Carbon Sequestration Study

Prepared for Queenstown Lakes District Council (QLDC)

George Hooper, Rocky Renquist, Eugene Robson, and Corina Comendant, with contributions from David Taylor and Toby Stevenson.

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Contents

Glossary iii

Executive Summary 1

1. Introduction 5
   - 1.1 Overview 5
   - 1.2 Scope of Study 6

2. Regulatory Context 9
   - 2.1 NZ Policy and Regulatory Context For Sequestration Activities 9
   - 2.1.1 Biological Sequestrations 9
   - 2.1.2 Non-biological Sequestrations 11
   - 2.2 QLDC Rules Relevant for Bio-sequestration Activities 12
   - 2.2.1 Conservation of Natural Values 12
   - 2.2.2 Changing Rules on Water Rights 15

3. Land Areas and Land Use in the District 16
   - 3.1 Overview 16
   - 3.2 Identifying and Categorising Lands Suitable for Sequestration 19

4. Options Assessment - Biological Sequestration 22
   - 4.1 Introduction 22
   - 4.2 Protocols for Carbon Sequestration Covering the Range of Land Categories in the Queenstown Lakes District 25
   - 4.2.1 Protocol 1: Community Native Forest Restoration 26
   - 4.2.2 Protocol 2: High Carbon Sequestration 28
   - 4.2.3 Protocol 3: Southern Aspect Afforestation 29
   - 4.2.4 Protocol 4: Northern Aspect Enhanced Vegetation 31
   - 4.2.5 Protocol 5: Carbon Farming in Tussock Land 32
   - 4.2.6 Protocol 6: Special Exotic Plantations 33
   - 4.2.7 Protocol 7. Offset Forest Swaps 35
   - 4.3 Pathways Descriptions 35
   - 4.4 Purpose Grown Species for Biomass Production 39
   - 4.5 Carbon Sequestration Estimates 42
   - 4.6 Findings and Recommendations 48

5. Options Assessment - Technical Sequestration 52
   - 5.1 Overview 52
   - 5.2 Commercial Readiness of the Various Technical Sequestration Options 53
   - 5.3 Case Studies 56
   - 5.3.1 Biochar via Pyrolysis 56
   - 5.3.2 Anaerobic Digestion 59

6. Conclusions and Sequestration Roadmap 62
References 65

Biological Sequestration; Sections 3 and 4 66

Appendices

Appendix A: Restrictions on *Pinus radiata* 70
Appendix B: Vegetation photos by Michael Sly and related materials 71
Appendix C: Summary of sequestration pathways 75
Appendix D: Use of Giant Miscanthus 80
Appendix E: Technical sequestration options - overview of the technology 69
Appendix F: About Us 79

Glossary

Abbreviation	Stands for
AFOLU	Agriculture, Forestry and Other Land Use
C	Carbon
CCS	Climate Capture and Sequestration
CO_2	Carbon Dioxide
DM	Dry Matter
ETS	Emissions Trading Scheme
LULUCF	Land Use, Land Use Changes and Forestry
MAC	Marginal Abatement Cost
MACC	Marginal Abatement Cost Curve
MfE	New Zealand Ministry for the Environment
MBIE	New Zealand Ministry of Business, Innovation and Employment
QLDC	Queenstown Lakes District Council

Executive Summary

New Zealand is very well placed to mitigate climate change through the growth of forests that hold carbon (C) in their large tree mass and non-woody plants through increased carbon storage below ground and in soil life. The QLDC has therefore sought to incorporate an analysis of carbon sequestration opportunities across the District as a part of its Climate Change Action Plan – this includes both biological sequestration and technical sequestration.

In order to achieve this objective this study begins with a review of the NZ policy and regulatory context for sequestration activities, including an assessment of the implications that Regional and District Planning objective, policies and rules will have on any sequestration activity. What is clear from this review is that rules pertaining to the conservation of natural values, and water access rights (for farm land) are likely to dominate biological sequestration activities.

Forestry activity and forest removals (including wildings) requires special consideration. Accounting rules under Kyoto mean that forests planted before 1990 that are reforested are considered pre-1990 forests, and sequestration from these forests does not count towards NZ's targets, unless the so-called "pre-1990 forest" is planted with trees/crops that achieve higher sequestration levels. This is important for the QL District as its current forest holdings are old-age forests and replanting of these forests has recently been directed towards replacing with native forests; meaning that any carbon storage contribution from these new forest is not to be counted.

Technological sequestration of captured CO_2 is more dependent on permitted activities within the District Plan although the regulatory framework is uncertain. Carbon capture and storage is currently treated as a "removal activity" under the NZ ETS, and CCS activities registered under the ETS can claim carbon units for carbon removed from the atmosphere. However, CCS activities not directly linked to NZ ETS participants, or those that seek to remove general carbon from air, do not quality for NZ ETS units – this is a disadvantage compared to forestry sequestration.

In addressing the opportunities for biological sequestration, the report examines the major land use systems and land management practices in the District to provide an overview of the different land classes, ownership regimes and the broader policy and regulatory frameworks that might govern future sequestration activity.

This review identified a number of inconsistencies and conflicting objectives that unless resolved could potentially limit carbon sequestration potential. Foremost amongst these is the conflict between the desire to protect existing landscapes and amenity values (including biodiversity) and the likely significant land-use change that will be necessary, including the revegetation of some tussock lands or other degraded lands, for any substantive carbon storage to occur.

Policy direction going forward will need to address land use change in ways in which the wider community can have confidence that their concerns and aspirations are being listened to. Whilst not specifically addressed in this report the concept of Mātauranga Māori will be also an important future inclusion to ensure a wider understanding of the relevant issues and risks associated with any climate change adaptation proposed.

What this study tells us is that due to both its topography and continental climate the Queenstown Lakes District is one of the more challenging areas in the country to grow plants with high carbon storage, since that requires high plant growth (dry mass). The District also comprises significant area of conservation estate, as well as other areas that have high landscape and biodiversity values, leaving a paucity of suitable lands for bio-sequestration, unless one begins to encroach on existing pastoral and farming lands and/or allow the establishment of fast growing species (both native and exotics) at higher altitudes.

In respect of biological sequestration, this report examines a number of different land use options and the establishment protocols that would be required to implement a successful carbon management regime. It will not be easy and there are many challenges that will need to be overcome. Foremost amongst these is attending to ecological values and achieving community acceptance of the trade-offs that will inevitably arise.

In summary, our major findings in respect of bio-sequestration are:

- The use of farm land in Land Use Capability (LUC) classes 3, 4, 5 and 6 should be the focus of investigation into the cropping of high yield biomass crops for use in bioenergy / biochar manufacture, and thereby maximising carbon sequestration potentials.
- We note that globally increasing attention is being given to the use of purpose-grown species to both enhance carbon storage and for the supply of biomass as a renewable energy source. The resulting land use change from existing pastoral / grazing use to a more intensive cropping regime presents opportunities to reduce ruminant methane emissions as well as improving carbon stocks. This would provide a double win.
- The pastoral lease lands managed by LINZ are the most pertinent land category for considering any long-term management interventions designed to sequester carbon in vegetation. In arriving at this conclusion we have also taken into account altitude, land use factors and scale, however, we recommend integrating ecological and soil science assessments into any such proposed new land management regime with the objective of carbon sequestration.
- The high altitude NZ vegetation is rare and will present risks if modified to any great extent. At the very least, it is necessary to do a botanical survey of species that are present at a site before seeking to modifying it.

- The greatest potential for carbon storage is with development at a commercial scale of tree/crop management regimes on existing farmland for biomass production (coppice-capable tree species, mainly Eucalyptus, and long-lived non-woody species, such as Miscanthus x giganteus).
- Other useful additions are likely to be provided by over-sowing tussock land up to 700m altitude with grey shrubs for carbon farming on an extensive (rather than intensive) basis as well as the introduction of sterile clones of exotic tree species grown from tissue culture, in the more remote, less environmentally sensitive parts of the District, including the large pastoral lease areas. These species are capable of producing high biomass (and C stock) in the harsh continental environment.
- Existing policies to reduce old age forests and wilding pines will have an immediate negative impact on total carbon stocks. However, replanting of these areas with native forest and grey shrubland native vegetation (such as *manuka, kanuka, Pittosporum spp*. and *kowhai*) will have long term benefit and enable the natural reinstatement of beech and other vegetative cover; thereby accelerating establishment rates, and carbon stocks over current direct-planting approaches.
- Whilst offering strong ecological and biodiversity benefits, the current local programmes for native forest restoration offer a limited carbon sequestration benefit in the near term. The rates of establishment and low biomass per plant simply means a very limited storage over the time frame out to 2050. We believe that this may be scalable, but much will depend on the success rate achieved with current community-led and QEII afforestation initiatives.

