestry is ~32 Mt forestry and can offer benefits to regional communities. However, the economic potential sequestration varies with species and soil type, and can be threatened by drought, fire, pests and disease. Environmental benefits such as reduced erosion are also balanced by environmental risks such as increased water use.

Actual (2010–2020)	Technical potential (2050)	Economic potential (2050)	Length of storage
11.5 Mt/year	631 Mt/year	~32 Mt/year	25–100 years

Adverse social or environmental impacts

- Impacts on catchment water flow and resources
- Increased fuel load and fire risk

Risks to the sequestration potential

- Climate change (increased temperature, altered rainfall)
- Drought, fire, pests and disease

Co-benefits

- Economic and social benefits for regional communities
- Improved biodiversity and landscape connectivity
- Improved soil health and soil carbon
- Reduced erosion

How easily can it be further developed and implemented?

Plantation and farm forestry technologies are well developed, but competition for land and high costs limit the expansion of these technologies for carbon sequestration. New processing methods and markets for wood products may improve feasibility for sequestration.

Readiness	Cost per tonne of carbon sequestered	Emissions Reduction Fund Methodology
Technology readiness level: 9 Commercial readiness level: 4–5	$10–$30	Yes

Current barriers

- Availability of suitable land
- Competition for land
- Capital for establishment and processing plants
- Regulatory burden on the establishment of new forests
- Operational and supply chain costs

Potential enablers

- Innovative market creation for wood-based products, such as bioenergy and biochar
- Better quantification of co-benefits
- Innovative methods for cost reduction
- Increased carbon price

Human induced regeneration of native forest

What is the technology?

Human induced regeneration of native forest involves changing the management of non-forested land to promote the establishment of native forest cover (e.g. ending land clearing, reducing rates of domestic livestock grazing and controlling feral grazing animals). The carbon in native forest is sequestered in the living biomass, forest debris and soil.

Emission type	Capture technology	Storage technology
Negative	Biological	Biological

What is the sequestration potential?

Human induced regeneration offers relatively low levels of sequestration because regeneration occurs opportunistically and is highly dependent on local seedstock and conditions. Native forests offer the same benefits as permanent plantings but are likely to take longer to establish.

Actual (2010–2010)	Technical potential (2050)	Economic potential (2050)	Length of storage
20 Mt/year	60 Mt/year	39 Mt/year	25–100 years

Adverse social or environmental impacts

- Disruption to conventional land use
- Potential increases in non-native species
- Increased fuel load and fire risk

Risks to the sequestration potential

- Climate change (increased temperature, altered rainfall)
- Drought, fire, pests and disease

Co-benefits

- Restoration of native cover
- Improved biodiversity and landscape connectivity
- Improved soil health and soil carbon
- Reduced erosion
- Improved productivity
- Diversification of farm income

How easily can it be further developed and implemented?

Methods to encourage natural regeneration are straightforward (e.g. fencing), and the costs of sequestration per tonne of carbon are very low. Better methods of verifying carbon sequestration, including soil carbon, could improve carbon pricing for natural regeneration.

Readiness	Cost per tonne of carbon sequestered	Emissions Reduction Fund Methodology
Technology readiness level: 9 Commercial readiness level: 5–6	$5	Yes

Current barriers

- Concerns with changes to conventional land use and potential impacts on communities
- Measurement and verification of sequestration

Potential enablers

- Further quantification of benefits and co-benefits
- Inclusion of soil carbon in assessment methodologies
- Further analysis of economic potential sequestration

Avoided land clearing

What is the technology?

Avoided land clearing aims to avoid emissions by retaining areas of mature native vegetation that would otherwise have been cleared. Carbon in uncleared land is stored in the living biomass, vegetation debris and soil and additional carbon can be sequestered as the forest continues to grow.

Emission type	Capture technology	Storage technology
Avoided	Biological	Biological

What is the sequestration potential?

