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Sustainably Managing Australian Riparian Zones in a Carbon-Constrained Economy: Management Practices for Farmers

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Abstract

The riparian zone is crucial in providing a number of important environmental services but its condition is becoming increasingly degraded and thus is under serious threat. Therefore protection, restoration and rehabilitation of riparian environments is a priority. In a carbon constrained economy, greenhouse gas (GHG) mitigation or carbon sequestration activities are rewarded. Therefore, for farmers, a better understanding of no regret farming activities, which increase the profitability and sustainability of the farming systems is desirable. This review provides farmers with recommendations for best management practices in Australian riparian zones. Adopting these practices represent significant opportunities for farmers to enhance carbon sequestration and reduce GHG emissions whilst improving the efficiency and profitability of their farming system. Many of these practices are eligible activities under the Australian Government Emissions Reduction Funds and those which are not, have the potential to be included in the future.

Keywords: Australia; GHG Emissions; Cropping; Riparian zone; Pasture; Forests; Freshwater habitats

Introduction

The riparian zone is the narrow interface between terrestrial and freshwater habitats [1]. It consists of the banks, vegetation, floodplain and the adjacent farmland and plays an important role in river health, on-farm productivity, biodiversity and sustainability, adaptation to climate change and carbon sequestration [2]. In Australia, many riparian zones have been cleared, mainly for pastures and crops, resulting in an increase in biomass carbon emissions [3]. Moreover, pasture and agriculture systems require more farms inputs. Production, packaging, transportation and application of these farm inputs demand more energy, resulting in more greenhouse gas (GHG) emissions [4]. Therefore, identifying and adopting management practise that improve productivity, profitability and the sustainability of riparian systems whilst reducing GHG emissions is vital. This study aims to provide a series of recommendations of best management practices for farmers in the riparian zones of Australia for enhancing carbon sequestration and reducing GHG emissions at the landscape level.

This manuscript is organised into four sections. After this introductory section, carbon management options through vegetation promotion activities is discussed in section 2 and carbon management options for cropping systems (section 3) and livestock systems (section 4) are discussed on subsequent sections. In the end, a brief summary of all best management practices are presented in Figure 1.

Carbon Management Options through Vegetation Promotion Activities in Riparian Zones

Forestry, perennial woody vegetation in orchards, vineyards, and agroforestry systems can all store significant quantities of carbon in long-lived biomass. All biomass-increasing activities can increase the carbon pool. The following management practices can help increase carbon stock within vegetated riparian zones.

Promote riparian woodland/forest management activities which have both adaptation and mitigation benefits

"No regret" activities which have both adaptation and mitigation benefits represent the most appealing solutions in the long term. Typical examples are:

- Planting halophytic trees in saline areas to reduce the salinity problem (adaptation) whilst increasing carbon sequestration (mitigation). Similarly, planting flood/cyclone resistant trees in flood/cyclone prone areas reduces stormwater runoff (adaptation) and increases carbon storage (mitigation).
- Planting shelterbelts and windbreaks (one or more rows of trees or shrubs between the crops) reduces crop damage and soil erosion (adaptation) and will also increase carbon sequestration (mitigation). Moreover, compared to block plantings, plantings in narrow belts of 3-4 rows can increase stem volume by up to 20% to 29% due to decreased intra-specific competition for light, water and nutrients [5-6]. Therefore, belt plantings will deliver more carbon sequestration than block plantings.
- Perennial woody vegetation in orchards and vineyards can also store significant carbon in long-lived biomass and should be encouraged.
- Planting suitable fodder trees around the pasture can provide food for livestock in drought season (adaptation) and also store carbon in their biomass (mitigation).

Develop native forests from managed regrowth

The regeneration of woody species in pasturelands reduces pasture production and clearing remains an expensive management option [7]. Considering the costs of clearing and the potential contribution of regrowth to carbon sequestration and biodiversity, the conversion of pastures to native forests through changes in management practices may be worthwhile [8]. Establishing native forests from managed regrowth

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in ex-pasture land through the cessation of mechanical clearing is an eligible activity under the Australian Government Emissions Reduction Fund (ERF) and farmers can secure carbon credits from this activity. The methodology for determining the carbon credits generated through this activity - called full carbon accounting model (FullCAM) - has already been approved by the Australian Government. These are tens of millions of hectares of cleared ex-forestry land that is potentially suitable for managed regrowth activity [9].