Modelling of these pathways was undertaken to arrive at a preliminary view of the quantities of carbon that could be potentially sequestered for the period out to the year 2050, expressed in terms of tCO_2e/ha. The total contribution towards carbon emissions mitigation within the QLDC based on these pathways and the areas planted is estimated at approximately 9.5 million tonnes CO_2e. Annual sequestration rates at the end of the period are determined to reach around 420,000 tonnes CO_2e / year.

It should be noted that these quantities simply reflect the pathways assumed and the assumptions used as to their deployment over time. As such, the numbers themselves should not be taken as specific sequestration targets, rather it is the protocols underpinning the different pathways that are important as they have enabled different options to be tested and gaps in our knowledge base to be identified.

Significant further analysis, science effort and policy evaluation will be required to before any determinant targets are postulated and to inform decision-making going forward. What we have observed is that the considerable voluntary effort and trial programmes currently underway in respect of native forest restoration using nursery grown native plants offers a very firm foundation for future programmes.

In respect of technical sequestration, the report concludes that at a macro level there is a paucity of opportunity for the adoption of these techniques within the District. This is largely due to the early stage development of many of the pathways canvased and/or the complexity of the underpinning science and technology. In addition, the avoided cost of carbon in many instances was determined to be very high and it is unlikely that the price point for commercial investment will be reached in the near-to-medium future.

Of the options canvased, the production of biochar for soil enhancement and the direct utilisation of CO_2 as an industrial gas / working fluid offer the least risk, subject to markets and CO_2 sources being properly delineated. There are also integration options worthy of further evaluation should a suitable CO_2 source be identified, and a local biomass source be established.

The two most obvious candidates for further examination identified were anaerobic digestion to biogas or biomass gasification with carbon looping to produce either bio-methane or hydrogen; with CO_2 recovered as a separate product stream. The pyrolysis of purpose grown biomass to biochar, where developed in association with a waste-to-energy plant, is also of potential interest.

Our analysis shows that biological and technical sequestration are not mutually exclusive, but instead offer synergies that will act to enhance QLDC carbon reduction initiatives and potentially offer a more than useful contribution towards mitigating the QLDC carbon emissions footprint. We suggest these opportunities are examined in more detail and further assessment be undertaken to establish whether there is a sufficient business case for investment; either by the District itself or through some form of public / private partnership.

1. Introduction

1.1 Overview

New Zealand is very well placed to mitigate climate change through the growth of forests that hold carbon in their large tree mass and non-woody plants through increased carbon storage below ground and in soil life. Additionally, improved management techniques based on the considerable science effort currently underway to improve land use, changing land use practices and new practices that enhance soil carbon are all measures that can be adopted to reduce the quantities of CO_2 being emitted to the atmosphere.

Carbon sequestration can be defined as the capture and secure storage of carbon that would otherwise be emitted to or remain in the atmosphere. That can entail a number of pathways including geological, biological and technical sequestration. In respect to this study our primary focus has been on terrestrial sequestration; that is increasing carbon fixation through photosynthesis and changing land use practices. However, we have also included a high level consideration of the direct removal of CO_2 via technological approaches to carbon storage so as to ensure completeness and to allow some measure of the contribution that this route might be able offer.

In respect of biological sequestration, this we define in accordance with the IPCC definitions which include; direct removal of CO_2 from the atmosphere through land-use change (LUC), afforestation, reforestation, revegetation, carbon storage and practices that enhance soil carbon. Technical sequestration in this report is used mean direct removals. Geological sequestration is ignored due to both scale and the absence of the necessary geological settings across the District to enable such an approach.

This work has been done in conjunction with other commissioned work[1] intended to inform the QLDC on ways in which the District can reduce its overall carbon emissions as a key action towards mitigating and adapting to the effects of climate change. This companion work stream has developed an emissions reduction master-plan as well as a decarbonisation interventions that will lead to measurable carbon reductions out to 2050. The outcomes from the present sequestration study is intended to feed into that plan so as to ensure QLDC have the clearest path forward for further detailed work and implementation.

This sequestration study involved three work streams; an examination of the regulatory context for carbon sequestration activity in New Zealand (Section 2), an options analysis of biological sequestration and the associated examination of the land areas and land uses in the District (Sections 3 and 4), and an options analysis and review of technical sequestration options, including case study analysis of a postulated bioenergy pathway

[1] Sapere, Emissions Reduction Plan, study for QLDC, October 2020.

(Section 5). Also in Section 4 a range of biological sequestration scenarios / pathways were examined as a framework to test key assumptions and as a basis for estimation of sequestration potentials across the District.

The output from this analysis and the bioenergy pathway analysis was then combined into a preliminary estimate of the Carbon Stocks potential that might be achieved under the different sequestration pathways enumerated (Section 6).

It is important to note that this study is very much an early stage analysis of the potential to use biological sequestration as a mitigation against climate change. The sequestration pathways examined do not purport to present a preferred "mitigation plan" but instead are presented in a way to allow options to be tested, the potential for carbon sequestration to be better understood, and gaps in our knowledge base identified.

Acknowledgments:
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1.2 Scope of Study

QLDC requires a sequestration study for the District that assesses options for sequestering carbon and which also outlines scenarios for future action covering both biological sequestration opportunities and emerging approaches using technical means to capture and store carbon. Key consideration for the QLDC were current policy and planning settings, the ability to sequester carbon on QLDC controlled land, and the biodiversity commitment of the district's Climate Action Plan.

In undertaking this work we have set out to meet these objectives through;

- A qualitative and quantitative assessment of the major land use systems and land management practices in the District in terms of suitability for biological sequestration,
- Review of establishment requirements; species selection, crop management and harvesting practice for a range of candidate cropping regimes and an assessment of bio-sequestration potential and fitness for purpose,

- An evaluation of land use changes and afforestation / reforestation protocols that would be required to enhance carbon sequestration,
- A review of technical sequestration opportunities for the District including case study analysis of two identified sequestration opportunities, and
- Compilation of a first-order assessment of the potential for increasing carbon stocks[2] based on the above analyses, and review of key uncertainties.

In addressing the opportunities for biological sequestration, land use systems and land management practices in the District were reviewed in order to provide an overview of the different land classes, ownership regimes and any existing policy and regulatory frameworks that might govern future sequestration activity. This had not been done before and, at this early stage, was necessarily a high level analysis but never-the-less important in bringing together a coherent view of those land types within the QLDC worthy of future consideration from the perspective of growing plants for C storage.

These pathways were then further enumerated and land use protocols established that set out a number of hypothetical planting regimes illustrative of how biological carbon sequestration could be achieved on the range of land categories present in the QLDC. These protocols and pathways examined were not intended to be determinant, but instead are hypothetical constructs to allow options to be tested and gaps in the knowledge base identified. Significant further analysis, science effort and policy evaluation would be required to be undertaken to inform decision-making going forward.

In order to bring together the required assessment of sequestration potential a model has been constructed with inputs on expected planting rates, species selection, total areas planted, biomass growth and effective sequestration expressed as an increase in carbon stock (tCO_{2e}/ha) on an annual basis[3]. The derived carbon sequestration estimates are then summed and presented graphically as a total carbon stock. These quantities, in turn, have then been inputted into the companion Emissions Reduction Master Plan.

These estimates are indicative only of what might be achieved based on the various assumptions adopted in the study. They do not constitute a target sequestration rate, but instead reflect the potential that might exit, subject to further study and confirmation.

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[2] The term Carbon Stock refers to the total carbon sequestered in tonnes ha^{-1}. This can be converted to CO_2 equivalents using the mass ratio of C to CO_2 (1:3.67)

[3] Note: The metric (tCO_{2e}/ha) as used here is intended to describe the carbon that has been sequestered from the atmosphere and is stored within the living biomass and soil (Carbon Stock). It should not be confused with the similar term used by the MFE in its emissions factors used for Kyoto reporting, based on removals of mature forests or crops.