The carbon sequestration potential for avoided land clearing is low, and the major emission type for the technology is an avoided emission rather than negative emission type. However, similarly to permanent plantings and natural regeneration, avoided land clearing offers significant environmental benefits.

Actual (2010–2020)	Technical potential (2050)	Economic potential (2050)	Length of storage
2.3 Mt/year	~9 Mt/year	~8 Mt/year	25–100 years

Adverse social or environmental impacts

- Reduced production on land
- Increased fuel load and fire risk

Risks to the sequestration potential

- Climate change (increased temperature, altered rainfall)
- Drought, fire, pests and disease

Co-benefits

- Maintenance of native cover
- Improved biodiversity and landscape connectivity
- Improved soil health and soil carbon
- Reduced erosion
- Improved productivity
- Diversification of farm income

How easily can it be further developed and implemented?

Avoided land clearing is straightforward and well established and costs are low. Avoided land clearing is best suited to less productive areas. The regulatory environment requires documented evidence to allow carbon pricing, and easing some of these restrictions may increase uptake.

Readiness	Cost per tonne of carbon sequestered	Emissions Reduction Fund Methodology
Technology readiness level: 9 Commercial readiness level: 2–3	$5–$10	Yes

Current barriers

- Concerns with changes to conventional land use and potential impacts on communities
- Measurement and verification of sequestration
- Low incentives in the policy and regulatory environment
- Documentation requirements for carbon pricing

Potential enablers

- Further analysis of barriers to uptake
- Relaxing land availability constraints
- Inclusion of soil carbon in assessment methodologies
- Further analysis of economic potential
- Reduced regulatory complexity

Savanna fire management

What is the technology?

Savanna fire management uses prescribed or planned fires for the purposes of reducing the extent of and likelihood of large, high-intensity, late dry-season fires. This land management practice in northern Australia reduces emissions from the late dry season fires, and increases carbon being sequestered in dead organic matter and in living plants. Only the sequestration component was considered for this review.

Emission type	Capture technology	Storage technology
Avoided or Negative	Biological	Biological

What is the sequestration potential?

The sequestration potential of savanna fire management is low, and the practice is restricted to two rainfall zones in northern Australia. However, the technology also reduces emissions and offers significant environmental and Indigenous community benefits.

Actual (2016–2020)	Technical potential (2050)	Economic potential (2050)	Length of storage
5.6 Mt/year	6 Mt/year	6 Mt/year	25–100 years

Adverse social or environmental impacts

- Limited land management options due to need to maintain sequestration
- Lack of intensive fire as a management option

Risks to the sequestration potential

- Climate change (increased temperature, altered rainfall)
- Drought and water stress

Co-benefits

- Employment opportunities for Indigenous communities
- Increased ground cover and biodiversity
- Reduced erosion
- Reduced mortality of flora and fauna
- Reduced invasive woody vegetation and grasses

How easily can it be further developed and implemented?

Savanna burning abatement estimation protocols are well established and based on extensive scientific study. Recent changes to the savanna burning methodology have not increased uptake. This indicates that the barrier may lie in the limitations that the technology places on future land management options.

Readiness	Cost per tonne of carbon sequestered	Emissions Reduction Fund Methodology
Technology readiness level: 9 Commercial readiness level: 3–5	$5	Yes (for sequestration)

Current barriers

- Area of land suitable for burning
- Possible concern by landholders in maintaining sequestration for 100 years

Potential enablers

- Further analysis of barriers to uptake

Soil carbon

What is the technology?

Land management can increase carbon sequestration in the soil by increasing the rate at which carbon is accumulated (such as improving plant cover and retaining stubble), decreasing the rate at which carbon is lost (such as reducing rates of decomposition and minimising erosion losses), or changing the material added to the soil so that it lasts longer.

Emission type	Capture technology	Storage technology
Avoided and Negative	Biological	Biological

What is the sequestration potential?