Although this activity is primarily focused on achieving carbon credits and biodiversity paybacks, it delivers additional benefits known as co-benefits. These include water quality improvements, soil and flood protection, aesthetic and land productivity enhancements [10,11]. Further value could be derived through building walking tracks and promoting ecotourism activities.

There are several other compelling reasons for farmers to consider encouraging regrowth forest in pastures in riparian zones. Firstly, as atmospheric carbon concentrations increase, regrowth will accelerate. Growing conditions may be more favourable for C3 plants (mostly woody tree species such as spotted gum, but some grasses are also follow C3 pathway) than for C4 plants (such as kangaroo grass, red grass and wire grass). Secondly, regrowth are better for climate adaptation, as maintaining a high proportion of natural cover has also been shown to ameliorate the impact of extreme heat events [12]. Thirdly, the enhancement of native regeneration from the cessation of mechanical clearing through the promotion of in situ propagules (including seeds, rootstock and lignotubers) provides a cost-effective option for regeneration.

Fourthly, large scale clearing of native vegetation exacerbates adverse impacts such as salinity on already stressed natural resources and agriculture. The Australian and State governments advocate the replacement of crops and pastures by deep rooted native species plantations. Planting trees is however very expensive. It is estimated that the cost to plant 200 hectares of woody vegetation at Brymaroo in the Condamine Catchment in 1992 to reduce recharge in a salt affected catchment was $898,000 [13]. However, native regrowth also reduces overland flow. Therefore, the benefits from promoting native regrowth are more likely to outweigh the costs of reduced overland flow in areas with a high salinity risk.

Establish mixed species of environmental plantings (MSEPs)

The MSEPs, also referred to as 'carbon plantings', 'biodiversity plantings' or 'enrichment plantings' [14], can include afforestation or reforestation activities. However, the species planted should be native to the local area and should consist of a mix of tree and understory species, or a single species if monocultures naturally occur in the area [15]. Over the past 200 years, about 40% of total forest cover has been lost in Australia [16]. MSEPs have considerable potential to contribute carbon sequestration benefits of between 350 Mt CO_2-e/yr to 600 Mt CO_2-e/yr [17], along with several other ancillary benefits. Therefore, like managed regrowth, MSEPs are a no regret option. MSEP are also an eligible activity for Australian Government Emissions Reduction Fund. The Australian Government has already developed and adopted the Reforestation Modelling Tool (RMT) for estimating carbon sequestration amounts in trees (above and below ground) and debris pools from the MSEPs.

The riparian zone is the most suitable area for MSEPs for several reasons. Maraseni and Carl [18] estimated the above-and-below ground trees/shrubs biomass and coarse woody debris in Queensland, Australia, and reported that the average value (143.58 tC/ha) was much higher than the global average of 89.4 tC/ha [19]. This indicates that remarkably high levels of biomass carbon are achievable in riparian zones, possibly because of fertile soils and abundant soil moisture. In the context of climate change and under elevated carbon dioxide levels, riparian plants absorb more carbon as these areas are more suitable for plant photosynthesis (due to the elevated temperatures and abundant soil moisture). Research in the USA has reported that wetland plants can absorb up to 32% more carbon than they currently do [20].

Retain coarse woody debris (CWD) for both carbon and biodiversity benefits

Coarse woody debris (CWD) include debris from fallen trees and branches and stumps left after cutting the trees [20]. Retaining CWD ensures stored carbon is retained and ecological function is promoted. In a study of a riparian zone of Condamine Catchement in in Queensland, Australia, Maraseni and Carl [18] reported that >95% of total carbon in riparian forests came from trees and shrubs biomass and <5% came from CWD. This is mainly because farmers burnt the debris for various reasons and this practice can have detrimental impacts both on carbon storage and biodiversity [18]. Therefore, encouraging farmers to retain CWD on the site could be beneficial for both carbon storage and biodiversity.

Manage forest fire for multiple benefits

Forest fire is one of the major contributors of national GHG emissions in Australia [21]. Biomass in forestry systems is recycled to the atmosphere through fire or microbial decomposition. Microorganisms release less GHG over a longer period of time than burning [21]. Moreover, a mutualism mechanism among soil microorganisms also helps to reduce GHG emissions. For example, methane (CH_4) released by termites during the digestion of plant material is re-absorbed by bacteria in the soil [21]. Therefore, developing a mechanism which reduces fire frequency could reduce GHG emissions, as more of the litter is decomposed/consumed via the microbial pathway [22]. Encouraging early dry season (EDS) burning or strategic prescribed burning would be highly beneficial, as late dry season (LDS) fires emit 52% more emissions per unit area than do EDS fires [23]. Prescribed burning may also help to promote biodiversity, increase productivity and the sustainability of the forestry system.