The review of technical sequestration opportunities for the District was treated as a separate workstream. Output from this work stream was used to examine a selection of nine different CO_2 utilization pathways from the perspectives of technical and commercial readiness, and likely economic viability.

Key risks were enumerated and an options analysis undertaken to identify preferred candidate technologies for further evaluation. These were examined via case study analysis and recommendations incorporated into the Emissions Reduction Plan.

In undertaking this work assessments were limited to information available in the public domain and information readily accessible in the scientific literature. No detailed engineering or cost estimating has been carried out with all cost information, yield data and sequestration estimates based in good engineering / land management practice.

2. Regulatory Context

2.1 NZ Policy and Regulatory Context For Sequestration Activities

2.1.1 Biological Sequestrations

Accounting rules under Kyoto Protocol

New Zealand carbon accounting rules have been determined by those under the Kyoto Protocol. Under the first commitment period (CP1) of the Protocol (2008-2012), New Zealand accounted for all new post-1989 forests and deforestation (under Article 3.3), but chose not account for net emissions under Article 3.4 from vegetation and soil from forest management (pre-1990), grazing land management and cropland management. However, under CP2 (2013-2020), accounting for forestry management under Article 3.4. became mandatory, and an additional voluntary activity was added for wetland management.

Under the Kyoto Protocol, post-1989 native and exotic forests that could count towards the 2020 emissions reduction target had to meet the following rules:

- Are a minimum area of 1 hectare
- Are a height of 5 metres at maturity
- Have a minimum crown over 30 per cent at maturity
- Have a minimum forest width of 30 metres of canopy cover.

These rules have been retained post-2020, and are now used to account for sequestration activities towards the 2030 target under the Paris Agreement (see further below). The rules also apply for post-1989 forests registered under the NZ ETS – a regulatory tool that has aimed to encourage forestry carbon sequestration activities by issuing carbon units for carbon removals.[4]

Forests planted before 1990 that are reforested are considered pre-1990 forests, and sequestration from these forests has not counted towards the 2020 target, unless specific management practices since 1990 have increased the carbon sequestration above what would have occurred under business as usual (ICCC, 2019). This is an important point – it suggests that unless pre-1990 forest is planted with trees/crops that achieve higher sequestration, then replanting of these forests cannot count towards the sequestration target under the UNCCC rules. Furthermore, if these lands are cleared and not replanted, then QLDC's emissions profile will in fact increase.

[4] Although, upon harvest, post-1989 forests also face ETS liabilities, i.e. they are required to return carbon units equal to the sequestration lost.

Accounting rules under the Paris Agreement

The Paris Agreement, which New Zealand signed up to in 2015, allows countries to develop their own nationally determined contributions (NDC) to reduce national emissions. In its first NDC, New Zealand indicated that it would use the same forestry accounting rules for the 2030 as for the 2020 target, with one additional rule around average accounting, whereby only carbon removals from plantation forests up to the long-term average of a forest are counted. This rule has been included for new post-1989 forests in the Emissions Trading Reform Bill.[5]

Under the Paris Agreement, which requires signatories to increase their emissions reduction ambitions over time, New Zealand is also considering whether there are significant unaccounted carbon emissions in non-forest land uses. Carbon emission factors represent the net above- and below-ground CO_2e from vegetation and soil resulting from biogenic processes. Although IPCC provides guidelines for these factors mostly at a national level, it recommends that best practice is to develop country-specific emissions factors. (Landcare Research, 2018) has recently developed such factors for non-ETS forestry land. In this study we have used mixed emission factors taking into account local planting conditions and establishment factors. These are set out in Section4.

Forestry offsets under the NZ ETS

The NZ ETS allows some deforestation activities to be "offset" with forest land established elsewhere. This offsetting land must be equal to or greater than the total area of the land being cleared, and must be able to achieve the carbon equivalence of the cleared land. For new post-1989 forests under the new carbon average rule these offsets are referred to as "swaps."

An important qualification for offset forests is that they need to become "forest land" before the current forest is deforested. Under the NZ ETS, land is a qualifying forest land if:[6]

a) each hectare of the land has forest species on it that have, or are likely to have, tree crown cover of more than 30%; and
b) those forest species were established by direct planting activities, including direct seeding but excluding natural forest regeneration; and
c) each individual parcel that makes up the land has an area of at least 1 hectare and has an average width of at least 30 metres.

The rules around forest offsets are relevant for the district's sequestration plan because they determine whether or not the regulatory context is permissive of using high-yield biomass cropping as potential forest offsets. For example, in contrast to eucalyptus,

[5] https://www.parliament.nz/en/pb/bills-and-laws/bills-proposed-laws/document/BILL_92847/climate-change-response-emissions-trading-reform-amendment

[6] Sections 181F and 192J in the Climate Change Response (Emissions Trading Reform) Amendment Bill

lucerne and miscanthus are not eligible for offsets as they are grass species under current regulatory settings.

We already know that there are intentions to plant offset forests in the Otago region – in its 2018 Deforestation Intentions Survey, MPI notes that most "offset planting from 2018 and 2022 will occur in Otago" (MPI, 2018). At this stage, the extent to which offset rules may affect incentives specifically for planting biomass crops (other than eucalyptus) in QLDC is not exactly known - we only note that those rules are potentially conducive for such activities.

Permanent forestry

The new Emissions Trading Reform Bill[7] will disestablish the existing Permanent Forest Sink Initiative, and will replace it with a new permanent post-1989 forest activity in the NZ ETS. This change aims to reduce administrative costs, making this option more viable for landowners. A cost-benefit analysis of this regulatory change has found that there would be an ongoing net incremental benefit to land owners as a result of this change(in the baseline scenario) (PwC, 2019). For our purposes, we assume that the new policy settings further contribute to afforestation intentions.

2.1.2 Non-biological Sequestrations

Carbon capture and storage is currently treated as a "removal activity" under the NZ ETS, and CCS activities registered under the ETS can claim a carbon unit for any carbon removed from the atmosphere. However, CCS activities not directly linked to NZ ETS participants, or those that seek to remove general carbon from air, do not qualify for NZ ETS units[8] – this is a disadvantage compared to forestry sequestration. A report by (Barton, 2013) also found that the existing New Zealand legislation is not set up to deal with the complexities of CCS, creating a barrier to the uptake of these technologies – these issues are still relevant today.

To deal with these issues, the Productivity Commission has made the following recommendations in its recent report on the low-carbon economy (Prod Comm, 2018):

- New regulation should be prepared to regulate CCS activities, addressing issues including long-term regulatory supervision of CCS, and
- Once new CCS is in place, the NZ ETS should be amended to recognise CCS as a removal activity, no matter the source of emissions being captured and stored.

In this report, we discuss the options for technical carbon sequestration assuming that the future NZ policy settings will be supportive of such activities. Our focus is not on proving their economic viability – rather, it is on presenting the technological opportunities as a means of augmenting biological sequestration and thereby strengthen mitigation actions in response to Climate Change.

[7] At the time of this report, the Bill was granted the Royal Assent.
[8] e.g. this may be because CCS technologies are not proven on a scale that allows confidence.

2.2 QLDC Rules Relevant for Bio-sequestration Activities

There are two main policy rules, as stemming from Otago regional and QLDC plans, that are particularly relevant for the nature of bio-sequestration activities that can take place within QLDC boundaries:

1. Rules pertaining to the conservation of natural values, and
2. Rules pertaining to water access rights.

2.2.1 Conservation of Natural Values

The Otago region has unique natural features and landscape that give the region its distinctive character. These outstanding natural features and landscapes are protected through regional and district plan provisions, and include Otago's

> **expansive tussock grasslands and semi-arid lowland tor country, the south-east Otago bush remnants and scroll plain wetlands, glacial lakes and block mountain ranges and heritage landscapes such as the historic goldfield sites. (ORC, 1998)**

The district's rural zoned land is divided into two areas, first being the area for Outstanding Natural Landscapes and Outstanding Natural Features, and the second area being the Rural Character Landscapes. This land mainly comprises private land managed in traditional pastoral farming systems with high landscape and amenity values, which the district plan aims to protect.