Soil is a very effective carbon sink, and land management changes leading to increased soil carbon are associated with a range of productivity and environmental benefits. However, soil carbon is not a permanent form of sequestration.

Actual (2021–2022)	Technical potential (2050)	Economic potential (2050)	Length of storage
0 Mt/year	115 Mt/year	5–29 Mt/year	25–100 years

Adverse social or environmental impacts

- Risk of increased nitrous oxide emission due to higher level of inorganic nitrogen in the soil
- Reduced future land use options

Risks to the sequestration potential

- Climate change (increased temperature, altered rainfall)
- Risk of reversal

Co-benefits

- Sustaining and improving productivity
- Reducing the need for fertiliser inputs
- Reducing drought impacts
- Improving farm resilience to climate change

How easily can it be further developed and implemented?

There has been rapid uptake of soil carbon technologies in farming management as the industry recognises the related benefits to productivity. It will be important to develop mechanisms to ensure that soil carbon levels are maintained. Cheaper methods to measure carbon levels are also needed to enable verification and monitoring.

Readiness	Cost per tonne of carbon sequestered	Emissions Reduction Fund Methodology
Technology readiness level: 9 Commercial readiness level: 3-4	$7–$13	Yes

Current barriers

- High cost of monitoring, reporting and verification in many applications to date
- Uncertainty of length of storage
- Onus on future managers to maintain

Potential enablers

- Clear articulation of benefits to productivity
- Direct subsidy to limit practices that deplete soil carbon
- Cheaper methods to measure soil carbon
- Market or value chain mechanisms that reward practices that build soil carbon

Blue and teal carbon

What is the technology?

Blue carbon describes carbon sequestration in vegetated coastal ecosystems, specifically mangrove, saltmarsh and seagrass ecosystems. Teal carbon describes carbon sequestration in inland freshwater wetlands. Carbon is sequestered in these ecosystems in the living biomass and soil (sediment), and management practices are used to promote carbon accumulation or prevent emissions.

Emission type	Capture technology	Storage technology
Avoided or Negative	Biological	Biological

What is the sequestration potential?

Blue and teal carbon ecosystems store more carbon on average than most terrestrial ecosystems and typically sequester carbon at faster rates. While there are no reliable estimates of the potential or economic sequestration levels of blue and teal carbon technologies, several large-scale regional projects show that emissions reduction strategies, such as tidal introduction, can yield substantial net abatement.

Actual (2021–2022)	Technical potential (2050)	Economic potential (2050)	Length of storage
1.1 Mt/year	3–4 Mt/year	Unknown Mt/year	25–100 years

Adverse social or environmental impacts

- Potential impacts on Indigenous values and ownership rights

Risks to the sequestration potential

- Climate change (sea level rise, increased temperature, changes in rainfall)
- Severe tropical storms
- Pests and disease

Co-benefits

- Improved biodiversity
- Sustaining and improving fisheries
- Protection of coastal regions from storm surges
- Ecosystem services (e.g. pollutant removal)
- Potential Indigenous community benefits

How easily can it be further developed and implemented?

The technologies for ecosystem restoration and tidal reintroduction are well established. However, the implementation costs are relatively high and the complexity of legal rights in the coastal zone can make permissions difficult. There is also a high cost of data collection to support modelled estimates.

Readiness	Cost per tonne of carbon sequestered	Emissions Reduction Fund Methodology
Technology readiness level: 9 Commercial readiness level: 3–4	\$18–\$30	Yes (for blue carbon) No (for teal carbon)

Current barriers

- Complex land tenure and permissions systems
- Poor estimates of technical potential and economic potential sequestration

Potential enablers

- Identification of feasible areas
- Innovative business models
- Better estimates of lifecycle costs
- Further analysis of economic potential sequestration
- Inclusion of sediment sequestration

Pyrolysis biochar

What is the technology?