Carbon Management Options for Cropping Systems in Riparian Zones

Management options for increasing carbon sequestration in soils

Soil is the largest pool of carbon after the ocean, storing about 1580 Gt of organic carbon in the top meter of soils [24,25]. At a global level, the conversion of forested lands to agriculture, including cultivation and pasture, has been linked to a soil carbon loss of about 136 GtC since 1970 [26] Although a full reversal is not possible, most of this can be recovered as globally, soil organic carbon (SOC) sequestration has the potential to mitigate 5% to 14% of total annual GHG emissions over the next 50–100 years [27]. In Australia, most of the SOC is lost due to clearing of vegetation for grazing and cropping. As a result, over the last 50-80 years, SOC levels have decreased from 2% to 1% [28]. With good management practises and cultivation of high yielding crops, a recovery of 1.2% to 1.5% SOC is possible [28].

SOC sequestration also offers several co-benefits. It improves the productivity, profitability and sustainability of the soil system as a result of increasing plant nutrient content and water retention capacity.

Therefore, sequestering carbon in soil is a highly desirable mitigation and adaptation option, mainly for food and water security [26,29].

The two major determinants of SOC levels are rainfall and soil type. Research indicates that SOC levels are greater in areas with higher rainfall and/or lower temperatures, as high temperatures combined with high soil moisture can accelerate the decay and loss of SOC. Two primary farm management practices - conservation tillage and the application of biochar - that increase SOC levels are discussed in the next sections. Here, additional management options identified from the literature [3-4,28,30-36] are documented:

- Practice mixed farming or crop rotation system. In a given region, SOC levels are generally higher in pasture systems than in cropping systems. Compared to monoculture, mixed farming systems can increase SOC level by 0.20 ± 0.04 tC/ha/yr.
- Change land use system from:
- Cropping to permanent pasture; this change may increase SOC for up to 35 years by 0.30–0.60 t C/ha/yr. This may eventually attain SOC values similar to the soil under native vegetation or even higher if nutrient limitation is also removed.
- Cropping to forests; this change provides duel benefits, both soil and biomass carbon will increase.
- Continuous cropping to ley pastures; ley pastures, especially grass-legume pasture increases SOC, about 0.5 tC/ha/yr or higher, during the pasture phase.
- Ley pasture to permanent pasture; this change results in continuous increase in SOC by eliminating the cropping phase.
- Use manures from intensive animal production. As manures are high in lignin, sequestered carbon resides in soil lasts longer than the labile carbon from crop residues. Animal manures also add nutrients more cheaply than mineral fertilisers.
- Stubble retention is another important way of increasing SOC. Depending on the soil, rainfall and types of stubble, this practice may increase SOC by 0.19±0.08 tC/ha/yr
- Plant high biomass yielding crops. Grain sorghum will produce around 1.5 times the biomass of wheat and twice the biomass of dryland cotton and chickpeas. Therefore, sorghum is better for increasing SOC level.
- Add clay to sandy soils. Research in Western Australia shows that soil carbon storage increases with increasing clay content. Soils with a clay content of 1.7% have 42 tCO_2e/ha whereas soils with 9.1% clay stored 99 tCO_2e/ha.
- Plant cover crops. In addition to soil carbon benefits, cover crop also reduces nitrogen leaching.
- Practice rotational grazing on pastures. This will increase soil carbon, soil water retention and reduce water and wind erosion.

Practice zero or no-till where possible, to achieve both adaptation and mitigation benefits

Continuous long-term cultivation systems result in a net loss of SOC. Consequently, 75% of agricultural lands in Australia have <1% SOC [4]. For example, 60 years of continuous cultivation have impacted the cereal cropping soils of northern New South Wales and southern Queensland, with a loss of >40 tC/ha and 4 tN/ha, valued at $2,933 ($20/tC) and $3,200 ($800/tN), respectively. This represents a replacement cost of $100/ha/yr for carbon and nitrogen alone [33]. During the same period, >165 tCO_2e/ha has been emitted from the soil, which equates to 2.75 tCO_2-e/ha/yr [33].