Pockets of land within the district also contain Significant Natural Areas (SNAs), which provide nature conservation values from indigenous vegetation and significant habitats of indigenous fauna. Indigenous biodiversity values specifically include (but are not limited to)

> **a range of characteristics that can be used to understand the significance of indigenous vegetation or habitat, such as an area's representativeness, the relative rarity of species or ecosystems, the diversity or patterns contained within an ecosystem, the distinctiveness of an area, and its ecological context (QLDC, 2020)**

The Council is responsible for maintaining indigenous biodiversity and to protect significant indigenous vegetation and habitats of indigenous fauna, through the control of indigenous vegetation clearance.

Box 1 over presents that areas within QLDC where preserving nature conservation values are of particular importance, as these represent land with least modified environments.

Box 1 – Areas of significant nature conservation values in QLDC

The areas of significant nature conservation value in QLDC, and where the above rules are of particular relevance:

- The upland areas to the west of the District, most of which form part of Mount Aspiring National Park. The lower McKerrow Range and the Dingle Burn area adjacent to Lake Hawea are in the Department of Conservation's stewardship.
- Some pockets of indigenous vegetation, particularly dominated with Kanuka, in the eastern downland lake basins, which have generally undergone extensive modification.
- Are above 1070m, which are sensitive to modification due to thin and infertile soils, and severe weather factors.
- Braided riverbeds, which are important habitats to fish and birdlife. The National Water Conservation Order (which includes Lake Wakatipu and its tributaries) recognises "the outstanding ecological, scenic, and recreational characteristics of these lakes and rivers"

Source: Chapter 4 in (QLDC, 2018).

The District Plan promotes "carbon sinks" by encouraging the retention of remaining areas of indigenous forest vegetation and minimising the restrictions on the plantings of exotic trees to those necessary to avoid any significant adverse visual effects on the environment. Specifically, the Proposed District Plan sets out the objective to protect

> **the District's landscape, biodiversity, water and soil resource values from the spread of wilding exotic trees (p.34-1 in (QLDC, 2019)).**

To this end, the Plan has the following restrictions with regards to the types of exotic trees that can planted within the QLDC boundaries:

- Planting of *Pinus radiata* is a restricted activity. Such plantations must avoid the spread of wilding trees and degradation to the landscape plantation(see Appendix A:), and
- Planting of other wilding exotic tree species listed in the table below is altogether prohibited.

Table 1 - Rule: Planting of wilding exotic trees

Rule	Planting of wilding exotic trees	Activity status
34.4.1	Planting of the following: a. Radiata pine (Pinus radiata) Except for Plantation Forestry where the Resource Management (National Environmental Standard for Plantation Forestry) Regulation 2017 prevails	Discretionary
34.4.2.	Planting of the following: a. Contorta or lodgepole pine (Pinus contorta)	Prohibited

Rule	Planting of wilding exotic trees	Activity status
34.4.2.	b. Scots pine (Pinus sylvestris) c. Douglas fir (Pseudotsuga menziesli) d. European larch (Larix decidua) e. Corsican pine (Pinus nigra) f. Bishops pine (Pinus muricate) g. Ponderosa pine (Pinus Ponderosa) h. Mountain pine (Pinus mugo uncinata) i. Dwarf mountain pine (Pinus mugo) j. Maritime pine (Pinus pinaster) k. Sycamore (Acer pseudoplatanus) l. Hawthorn (Crataegus monogyna) m. Boxthron (Lycium ferocissimum) n. Buddleia (Buddleja davidii) o. Grey willow (Salix cinereal) p. Crack willow (Salix fragilis) q. Cotoneaster (Simonsii) r. Rowan (Sorbus aucuparia) s. Spanish heath (Erica lusitanica) Except for Plantation Forestry where the Resource Management (National Environmental Standard for Plantation Forestry) Regulation 2017 prevails.	No application for resource consent can be accepted

Source: Chapter 34 of QLDC's proposed district plan:

The constraints on the types of trees that can be planted within QLDC are a key parameter for our modelling. Rather than seeking to define specific planting recommendations, we have instead adopted a range of different protocols that reflect the exact nature and opportunity of sites that can be replicated across the District. Generally we assume that:

- A permanent native forest planted on deforested plantation land, arable land converted to forestry land, or other areas with severe limitations for arable use would emphasize beech species, but use grey shrub species, starting with Manuka/Kanuka, to enable early establishment.
- For urban park lands not conducive to harvesting wood, these could be planted with a typical native forest species mix, or with sterile exotic trees that grow fast and store carbon well
- Areas with good potential for biomass production (e.g. in the Hawea plains) could be planted with coppiced trees and long-lived perennial crops such as *Miscanthus x giganteus*. Eucalyptus species that are adapted to the local climate and coppice well include *E. macrorhyncha, E. youmanii and E. viminalis*.

We note that the spread of exotic species has also been a factor in QLDC's decision for an early harvest of the Coronet Forest – a Douglas fir forestry (p.41, Volume 1 in (QLDC, 2018a)). In our scenarios, we make the general assumption that the policy objective to stop the spread of wildings within QLDC will also have an impact on forestry intentions of private land owners.

We assume, for the purposes of carbon sequestration, that all privately owned pre-1990 forestry (however small) would be cleared and replanted with native forest capable of greater management to maximise C stocks, or replanted for biomass production. We acknowledge that currently not all forest blocks that are removed are replanted in native species or otherwise restocked, but this becomes an issue for future policy consideration or planning interventions.

2.2.2 Changing Rules on Water Rights

The Otago Regional Council has recently proposed a change to the Regional Plan: Water for Otago to add an objective, policies and rules with regards to the replacement of expiring deemed permits and water permits, with an aim to improve freshwater management. The plan change is the first step in the transition from the Regional Plan: Water for Otago to a new "fit for purpose" Land and Water Regional Plan (LWRP).[9]

Specifically, it is proposed that the replacement of expiring consents is granted for a duration of no longer that six years, and that a similar duration limit is applied to new water permits.

Although at the time of this report water rights remains an unresolved issue,[10] it can create some vectors that may change land use behaviour – a possibility that deserves further study. For example, it could affect incentives for land use activities in Hawea Flat. For the purpose of our paper, the proposed changes to water permit rules are relevant to the extent that they further encourage conversion of water-intensive land use to biomass cropping – in our analysis, we are choosing species that do not require water, and are able to operate in the harsh environment.

[9] https://www.orc.govt.nz/plans-policies-reports/regional-plans-and-policies/water/proposed-water-permits-plan-change-plan-change-7

[10] The process for making the proposed plan changes is ongoing, with the initial public submissions having closed in August, and another round of submission will be called for under section 149F of the RMA.

3. Land Areas and Land Use in the District

3.1 Overview

We present here a brief summary and definitions of the land types and land uses that characterise the QL District. The overall setting of the District is all about the natural beauty and natural values. But also, the District is characterised by its large area of high country and by its glacial lakes: Wakatipu, Wanaka and Lake Hawea. The total land area of the District is 937,500 ha.

Rainfalls vary between about 600 mm per annum in the part of the Kawarau Gorge in this subregion, to in excess of 8000 mm per annum in some parts of the Southern Alps which form the headwaters of many of the catchments feeding the Clutha River/Mata-Au system. A recent report commissioned by QLDC of suggests that as a result of climate change, the Queenstown Lakes District is likely to warm by several degrees by the end of the 21st century, while the distribution and intensity of rainfall is likely to change, with a greater likelihood of more extreme rainfall events[11].

Figure 1 below presents a map of the District with key topographical features outlined.

Figure 1: QLDC Topographical features and territorial boundary

[11] Bodeker Scientific, Climate change implications for the Queenstown Lakes District, April 2019

Whilst a mountainous region, the total alpine area in hectares above 900 metre is actually quite limited (9,400ha) which means that much of the land area, although alpine in nature, is below an elevation at which we might expect to see natural beech forest vegetation, or the like.

For the purposes of this analysis we have largely focused on the land areas below a nominal 700m elevation, with separate consideration given to the areas between 700 and 900 metres, with the following land area distributions; above 900m (9,400 ha), 700-900m (113,700 ha) and below 700m (814,400).