Biochar is a charcoal-like material produced from the slow pyrolysis (heating in the absence of oxygen) of biomass (e.g. forestry and crop residues, and food, green or municipal organic waste). Biochar sequesters the carbon that was the original plants, and has various uses.

Emission type	**Capture technology**	**Storage technology**
Negative	Biological	Biological

What is the sequestration potential?

The technical potential of pyrolysis biochar is reasonable, and it offers long storage times and additional environmental and economic benefits (e.g. from increased soil health).

Actual (2021–2022)	**Technical potential (2050)**	**Economic potential (2050)**	**Length of storage**
0.04 Mt/year	30–60 Mt/year	Unknown Mt/year	>500 years

Adverse social or environmental impacts

- If land is specifically used to produce biomass, disruption to conventional land use
- Potential human health impacts (fine dust)
- Potential environmental impacts of any harmful components

Risks to the sequestration potential

- No risks identified

Co-benefits

- Biochar can be added to soil to increase soil carbon and productivity
- Biochar can be used in various industries (e.g. in the manufacture of composite materials, where it increases mechanical properties and durability)

How easily can it be further developed and implemented?

Pyrolysis technologies are well developed and significant amounts of biomass are available from farm, garden and food waste. However, the industry in general is not yet developed and will require decreased costs and increased end markets to drive uptake.

Readiness	**Cost per tonne of carbon sequestered**	**Emissions Reduction Fund Methodology**
Technology readiness level: 9 Commercial readiness level: 2–4	$80–$120	Yes (for application of biochar to agricultural soil)

Current barriers

- Cost/economics
- Competition for land use and biomass
- Complex logistics and supply chains
- Limited end markets

Potential enablers

- Innovative business model and development of end markets
- Policy incentives to drive industry investment and development
- Better estimates of lifecycle costs
- Further analysis of possible measurement methods for carbon pricing

Geological storage

What is the technology?

Geological storage is the final part of the carbon capture and storage process. CO_2 is captured using various approaches either at emission sources or from the atmosphere. It is then transported by pipeline or ship, compressed and injected into permeable rock layers. In Australia, the 2 most applicable types of reservoirs are depleted oil or gas fields and saline aquifers, and there are currently several projects in different stages of development.

Emission type	Capture technology	Storage technology
		Engineered

What is the sequestration potential?

The sequestration potential with geological storage is high and offers a very long-term option. Carbon capture and storage projects have reached the operational stage in several places around the world.

Actual (2021–2022)	Technical potential (2050)	Economic potential (2050)	Length of storage
2.26 Mt/year	227 Gt/year	50 Mt/year	>million years

Adverse social or environmental impacts

- Potential CO_2 leakage and groundwater contamination or level increase risk
- Risk of transportation leakage

Co-benefits

- Potential for regional community benefits associated with regional hubs
- Potential carbon credit trading

Risks to the sequestration potential

- No risks identified

How easily can it be further developed and implemented?

The technology for geological storage is well developed; however, uptake is low and a number of projects are experiences difficulties. Some people view the technology as prolonging the use of fossil fuels and delaying the uptake of renewable energy; communities are concerned about well integrity, groundwater contamination and leaking emissions. The technology is also relatively expensive; the main costs are associated with transportation and compression of CO_2.

Readiness	Cost per tonne of carbon sequestered	Emissions Reduction Fund Methodology
Technology readiness level: 9 Commercial readiness level: 4–5	$14–35	Yes

Current barriers

- Requires large capital investment
- Complexity of policy and regulatory environment
- Lack of social license and Indigenous engagement
- Timeframes for development

Potential enablers

- Reduction in regulation complexity
- Development of innovative business models (e.g. long forward contracts to de-risk upfront investment)
- Reduction of costs and timeframes for development

Bioenergy with carbon capture and storage

What is the technology?