Continuous cultivation leaves soils vulnerable to water and wind erosion, increases agricultural runoff, degrades soil productivity, while GHGs are released by disturbing soils and from burning fossil fuels by farm machinery [34-38]. The loss of carbon adversely affects soil fertility, the soil water holding capacity and plant-available water capacity.

Zero till, which involves sowing seeds directly under the mulch layer from the previous crop can reverse this process by minimizing mechanical soil disturbance, provides permanent soil cover by organic materials and diversifying crop species grown in sequence and/or association [38]. Therefore, the Australian Federal and State governments recommend farmers move from traditional dryland farming systems to reduced tillage systems and, where appropriate, towards zero till [39]. The uptake rate is very high. From 1976 to 2007/08, >17 million hectares of farming land has been converted to zero till, avoiding around 95.2 $MtCO_2e$ of GHG emissions [40]. Most of this uptake is very recent, as there was only about nine percent of cropland under zero till in 1990 which increased to 74% in 2010 [37]. Zero till is also an eligible option under the Australian Government Emissions Reduction Funds and a participating landholder can also access tax offsets of 15% off the purchase price for eligible no-till seeder.

West and Post [41]– using a global meta-analysis - report that the mean relative sequestration rate for conversion of conventional tillage (CT) to zero till is 0.57 ± 0.14 tC/ha/yr, with a new equilibrium level in 15-20 years. Given the drier conditions, when compared with Europe, Canada and USA, zero till in Australia has limited carbon sequestration benefits [42] However, if zero till is integrated into a number of other management options [33] or practiced in higher rainfall areas (>700 mm) [42], positive sequestration outcomes are more likely. For example, a 33 year trial at the Hermitage Research Station (28°12'S and 152° 06'E) in southern Queensland showed that compared to a conventional tillage system (39.8 tC/ha, up to 20cm depth) zero-till (42 tC/ha, up to 20cm depth) practices increased SOC by 0.24 tCO2e/yr [33]. In this case, although conversion to zero till did not increase SOC, it did reduce the rate of soil carbon loss.

Zero till has some other co-benefits, such as increased yields by increasing water use efficiency and reduced soil erosion. For example, a seven year zero till trial on the Darling Downs showed an average increase in wheat yields of 19%, and a decrease in soil erosion of 70% to 90%. Moreover, zero till also offers adaptation benefits as it improves soil moisture. Therefore, under drought conditions, crops grown under zero till are more resilient and produce higher yields [43].

Apply biochar to soils to generate environmental and financial benefits

Research shows that applying biochar (a carbon-rich stable form of charcoal) to soils can address a number of issues including improving soil moisture and soil health while reducing GHG emissions. Greenhouse gas benefits include: (1) the avoidance of CH_4 and carbon dioxide emissions from organic waste/biomass; (2) the replacement of fossil fuels with syngas; (3) biochar carbon sequestration in soils; (4) the reduction of N_2O emissions from certain soil types; (5) a reduction in agrochemicals requirements and related GHG emissions; and (6) a reduction of fossil fuel use as a result of improved soil workability [44,45].

Biochar benefits largely depend on the type and amount of feedstock, and on the right mix of fertilisers, crop types, and soil attributes (texture, pH, moisture level etc.). Wood-derived biochars are richer in carbon and are good for carbon storage. Whereas, biochars produced from animal manures (piggeries and poultry) have higher levels of nitrogen and phosphorus and may be used to replace nitrogen and phosphorus fertilisers [31].

Producing biochar from organic waste is equally important for waste management. Australia produces 38 Mt of waste annually, 60% of which is organic. Managing this waste requires an annual expenditure of $4 billion [46]. Queensland alone annually produces: 12 Mt bagasse; 2.8 Mt forest residues; 1.4 Mt sawmill waste; 380,000 t feedlot manure; 22,000 t cotton trash; and 6,800 t macadamia shells that could be used for biochar production [47]. Most of these organic wastes remain (or are burnt) on farm or end up in landfill, resulting in higher emissions of GHG. On the other hand, as noted, intensive cultivation has left many Australian soils seriously degraded. If these wastes were converted into biochar, and injected into farm soils, there would be multiple environmental and financial benefits.