An additional factor, although not considered in any detail this analysis, is the geology of the District. The nature of the terrain, especially the steep slopes does present some geotechnical constraints. Liquefaction and alluvial fans are also issues in Queenstown Centre whilst the area south of the Kawarau River is subject to geotechnical hazards including alluvial fan liquefaction.

The future impacts of climate change on these settings has not been considered here.

Most of the District, with the exception of LINZ pastoral leases, is protected as publicly owned open space, conservation reserves, or as QEII Trust covenants. When the assessment of Outstanding Natural Landscape is included, approximately 97% of the whole QL District may be considered as 'protected'. The Queenstown and Wanaka urban areas occupy a very small part of the land area in the District (approximately 50,000ha).

The biodiversity in the often either cold or dry climate is probably less than in other regions of NZ, but it is quite unique and therefore valuable[12]. The most significant biodiversity is found in the alpine environment or within public lands.

The district has a heritage which includes ancestral sites of the Kai Tahu, including ancient trails (ara tawhito). The settler heritage is found in historic districts of Arrowtown and Queenstown. The local community and visitors both appreciate the Upper Clutha, Wakatipu Basin and Gibbston Valley for the character of their landscapes.

The landscapes and character of the Wakatipu Basin, Gibbston Valley and Upper Clutha are valued by the local community and visitors. The good farmland with LUC Class 1-3 soils is valued for its economic output and appreciated for its contribution to the landscape. These are Hawea Flat, south of the Cardrona River and along the Kawarau River in the Wakatipu Basin.

The Department of Conservation (DOC) administers a very large component of the land area within the district; second only to the grazing leases overseen by LINZ (Figures 2 and 3 over). This includes parts of two National Parks to the west, Conservation Reserves located in proximity to the large lakes, QEII Trust land, and other categories of public conservation land of lesser size.

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[12] C Meurk, personal communication.

Total land areas in these categories are various assessed at:

- Total DOC lands (421,200 ha of Public Conservation Land under the Department of Conservation)
- Pastoral leases managed by LINZ (298,600 ha)
- QEII Trust lands (47,200 ha covenanted)
- Other QEII lands (not assessed)

The Pastoral Leases held by LINZ is the most pertinent category high-country areas for considering management interventions designed to sequester carbon in vegetation, due both to the amount of land potentially available and the potential carbon benefits that might accrue through land use change to more intensive C stocking. These are shown in blue in Figure 2 below.

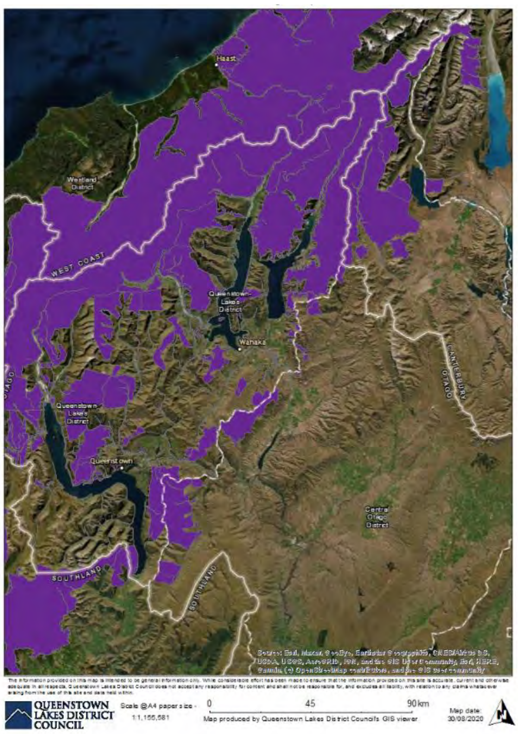

Figure 2: Department of Conservation land

Figure 3: Land Information NZ managed land mostly pastoral leases (in blue).

The District (most of it with a grazing history) has multiple land categories, based on administrative control. These include two categories under DOC administration, private land as identified in the LINZ database, mostly pastoral leases (some of it with QEII Covenants) or in forest plantations.

Publicly managed land (by LINZ) increased by 73,400 ha in Otago region in 2009 due to High Country Tenure Review (MfE, 2010), a significant amount of it in the QLDC.

3.2 Identifying and Categorising Lands Suitable for Sequestration

This topic is reviewed in more detail in Section 4.3. What this review shows is that whilst the use of farm land in Land Use Capability (LUC) classes 3, 4, 5 and 6 should be the focus of investigation for producing high yields of biomass crops, the pastoral lease lands managed by LINZ are the most pertinent land category for considering any long-term management interventions designed to sequester carbon in vegetation.

This would entail land use changes to enable carbon farming as permanent shrubland or forests. In arriving at this conclusion we have also taken into account altitude and land use factors.

Altitude strongly influences temperature limits on growth, while northern exposure results in hot/dry limits on summer growth and survival. Therefore, those subcategories enable a more targeted assessment of the land area where a particular type of vegetation management is appropriate or successful[13].

In this study we have chosen to look at the overall land categories partitioned into altitude sub-categories and in addition into two subcategories based on predominant exposure: northern versus southern.

Some of these areas have been severely impacted upon both by infestations of wilding pines and also pests. We have made no assumptions in this study as to the possible benefits of pest control apart from noting that effective measures in this area largely fall within the District's resident's first-hand experience. A professional ecologist[11] view is that high altitude NZ vegetation is rare and is risky to try to modify and thus any interventions proposed in these areas will need to take account of site, pest and plant eradication, and also ensure proven planting protocols.

What we know is that a southern aspect is beneficial at low elevation in the thermal zone (above frost line) to mitigate drought; but detrimental at high elevation because of lack of warmth. Tree lines are lower on south aspects.

Another 'low hanging fruit' among land types is the lower altitude private land in the peri-urban belt and nearby slopes. Native plantings have been ongoing in such lands by community groups such as Te Kakano Trust in the Wanaka area (see Appendix B for photographs and related data of community group activity). As will be described later, this may not be the most productive means of increasing carbon stocks over the long term - if that is the desired goal - but we acknowledge that there are other values at play. Nor does this suggest that QLDC should not look to scale up locally-led native forest planting projects as success in such reforestation efforts will greatly depend on sourcing local knowledge of adapted NZ native species.

[13] Renquist R, 2012

There are several fairly new land and vegetation assessment tools which may well inform future decision making in this area. Some of these, such as LUCAS by Ministry for the Environment, and Land Cover (LCDBS) by Landcare. As yet these are not sufficiently populated with enough data from the high country of the QLDC for the area to be mapped.

Soil carbon stocks are important and being monitored by Landcare Research and changes are reported by Ministry for the Environment (MfE) in their Soil Carbon Monitoring System, a statistical model designed for estimating soil organic carbon stocks in New Zealand's mineral soils. It follows methodology recommended by the Intergovernmental Panel on Climate Change (IPCC).

The model used by MfE combines actual soil carbon data (samples collected from New Zealand soils under different land uses) with national spatial datasets of soil type, climate, land use and topography. MfE uses the model to derive estimates of soil organic carbon stocks for all land uses, and to estimate changes in soil organic carbon following changes in land use.

Recent research findings on soil C stock in grassland on hillsides showed no clear loss of soil carbon in recent decades, but little data relates to high country grazing lands with much less grass, other than some indication that fertilising tussock grasslands can increase soil C if not over-grazed[14]. In other soil science research in NZ[15] more advanced methods to determine soil C stock with respect to soil carbon saturation deficit have been developed.

All of these data will become important consideration going forward. In the meantime, we have simply relied upon the land use classifications and definitions[16] as developed by AgResearch – see below Figure. 4.

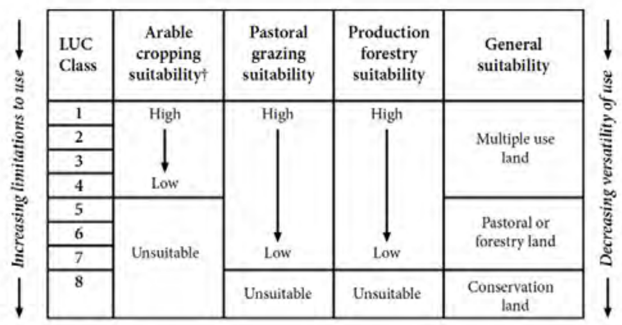

Figure 2: Increasing limitations to use and decreasing versatility of use from LUC Class 1 to LUC Class 8 (modified from SCRCC 1974). † Includes vegetable cropping.