Bioenergy with carbon capture and storage is a 2-step negative emissions technology. In the first step, biomass is converted to energy (either heat and electricity through combustion; biofuels through gasification or fermentation; or hydrogen through gasification, pyrolysis or fermentation). In the second step, CO_2 released in the conversion is captured, compressed and stored underground in rock layers. This review considers both steps separately; see Geological storage for the second step.

Emission type	Capture technology	Storage technology
Negative	Biological	Engineered

What is the sequestration potential?

The sequestration potential with bioenergy is relatively high, and together with geological storage offers a very long-term storage option. Current energy production from biomass accounts for 47% of Australia's renewable energy production and 3% of total energy consumption.

Actual (2021–2022)	Technical potential (2050)	Economic potential (2050)	Length of storage
No estimate	181 Mt/year	25–38 Mt/year	>million years (with geological storage)

Adverse social or environmental impacts

- Disruption to conventional land use
- Risk to food security
- Reduced soil health due to the use of crop residues

Risks to the sequestration potential

- Biomass supply

Co-benefits

- Generation of electricity from biomass waste streams

How easily can it be further developed and implemented?

The individual components of the technology (converting biomass into energy; capturing, transporting and storing CO_2), are all mature; however, the combination of the technologies has low uptake due to uncertain policy support and economic feasibility. Innovate business models and incentives will be needed to encourage uptake.

Readiness	Cost per tonne of carbon sequestered	Emissions Reduction Fund Methodology
Technology readiness level: 2–9 Commercial readiness level: 2	$100	Yes

Current barriers

- Cost/economics
- Requires large capital investment
- Competition for land use
- Lack of incentives in the regulatory and policy environment

Potential enablers

- Innovative business models
- Provision of subsidies and tax credits and other incentives
- Better understanding of the technical and economic potential sequestration

Direct air capture

What is the technology?

CO_2 is present in air at about 400 parts per million. In direct air capture, CO_2 is separated from air using solid adsorbents or liquid absorbents, and prepared for storage or use in further applications.

Emission type	Capture technology	Storage technology
	Engineered	

What is the sequestration potential?

The carbon capture potential is relatively high; however, the length of storage depends on its use (e.g. use as a fuel will re-release the carbon).

Actual (2021–2022)	Technical potential (2050)	Economic potential (2050)	Length of storage
No estimate	980 Mt/year globally	No estimate	Depends on storage type

Adverse social or environmental impacts

- Potential environmental impacts through use of absorbents and adsorbents
- Localised impact on land and water use

Risks to the sequestration potential

- No risks identified

Co-benefits

- Use of captured CO_2 as feedstock for other products (e.g. sustainable aviation fuel or urea for fertiliser)
- Generation of new economic activity and employment opportunities

How easily can it be further developed and implemented?

Direct air capture technology is developed but the process is expensive. Energy costs are a particular barrier; the theoretical minimum energy requirement for separating CO_2 from an air stream is around triple that of capturing CO_2 from a power station flue.

Readiness	Cost per tonne of carbon sequestered	Emissions Reduction Fund Methodology
Technology readiness level: 4–7 Commercial readiness level: 1	\$300–\$600	No

Current barriers

- High cost of current technologies
- High energy requirement
- Potentially large water usage
- Considerable land requirements
- Lack of support in policy and regulatory environment
- Public acceptance

Potential enablers

- Development of low-cost, low-emission pathways for use
- Development of a full analysis methodology to support direct air capture carbon trading
- Development of scaling pathways including innovative business models

Mineral carbonation and enhanced weathering

What is the technology?

Mineral carbonation and enhanced weathering capture CO_2 from the atmosphere through chemical reactions. In mineral carbonation, CO_2 reacts with minerals containing calcium (Ca) and magnesium (Mg) to form stable carbonate minerals. In enhanced weathering, silicate minerals react with CO_2 in water to break down, but the CO_2 stays dissolved in the water and is eventually washed into the ocean. Both processes occur naturally as part of the global carbon cycle, but engineered solutions can increase the rate of atmospheric CO_2 removal to achieve negative emissions.