The benefits of biochar in agricultural land are greater: (1) in sandy soils than in clayey and loamy soils; and (2) for crops which have symbiotic relationships with micro-organisms than other. This is because, the enormous number of micropores and the high surface area of biochar: (1) increases the water holding properties of sandy soils, but in loamy and clayey soils, no significant changes were observed [48]; and (2) enhances habitat for micro-biota and their proliferation [49]. Similarly, the application of biochar to wheat and legume crops (or crops which have symbiotic relationships with bacteria and fungi) would be more beneficial than the application of biochar to soils with non-symbiotic crops. Similarly, the biochar benefit would be higher in acidic soils than in alkaline soils, as regardless of the type of feedstock, biochar tends to increase pH values, reducing the need to add significant amounts of lime to acidic soils, and thus avoiding additional GHG emissions.

Any reduction in N_2O emissions depends on soil type and climatic conditions. For example, biochar did not reduce N_2O emissions under dryland agricultural conditions in Western Australia, but the same biochar source did decrease N_2O emissions under moist soil conditions in northern NSW [31].

Adopt legume-based cropping systems to reduce the need for N-fertiliser, resulting in lower costs and fewer GHG emissions

Agriculture is one of the major global sources of GHG emissions; on-farm sources alone emit 60% of all N_2O and 50% of all CH_4 emissions [50]. Modern agriculture is more intensive and mechanised than ever before, with increasing demands for fuel, electricity, farm machinery and agrochemicals [3,4,44,51-58].

Currently, synthetic nitrogen fertiliser is one of the major sources of N_2O emissions. In the past, legume-dependent cropping systems were globally very popular, playing a key role in maintaining nitrogen levels in the soil. However, due to the invention and adoption of the cost effective Haber process, use of synthetic nitrogen fertiliser grew rapidly. There is some debate within the scientific community about whether the biologically-fixed nitrogen from legumes emits as much GHG as nitrogen-fertiliser, but a recent study shows that the legume-based cropping systems remain a better, feasible and more compelling option in Australia for several reasons [59].

Reduce N_2O emissions from soils

Among the three major GHGs linked with farming systems, nitrous oxide (N_2O) has the highest global warming potential (1 t N_2O = 298 tCO_2), which is produced naturally in soil by microbial nitrification and de-nitrification processes. During these processes, part of the applied N fertilisers is emitted into the atmosphere as N_2O. In Queensland on average 60 kg N/ha is applied to cereals and 120 kg N/ha for cotton and intensive horticulture. If a pasture legume phase is included with crops, the N application rate could be reduced by 10 kg N/ha [32]. Therefore, including a pasture legume phase is a key strategy in reducing N_2O emissions.

Other management practices with the potential to reduce N_2O emissions include avoiding:

- Large irrigation volumes after fertilisation or when soil mineral N content is high [30]. Soils with water saturation levels <40% or >90% have very low N_2O emissions. Avoid using fertilizers before rainfall as it increases N_2O emissions rates [31].
- Large applications of N fertiliser before planting. Fertiliser application can lead to increased N_2O emissions if the amount of N that plants can absorb is exceeded [30,31].

Strategies that minimise any excess of inorganic N within the soil and thereby diminish the potential for N_2O emissions [32,33,60,61] include:

- Monitor crops and test soils for plant available N and adjust fertiliser application rates and timing according to the crop requirement.
- If there are salinity, sodicity and acidity problems in the sub-soil, they restrict the ability of crops to effectively utilise soil N. Under these conditions, N inputs should be reduced.
- Apply N fertiliser at optimum rates by taking into account all N sources available to the crop/pasture.
- Avoid N fertiliser application outside the crop/pasture growing season.
- Apply fertiliser evenly. In irrigated agricultural systems, application via sprinkler/drip irrigation may be an effective option.
- Plant cover crops to utilise the residual mineral N following N-fertilised main crops.

Applying nitrification inhibitor, 3,4 dimethylpyrazole phosphate (DMPP), with urea could also reduce N_2O emissions. In Kingaroy, using this inhibitor reduced N_2O fluxes by >60% during the corn season [30]. Similarly, split applications and formulations with nitrification inhibitors (Entec®, Agrotain®) reduced daily N_2O losses by up to 90%. The effects were similar in all cropping regions but are most dramatic in summer crops and later in the winter season [30].