Figure 4: Land Use Classification *after AgResearch*.

[14] Schipper et al, 2017
[15] Baldock, et al, 2017
[16] Reference : AgResearch Ltd., *Land Use Capability Survey Handbook,* 3rd Edition, 2009

The areas within the QL District measured for each category is as summarised below.

LUC classification	Area		LUC classification	Area
LUC 2	3,162ha		LUC 5	4,633ha
LUC 3	17,620ha		LUC 6	15,206ha
LUC 4	29,482ha			

As can be seen there is some 50,000ha of land that falls within categories LUC classes 4, 5 and 6; which become an important sequestration target. This opportunity is discussed later in this report.

Again, in order to arrive at a relevant picture of the capacity of the different land types within the QLDC for C storage, we have necessary focussed on conventional approaches to land use and land management strategies. The value of Mātauranga Māori and regenerative farming practices for example are important additional considerations. The latter, in particular, is most relevant to agricultural practice, such as how to raise livestock and grow pasture/feed etc., but at this early stage the dominant considerations for transitioning to a viable carbon sequestration regime relate mostly to land use change, and the limitations that arise due to local environment conditions and soil types.

4. Options Assessment - Biological Sequestration

4.1 Introduction

In this section we examine the opportunity for QLDC to use biological sequestration as a mitigation against climate change. As previously described, New Zealand is well placed to mitigate climate change through further afforestation and the growth of forests that hold carbon in their large tree mass and as well encouraging targeted plantings of non-woody plants that act to increase C storage below ground and in soil life.

In the previous Section 3 we presented a summary of the land types and land uses that characterise the District. What we know is that the Queenstown Lakes subregion contains a large area of high country and is dominated by its glacial lakes: Wakatipu, Wanaka and Hawea and, as well, by its continental climate and uncompromising cold winters and hot summers.

It is this climate, combined with a high proportion of high altitude sloping ground and not very deep soils, which makes the Queenstown Lakes District arguably one of the more challenging areas in the country to grow plants with high C storage, since that requires high plant growth rates (dry matter). The District also comprises significant area of conservation estate, (421,200 ha of Public Conservation Land under the Department of Conservation) as well as other areas that have high landscape and biodiversity values.

These features reinforce the constraints one is likely to face with any large-scale reforestation (or carbon farming) effort, but also allows us to point to where opportunity might lie for more targeted interventions that offer a good chance of success to increase carbon stocks. For example, the less sloped areas with better soil are currently in use for pastoral and arable agriculture but present currently an unrecognised potential for biomass cropping and/or improved land use to increase C stocks.

A very important overlay is also the values attributed to landscape, conservation and biodiversity. These all need to be included in the mix when considering biological sequestration options. It has not been our role in this study to seek to clarify those values, but again we note that it is our expectation that through this technical report the various policy and regulatory paths to emissions offsets via carbon sequestration can be more fully addressed.

Species selected in this analysis include NZ native species (which are favoured by many of the local residents) and also small numbers of selected exotic species allowed in QLDC planning rules. Among native species only old growth beech forest has high dry matter (DM) plant cover and it occupies a low proportion of District land. It is very difficult to restore once gone (although recent progress has been made in techniques).

Beech is even more difficult to establish in new terrain, usually requiring a favourable microenvironment created by growing native shrubs.

Our assessment of the Queenstown Lakes District land types/categories and their potential to be converted to higher DM vegetation has indicated that there are some approaches that offer a higher potential to sequester carbon than current practice. However, such approaches need to be better underpinned by robust plant science and further research to confirm the best plant species or mix of species, and establishment practice.

The practical means to achieve native forest restoration was first described in the 1990s. Detailed guides in 1993 by Porteus[17]and in 1997 by Meurk[18] outlined step by step approaches to restore or establish native South Island forests. Two collaborative research project are currently under way. One is the 'Wakatipu Beech Seeding Project'[19] in collaboration with Otago University and the CRI Scion. The other is 'Restoring wilding stand in the Wakatipu basin by seeding native trees' by Scion[20].

Scaling up locally led native forest planting projects 50- or100-fold has good support by enthusiasts in the community. A key factor to identify for any native planting is whether the site is favourable for eventual beech forest establishment. Plantings that aim to build up the carbon stock of the District should likely focus on such beech sites and also acknowledge that the high sequestration levels that could eventuate from established beech forest will only occur well after the 2050 target date for this study. We refer to a recent Landcare paper that offers good insight into the values that can be ascribed to natural forest re-establishment (Walsh, et al. 2017)[21]

Integrating a professional ecologist's point of view on forest restoration is also essential when proposing a new management objective such as carbon sequestration. This is an area of unfolding research interest. The general view offered (see 6.1 References) is that high altitude NZ vegetation is rare and is risky to try to modify. At the very least, it will be necessary to do a botanical survey of species at any specific site before modifying it.

Research ecologist and consultant, Colin Meurk, has considerable experience in the afforestation of natural forests, including the development of forest land above the Wakatipu Basin. The lessons from his work also applies to the planting of grey shrubland species to create a favourable environment for the planting of higher dry mass species.

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[17] Porteus, T. 1993.
[18] Meurk, C. 1997.
[19] Wakatipu Beech Seeding project, 2017.
[20] Scion, 2020.
[21] Walsh, Patrick, Tarek Soliman, Suzie Greenhalgh, Norman Mason, David Palmer. 2017. Valuing the Benefits of Forests. Report by Landcare Research for Elizabeth Heeg of MPI. MPI Technical Paper No: 2017/68.

His advice is that a good approach should include:

1. drastic pest plant eradication (of wildings and other exotic weeds);
2. eradication of goats and as close as possible of rabbits as well;
3. staying below 700m altitude, which is the native tree line (other than wilding species eradication, since they are adapted to the climate and already higher up-slope);
4. selection of sites to modify using the LENZ land categories and S-map soil classification tools developed by Landcare Research for future project work involving high country land use;
5. make any plantings by following a proven protocol (his 1997 guide[12] and the new Scion one by Paul et al[22]);
6. when selecting sites to add native species, a southern aspect is beneficial in the thermal zone, but the tree line is lower on that side, another reason not to go higher up than 700m.

The overarching observation by Meurk is that large-scale modification of the high country tussock lands, for purposes we are proposing in respect of sequestration, is likely to present difficulties and may prove to be unacceptable in practice. We comment on this observation further in the protocols developed for this particular pathway.

Globally, increasing attention is also be given to the use of purpose-grown species to both enhance carbon storage and also provide opportunity to supply biomass as a renewable energy source, or as a means of fixing carbon from the atmosphere. Land use change from existing pastoral/grazing use to more intensive cropping regimes presents opportunities for both reducing ruminant methane emissions as well as improving carbon stocks on the land; a double win.

The greenhouse gas effects of changing from ruminant livestock to forests was modelled in depth back in 1999 by Ford-Robertson *et al*[23.] Their modelling determined changes in carbon stocks from different combinations of soil type, browsing animal, livestock carrying capacity and site productivity. Land use change from grazing to agroforestry greatly improved the carbon balance of cropping land.

Overall, our approach has been to examine the different land categories and associated land use options from the perspective of maximising C storage. With this understanding we have then taken a high-level look at the various climatic, ecological and other factors that influence establishment and growing regimes and sought to establish plausible sequestration pathways that might be a consideration for future evaluation. These pathways then have been used to build a picture of what might, hypothetically, be

[22] Paul, 2020
[23] Ford-Robertson *et al*, 1999

possible and thus allows us to begin to estimate the carbon storage potential within the District.

Our working position was that determination of carbon storage potential needed to bring together both land category and the various species/planting options that might be used to increase carbon stocks:

- We thus start with establishing the various Land Category (by type, not use) and their respective land areas;
- Different Pathways to 2050 are then developed as a means of quantify carbon sequestration potential from one or more of the different Land Categories. This leads to an estimated quantity of carbon sequestered above ground at the end of growing season 2050;
- A pathway will have an associated Protocol describing in very high-level terms (fitting the short time spent in the project) the assumptions and issues and laying out the way in which plant biomass and C stock is increased - in essence a hypothetical case study;
- The vegetation type in each land category also enable us to arrive at an estimate of the dry biomass per ha, calculated from land area per type and leading on to an estimate of the total C stock change over time, expressed as $CO2_e$/ha;
- The C stock output derived from that process is fed into a sequestration model that combines the various pathways into a plausible estimation of the 2050 sequestration totals.
- This becomes our final estimate.