Emission type	Capture technology	Storage technology
Negative	Engineered	Engineered

What is the sequestration potential?

Mineral carbonation and enhanced weathering offer high sequestration potential, and long-term storage. The main challenge for mineral carbonation and enhanced weathering is that they are very slow processes.

Actual (2021–2022)	Technical potential (2050)	Economic potential (2050)	Length of storage
0.1 Mt/year	36 Mt/year	No estimate	>1000 years

Adverse social or environmental impacts

- Generation of possible harmful by-products
- Potential increased seismicity and groundwater contamination

Co-benefits

- Could make use of tailings as a value stream
- Resulting carbonates can be incorporated in industrial products (e.g. concrete)

Risks to the sequestration potential

- No risks identified

How easily can it be further developed and implemented?

At present, there is only demonstration-scale technology available for mineral carbonation, and the technology is expensive. Further research is required to assess the potential of the technology for carbon sequestration in Australia.

Readiness	Cost per tonne of carbon sequestered	Emissions Reduction Fund Methodology
Technology readiness level: 5–7 Commercial readiness level: 1	\$28–\$300	No

Current barriers

- Cost of grinding and transporting feedstock material
- Low reaction rates requiring excess feedstock
- Lack of suitable locations
- Access to sufficient raw materials

Potential enablers

- Research to improve reaction rates and lower costs
- Research to identify location and quantities of feedstock
- Establish a pilot project

Summary tables

Tables 1–3 summarise the results of the technology assessments, for carbon sequestration levels and storage time, adverse impacts and co-benefits, and barriers and enablers.

Table 1. Economic potential estimated for 2050 and actual carbon sequestration levels for 2021–22 with corresponding length of storage

TECHNOLOGY TYPE	ECONOMIC POTENTIAL SEQUESTRATION 2050 (MT PER YEAR)	ACTUAL SEQUESTRATION 2021-22 (MT PER YEAR)	LENGTH OF STORAGE (YEARS)
Permanent plantings	16	2.1[1]	25–100
Plantation and farm forestry	32	11.5[1]	25–100
Human induced regeneration of native forest	39	20[2]	25–100
Avoided clearing	7.7	2.3[1]	25–100
Savanna fire management	6	5.6[1]	25–100
Soil carbon	5–29	0	25–100
Blue and teal carbon	No estimate	1.1[1]	25–100
Pyrolysis biochar	No estimate	<0.1	>500
Geological storage	24	2.26 – (Gorgon project 2020-21)	>million
Bioenergy carbon capture and storage	25–38	No estimate	>million
Direct air capture	No estimate	No estimate	Depends on storage technology
Mineral carbonation and enhanced weathering	No estimate	0.1	>1000

Summary of technology potential. [1]AGEIS 2010-2020. [2]AGEIS 2016-2020
Footnote: AGEIS – https://ageis.climatechange.gov.au/

Table 2. Adverse impacts and co-benefits

TECHNOLOGY	ADVERSE SOCIAL OR ENVIRONMENTAL IMPACTS	CO-BENEFITS
Permanent plantings	• Disruption to conventional land use • Large-scale plantings can affect catchment water flow and resources • Increased fuel load and fire risk	• Restoration of native cover • Improved biodiversity and landscape connectivity • Improved soil health and soil carbon • Reduced erosion • Improved productivity, especially in areas where plantings are mixed with other land uses • Diversification of farm income
Plantation and farm forestry	• Impacts on catchment water flow and resources • Increased fuel load and fire risk	• Economic and social benefits for regional communities • Improved biodiversity and landscape connectivity • Improved soil health and soil carbon • Reduced erosion • Diversification of farm income