Carbon Management Options from Livestock Systems in Riparian Zones

Reduce CH_4 and N_2O emissions from livestock

In Australia, livestock accounts for 70% of total agricultural emissions or 10.2% of total GHG emissions [31]. Methane and N_2O are the two main GHG emitted from the livestock industry. Almost all CH_4

in livestock comes from enteric fermentation in ruminants. Some CH_4 also comes from livestock urine and manure.

Farmers can reduce N_2O and CH_4 emissions from livestock through: (1) selective breeding of low-emission animals; (2) inhibiting CH_4 production in the rumen; (3) managing manure and urine; and (4) capturing and using CH_4 [31].

Some of the major management options that reduce CH_4 emissions from livestock include [31]:

- For both cattle and sheep, the level of CH_4 production varies by individual animals, and determining factors are their rumen size, rumen microbe population, digestive functions, feed intake and feed-use efficiency. Progeny of some sires may produce 11% to 24% less CH_4 than the progeny of other sires. In general, sheep with larger rumens emit more CH_4, so where possible, select sheep progeny with smaller rumens.
- Some legumes, forages and plant extracts can reduce CH4 production in the rumen. For example, *Eremophila glabra* have a capacity to reduce CH4 emissions by up to 50%.
- Compared to lower digestibility feeds (such as mature pasture, tropical grass and hays), cereal grain feeds produce some hydrogen gas and a highly acidic rumen, both of which are restrictive to CH_4 producing rumen microbes. Grain production produces GHG emissions from cultivation, transport and the application of agrochemicals. On balance, the use of grains as feed would still reduce total emissions. Similarly, higher proportions of forage legumes in the diet also help to reduce CH_4 emissions, partly due to lower fibre content, faster rate of passage and the presence of condensed tannins [61]. A higher proportion of cereals and forage legumes in the diet will reduce GHG emissions.
- The use of grape marc as a food supplement can reduce CH_4 emissions from dairy cows, and maintain or increase productivity. Other useful supplements which can reduce CH_4 include lipids, tannins and various plant products.
- With an increase of 1% of total oil in the diet, CH_4 emissions can be reduced by up to 3.5%. Using oil supplements such as whole cotton seed, cold pressed canola, hominy meal and micro-algae in the feed used in intensive livestock production systems can reduce CH_4 emissions by 10% to 25% [61].
- Through earlier finishing of beef cattle in feedlots, slaughter weights are achieved at younger ages, with reduced lifetime emissions per animal, and thus proportionately fewer animals producing CH_4 [61].
- Nitrate supplementation can reduce CH_4 production by 22% in penned sheep and by 8% in sheep grazing in paddocks. However, dietary nitrate is recommended only for those areas where forage quality is low. Where there is good forage quality there is a risk of nitrate poisoning.