It should be reinforced that the estimates we derive via this process are not intended to be taken as targets or even as desirable outcomes. Simply, they are intended to be looked at as carbon sequestration potentials when the objective is to maximise C stocks. There are many other considerations that will need to be taken into account before any final decisions are made.

4.2 Protocols for Carbon Sequestration Covering the Range of Land Categories in the Queenstown Lakes District

A protocol is essentially a 'how to' guide, such as a farmer/user guide sheet, prepared by agricultural scientists on how to manage a particular crop. In this case it applies expertise to how crops can be grown to achieve high biomass yields and how species compare, factoring in the soil and other growing conditions.

Whilst there are many ways or approaches that could be adopted to revegetation / reforestation we have decided here on six Protocols as illustrative of how biological carbon sequestration can be achieved on the range of land categories present in the QLDC. Each protocol is fitted to the landscape features and the current land uses, to identify from this early stage analysis the likely most successful approach to sequester greater amounts of carbon than with other land use choices.

The first two protocols target peri-urban land, farm land and steeper, low altitude farm land. Our other protocols target the High Country land that makes up such a large part of the land within the District. As previously described, the District lands comprise multiple land categories, based on administrative control (DOC, pastoral leases (LINZ), other public lands (QLDC) and private land). But also we need to take into account altitude and also predominant exposure (northern versus southern). Altitude strongly influences temperature limits on growth, while northern exposure results in hot/dry limits on summer growth and survival.

To this end the high country protocols include suggested trials at two areas situated near Queenstown on southern and northern exposure sites at moderate altitude. The southern aspect protocol contains a QLDC owned forest plantation near Coronet Peak; the northern aspect sequestration candidate site is on the upper end of the Remarkables.

We have selected these two contrasting areas on the recommendation of a local native tree planting specialist, Michael Sly, of the company Wildings & Co. He has very generously been able to give us local eyes to 'ground truth' our sequestration site concepts; including providing photos of relevant vegetation in regenerating areas, supporting our preliminary observations (see Appendix B). His GIS images of Protocol sites are included here.

4.2.1 Protocol 1: Community Native Forest Restoration

This protocol is applicable to the low valleys and more accessible hillsides within the District and represents the land category for which there is currently a developing good knowledge base for native forest restoration using nursery grown native plants. These have usually been planted by community groups and projects. The current rate of planting is about 24,000 plants per year, with a total area planted between 1 and 2 ha/yr.

Planting success to date has been variable, but is improving with experience. We have noted significant ongoing research and trials both here and around NZ (Tane's Tree Trust[24] ; Paul, T, et al, Scion 2020[25]) which are supporting current planting projects, such as the Wakatipu Restoration Trust; giving some confidence on success rate going forward.

The land category associated with this Protocol and the community approach represents the 'low hanging fruit' and may well warrant emphasis in any early efforts to sequester carbon as part of forest restoration. However, the scale of nursery seedling

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[24] Tane's Tree Trust 2015

[25] Paul, T., et al 2020, Scion

production to achieve reasonable carbon sequestration in coming decades in the land category represented by this Protocol would need to increase by at least 50-fold, (perhaps using public development funds) if any material carbon sequestration target is to be achieved.

The nursery practices are now very well grounded in the science of forest restoration / afforestation of NZ natural forest, which is largely based on the use of reasonably sized and properly handled nursery plants. Appropriate species planting succession on a site is also better understood, for example not to rush the introduction of beech trees. A key action for this plan is to assess feasibility of collecting sufficient eco-sourced seed for nurseries to use.

That may need ecologist input as to how much deviation from the planting site microclimate is acceptable. For example, the large Southland nursery that supplies the retail native plant market within the Queenstown Lakes District for lifestyle blocks and gardens apparently sells many more plants than the local projects identified above. They indicated that an even larger nursery is growing 400,000 beech trees right now, (we are guessing that the seed is sourced from higher rainfall forests to the west), but seed collection potential has yet to be addressed within the District.

A key factor to identify for each native planting is whether the site is favourable for eventual beech forest establishment. There is a well described step by step approach to the methods from site selection to picking the right planting date and establishment in the Meurk publication, 'Rediscovering and Restoring Natural Heritage in the Wakatipu Basin'.

The author's objectives start with "prepare a 'revegetation kit' for part of the Wakatipu Basin based on the known historic and contemporary vegetation patterns of the region, and covering the theory of planting, practical methods of planting, and appropriate plant materials." This is necessary to heed, since the growing conditions are very challenging. This advice was based on the underlying plant, soil and climate science done by Landcare Research.

This Protocol thus aims to inform and assist the community in accelerating the efforts to revegetate land within the District land closest to the places where most people live. We would suggest that any plantings that aim to build up the carbon stock of the District should likely stay on sites identified as being favourable for beech forest establishment, but also acknowledge that initial plantings will have limited C stock impacts and require many decades growth before significant levels of long term carbon sequestration is achieved (in beech forests). The C stock of shrubs will peak in less than 50 years.

We have applied this Protocol to Pathway 1 of the same name as set out in Table 2 in Section 4.3, and can make use of peri-urban land, farm land and steeper farm land.

With respect of the QLDC parks and reserves within the urban boundaries we note there is little scope for commercial forestry of exotic conifer species or plantings of some of the higher C stock species as these are disallowed under the District's outstanding features designation, and thus this protocol may well apply.

4.2.2 Protocol 2: High Carbon Sequestration

The land category that Protocol 2 can best be applied to is farm land, but it includes all land areas designated by MPI as Land Use Capability classes 2, 3 and 4. These are defined by lower slope and fewer soil limitation than the higher LUC classes 6, 7, and 8. This includes flat and rolling farmland, the land with the highest potential for increasing carbon sequestration in the District. This would involve changing land use to maximise biomass production, both in below-ground plant parts and soil and in above-ground biomass for periodic harvest.

High carbon stock options in the near term would need to utilise land often in current pastoral farming. The two categories of plants offering high carbon stocks or biomass for regular harvesting to produce bioenergy are a) non-woody perennials with both large top growth and large storage of carbon underground, such as giant miscanthus and Jerusalem artichoke (Renquist, 2014)[26] and b) hardwood trees that can be coppiced, such as eucalyptus and poplar (Sims, et al, 2001)[27], (Sims and Venturi, 2004)[28] and (van Ballekom, 2017)[29.]

On the flat or rolling land (LUC classed 3 and 4) we already know, based on over a decade of experience by author R Renquist, that giant miscanthus is an excellent tall grass with high carbon capture due to its very high dry mass (all dry mass is about 50% carbon). Miscanthus is well known in several NZ regions and the company supplying propagation material gives research-based advice for new plantings and plantation management.

As a case study we have identified that the best way to illustrate Protocol 2 is by examining the QLDC-owned Hawea Flat 40ha reserve, located south of Lake Hawea (marked in blue in Figure 5 below). Part of this site could be developed by the QLDC (perhaps in partnership with private interests) as a commercial scale demonstration of how to maximise carbon sequestration through growth of exotic species on the better land in the District.

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[26] Renquist, R. 2014. Life Cycle Assessment and Synchrony of Supply of Three Biomass Species: Giant Miscanthus (Miscanthus × giganteus), Triticale (× Triticosecale) and Jerusalem artichoke (Helianthus tuberosus). Report to the BTSL Project by Bioenergy Cropping Solutions Ltd.
[27] Ralph E.H. Sims, Tavale G. Maiava, Bruce T. Bullock. Short rotation coppice tree species selection for woody biomass production in New Zealand. Biomass and Bioenergy 20 (2001) 329–335.
[28] Sims, Ralph E. H. and Piero Venturi. 2004. All-year-round harvesting of short rotation coppice eucalyptus compared with the delivered costs of biomass from more conventional short season, harvesting systems. Biomass and Bioenergy 26: 27 – 37.
[29] Van Ballekom, Shaf. 2017. NZDFI: achievements, constraints and opportunities. (Marlborough Research Centre research on eucalypts).