TECHNOLOGY	ADVERSE SOCIAL OR ENVIRONMENTAL IMPACTS	CO-BENEFITS
Human induced regeneration of native forest	• Disruption to conventional land use • Potential increases in non-native species • Increased fuel load and fire risk	• Restoration of native cover • Improved biodiversity and landscape connectivity • Improved soil health and soil carbon • Reduced erosion • Improved productivity • Diversification of farm income
Avoided land clearing	• Reduced production on land • Increased fuel load and fire risk	• Maintenance of native cover • Improved biodiversity and landscape connectivity • Improved soil health and soil carbon • Reduced erosion • Improved productivity • Diversification of farm income
Savanna fire management	• Limited land management options due to need to maintain sequestration • Lack of intensive fire as a management option	• Employment opportunities for Indigenous communities • Increased ground cover and biodiversity • Reduced erosion • Reduced mortality of flora and fauna • Reduced invasive woody vegetation and grasses
Soil carbon	• Increased nitrous oxide emission due to higher level of inorganic nitrogen in the soil • Reduced future land use options	• Sustaining and improving productivity • Reducing the need for fertiliser inputs • Reducing drought impacts • Improving farm resilience to climate change • Diversification of farm income
Blue and teal carbon	• Potential impacts on Indigenous values and ownership rights	• Improved biodiversity • Sustaining and improving fisheries • Protection of coastal regions from storm surges • Ecosystem services (e.g. pollutant removal) • Potential Indigenous community benefits
Pyrolysis biochar	• Disruption to conventional land use • Potential human health impacts (fine dust) • Potential environmental impacts of any harmful components	• Biochar can be added to soil to increase soil carbon and productivity • Biochar can be used in various industries (e.g. in the manufacture of composite materials, where it increases mechanical properties and durability)
Geological storage	• Potential CO_2 leakage and groundwater contamination or level increase risk • Risk of transportation leakage	• Potential for regional community benefits associated with regional hubs • Potential carbon credit trading
Bioenergy with carbon capture and storage	• Disruption to conventional land use • Risk to food security • Reduced soil health due to the use of crop residues	• Generation of electricity from biomass waste streams
Direct air capture	• Potential environmental impacts through use of absorbents and adsorbents • Localised impact on land and water use	• Use of captured CO_2 as feedstock for other products (e.g. sustainable aviation fuel or urea for fertiliser) • Generation of new economic activity and employment opportunities
Mineral carbonation and enhanced weathering	• Generation of possible harmful by-products • Potential increased seismicity and groundwater contamination	• Could make use of tailings as a value stream • Resulting carbonates can be incorporated in industrial products (e.g. concrete)

Table 3. Barriers and enablers

TECHNOLOGY	BARRIERS	ENABLERS	COST ($/t)	TRL	CRL
Permanent plantings	• Concerns with changes to conventional land use and potential impacts on communities • Costs/economics • Availability of suitable land • Limited availability of seeds or tubestock • Cost of seeds or tubestock	• Better quantification of co-benefits • Inclusion of soil carbon in assessment methodologies • Innovative methods for cost reduction • Increased carbon price • Improved supply chain for seeds or tubestock	20–30	9	4–5
Plantation and farm forestry	• Availability of suitable land • Competition for land • Capital for establishment and processing plants • Regulatory burden on the establishment of new forests • Operational and supply chain costs	• Innovative market creation for wood-based products, such as bioenergy and biochar • Better quantification of co-benefits • Innovative methods for cost reduction • Increased carbon price	10–30	9	4–5
Human induced regeneration of native forest	• Concerns with changes to conventional land use and potential impacts on communities • Measurement and verification of sequestration	• Further quantification of benefits and co-benefits • Inclusion of soil carbon in assessment methodologies	5	9	5–6
Avoided land clearing	• Concerns with changes to conventional land use and potential impacts on communities • Measurement and verification of sequestration • Low incentives in the policy and regulatory environment • Documentation requirements for carbon pricing	• Further analysis of barriers to uptake • Relaxing land availability constraints • Inclusion of soil carbon in assessment methodologies • Reduced regulatory complexity	5–10	9	2–3
Savanna burning	• Area of land suitable for burning • Possible concern by landholders in maintaining sequestration for 100 years	• Further analysis of barriers to uptake	5	9	5
Soil carbon	• High cost of monitoring, reporting and verification • Uncertainty of length of storage • Onus on future managers to maintain	• Clear articulation of benefits to productivity • Direct subsidy to limit practices that deplete soil carbon • Cheaper methods to measure soil carbon • Market or value chain mechanisms that reward practices that build soil carbon	7–13	9	3–4