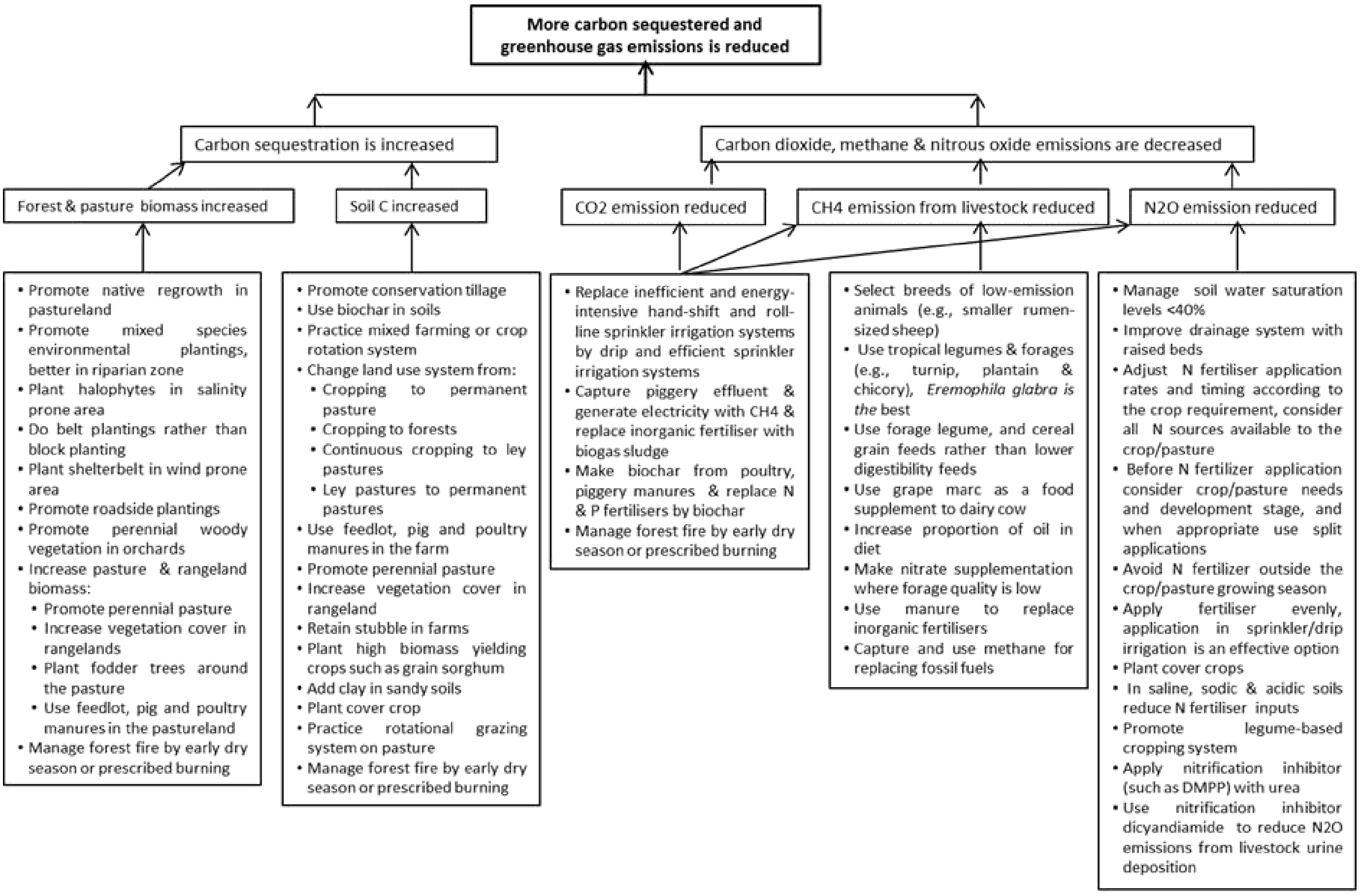

Figure 1: Best management options for increasing carbon sequestrations and reducing greenhouse gas emissions.

- As livestock urine is one of the major sources of N_2O the use of nitrification inhibitor dicyandiamide (DCD) can reduce up to 45% N_2O emissions from urine deposition, without leading to a measureable increase in pasture production [30].

Utilise intensive animal production wastes

Piggeries are important to Australia's rural economy. Pigs return more than half of the feed they consumed as waste, with ~15,000 pigs producing 275,000 L of sewage effluent per day; equivalent to the sewage output of a town with a population of 50,000 people [62]. The disposal of effluent from piggeries can generate water pollution (both surface and ground), eutrophication and phosphate leaching [63]. They can also spread putrid odours, promote fly infestation and disease in adjoining regions [64]. In addition, current anaerobic lagoon systems lead to the production of biogas consisting of CH_4. Capturing and using this effluent and CH_4 would: (1) avoid CH_4 emissions; (2) reduce GHG emissions by generating electricity from captured CH_4 (replacement of other fuel sources); and (3) reduce GHG emissions by replacing inorganic fertiliser with biogas sludge [65]. This process would also decrease the associated odour, pest, disease and water contamination problems.

A brief snapshot of all these best management practices for more carbon sequestration and reduction of GHG emissions are presented in Figure 1.

Conclusion

This study reviewed and recommended several management practices for farmers in the riparian zones of Australia wishing to enhance carbon sequestration and reduce GHG emissions at landscape level. Some mitigation options presented here will not reduce all three GHGs. For example: (1) zero till can increase SOC but can lead to increased soil N_2O emissions because of increased plant material such as plant litter and root exudates, which are sources of carbon and energy for denitrifying organisms; (2) wetlands can sequester carbon over long time periods but could be a source of CH_4; (3) cereal grain feeds help to reduce CH_4 emissions from cattle, but producing grains may need more agrochemicals and energy and thereby increasing related GHG emissions; and (4) biochar increases SOC levels but at the same time reduces herbicide efficacy thus increasing herbicide-related emissions. Nonetheless, on balance, all these activities would reduce total GHG emissions whilst delivering additional benefits.

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