TECHNOLOGY	BARRIERS	ENABLERS	COST ($/t)	TRL	CRL
Blue and teal carbon	• Complex land tenure and permissions systems • Poor estimates of technical and economic potential sequestration	• Identification of feasible areas • Innovative business models • Better estimates of lifecycle costs • Inclusion of sediment sequestration	18–30	9	3–4
Pyrolysis biochar	• Cost/economics • Competition for land use and biomass • Complex logistics and supply chains • Immature and/or competing end-markets	• Innovative business model and development of end markets • Policy incentives to drive industry investment and development • Better estimates of lifecycle costs	80–120	9	2–4
Geological storage	• Requires large capital investment • Complexity of policy and regulatory environment • Lack of social license and Indigenous engagement • Timeframes for development	• Reduction in regulation complexity • Development of innovative business models (e.g. long forward contracts to de-risk upfront investment) • Reduction of costs and timeframes for development	14–35	9	4–5
Bioenergy with carbon capture and storage	• Cost/economics • Requires large capital investment • Competition for land use • Lack of incentives in the regulatory and policy environment	• Innovative business models • Provision of subsidies and tax credits and other incentives • Better understanding of the technical and economic potential sequestration	100	2–3	2
Direct air capture	• High cost of current technologies • High energy requirement • Potentially large water usage • Considerable land requirements • Lack of support in policy and regulatory environment • Public acceptance	• Development of low-cost, low-emission pathways for use • Development of a full analysis methodology to support direct air capture carbon trading • Development of scaling pathways including innovative business models	300–600	4–7	1
Mineral carbonation and advance weathering	• Cost of grinding and transporting feedstock material • Low reaction rates requiring excess feedstock • Lack of suitable locations • Access to sufficient raw materials	• Research to improve reaction rates and lower costs • Research to identify location and quantities of feedstock • Establish a pilot project	28–300	5–7	1

References

ARENA (2014) Technology Readiness Levels for Renewable Energy Sectors. URL: https://arena.gov.au/assets/2014/02/Technology-Readiness-Levels.pdf

AEGIS – Australian National Greenhouse Accounts https://ageis.climatechange.gov.au/

UNFCCC 2015 – https://unfccc.int/files/meetings/paris_nov_2015/application/pdf/paris_agreement_english_.pdf

NASEM – 2019 National Academies of Sciences, Engineering, and Medicine. 2019. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.* Washington, DC: The National Academies Press. https://doi.org/10.17226/25259

Minx et al: Minx, J. C *et al* 2018 Negative Emissions – Part 1: Research Landscape and Synthesis, *Environ. Res. Lett.* **13** 063001

CSIRO Low Emission technology Roadmap, Campey, T., Bruce, S., Yankos, T., Hayward, J., Graham, P., Reedman, L., Brinsmead, T., Deverell, J. (2017) Low Emissions Technology Roadmap. CSIRO, Australia.

CSIRO 2018, Mendham DS (2018). Modelling the costs and benefits of Agroforestry systems – Application of the Imagine bioeconomic model at four case study sites in Tasmania.

Aerial photo of farmland on the Murrumbidgee River outside Murrumbateman, NSW

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Contact

1300 363 400
+61 3 9545 2176
csiro.au/contact
csiro.au

Further information

Peter Fitch
peter.fitch@csiro.au

Michael Battaglia
michael.battaglia@csiro.au

Andrew Lenton
andrew.lenton@csiro.au

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