Doing so offers pastoral farmers insight into the opportunity and access to trial data to confirm yields and species selection. The following details are suggestions to consider.

Figure 5: QLDC Hawea Flat Reserve.

This would include tree/crop management and periodic harvest systems for biomass production (coppice-capable tree species, mainly Eucalyptus, and long-lived non-woody species, such as giant Miscanthus).

The perimeter of the site could also grow/store biomass in visually acceptable way using non-wilding capable species of fast growing exotic trees *(Sequoia giganteum, Thuja plicata, Cedrus spp*, and Leyland cypress) with the outermost trees being adapted species that also provide bright autumn colours (Acer Platanoides, Quercus ilex).

Additionally, eucalyptus species that are adapted to the local climate and coppice well include *E. macrorhyncha, E. youmanii and E. viminalis*.

The application of this protocol applies to Pathway 2 by the same name, and applied to land categories farm land and steeper farmland (Table 2 in Section 4.3).

We also set out a more detailed description of the biomass purpose grown species in Section 4.4. and Appendix C. This is shown as an example of what might be possible in an industrial biomass cropping regime.

There are many other species possible, such as shoots of Jerusalem artichoke (*Helianthus tuberosus*) or tree species within a few genera (e.g., Salix and Populus) but we have not sought to make a wide assessment here. The species selected should be seen as analogues for a properly constructed species selection and options analysis.

4.2.3 Protocol 3: Southern Aspect Afforestation

This involves planting on southern exposure slopes of LINZ land in pastoral leases or weedy DOC lands and private land. It is likely that land with this exposure has better potential for beech forest development within the right altitude bands on these wetter slopes. The upper altitude limit for trees and shrubs with either north or south exposure is suggested as 700m, but with southern exposure there is less sun so winter temperatures can be too cold both at the lower and upper altitudes[30]

[30] C. Meurk, personal comm.

The planting of grey shrubland species (selected for adaptation to these exposures) will be the main task in the first decade, to create a favourable environment for also planting higher dry mass species (likely beech, but others need to be investigated). Much relevant science research has been undertaken by the Crown Research Institutes Landcare Research (Walsh, et al. 2017)[31] and Scion (Williams and Norton, 2012)[32].

The southern exposed slope above Speargrass Flat near Queenstown is a special case since QLDC owns forests that occupy part of the 1000+ ha of land on that slope from Arthur's Point to Arrowtown. These forests and wilding pine areas will be removed due to the wilding issue, but those sites are relevant in terms of whether they will be returned to tussock (if an area fits a criterion for scenic landscape on that basis) or replanted for a different purpose to contribute to the QLDC Climate Action Plan.

Figure 6 below identifies and area near Coronet Peak along the south and east-facing land from Arthur's Point below the ski field road almost to Arrowtown (>1000ha), that is undergoing exotic forest conversion to native forest. This area has a fair prospect for establishment of red beech forest. Successful examples of reforestation using nursery trees already exist, with trees more than 5m tall after less than 10 years.

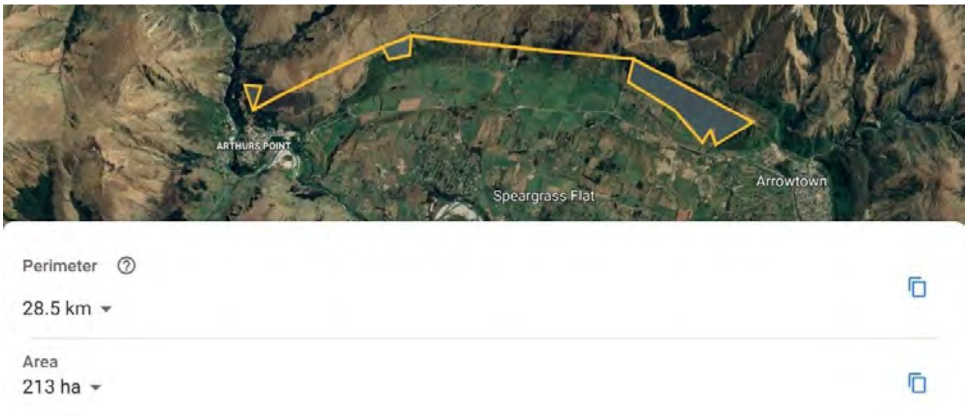

Figure 6: Potential reforestation land above Speargrass Flat

The Coronet Peak research and efforts will be well known to the QLDC since it owns the two forest plantations at the centre of current plans/efforts to convert from exotic species to native species, ultimately beech forest. This existing/emerging knowledge and experience can provide many details for this Protocol 3 and there is a productive overlap with the practical knowledge being gained within the community through the efforts described in Protocol 1.

We comment that much of the identified favourable high country land is likely to be under grazing leases. So, as discussed earlier for intensive biomass cropping, conversion

[31] Walsh, Patrick, Tarek Soliman, Suzie Greenhalgh, Norman Mason, David Palmer. 2017. Valuing the Benefits of Forests. Report by Landcare Research for Elizabeth Heeg of MPI. MPI Technical Paper No: 2017/68.
[32] Williams, Alwyn and David A. Norton. 2012. Estimating carbon stocks in stands of Podocarpus cunninghamii in the eastern South Island high country of New Zealand. New Zealand Journal of Forestry Science 42 (2012) 29-38.

of this land away from pastoral farming may offer additional carbon benefit from a lowered ruminant methane footprint. The potentially very large area of such Protocol 3 land means a considerable area can be planted and still not greatly impact pastoral leases overall. But the total reduction in ruminant methane could still be important.

Whether or not the benefits from carbon sequestration are also supplemented this way may depend on policies that make carbon farming both profitable and easier to manage than livestock.

However it is important to note that establishment and the scale up of nursery stock for seedlings is a major impediment and is likely to limit the rate of planting and thus the amounts of carbon sequestration. With preferred native species (such as beech) it is also important to recognise that the build-up of C stocks is very low during early decades of growth, giving a growth curve with a long lag phase as part of a typical S-curve.

This Protocol, Southern Aspect Afforestation, is applied to Pathway 3 with the same name in Table 2 in Section 4.3 and can make use of leased, private and some DOC land.

4.2.4 Protocol 4: Northern Aspect Enhanced Vegetation

Across Queenstown from Coronet Peak the exposure is mainly northern at the near side of The Remarkables. For example, the Station of Remarkables Park Ltd (RPL) includes land grazed on about 800 ha below an altitude of 800m (estimated by Michael Sly). This site would not support new beech plantings and is better suited to what is called grey shrubland native vegetation. Suitable species would include *Pittosporum spp*, manuka, kanuka and kowhai.

This site has some advantages for good establishment and growth rate of grey shrubland being at the elevations known as the thermal zone (600 to 800m) where the winter air temperature profile is inverted, with air warmer at night than either lower or higher altitudes. The lower half of these altitudes, with easier ground access, could be planted with nursery-grown native species, as per the experience of community planting projects and applying the recommended methods described in Protocol 1. Larger scale planting could follow once success with species has been demonstrated.

The Figure 7 view of the proposed site is within the currently-grazed land of the RPL pastoral property, and outlines the area falling inside the 'thermal zone'.

Figure 7: Remarkables Park Ltd pastoral property, near Queenstown

It needs yet to be fully determined if there is a good potential for beech forest development on these drier but warmer slopes. A key uncertainty is the growing of grey shrubland on higher slopes but will, irrespective, follow the same growing guides as applies to the basics of site selection, plant propagation in nurseries, planting procedures, etc. Whilst local experience will be important, advice from experienced consultants would likely include confirming the best plant species or mix of species, planting each topographical zone within a site using the species (among the mix) best adapted to the zone and development of specific deployment steps for each planting sites, such as weed management to match weed species mix.

As in the case of Protocol 3 it is likely, but needs to be confirmed, that there is a large land area available to be used for sequestration purposes. How to scale up with these species, and whether there are pioneer species that need to precede them (such as Manuka) will require investigation. As with the other native protocols, nursery supply of seedlings is a major impediment and is likely to be a limit on achievable rates of planting in the first decade or more.

Steeper areas might also be planted by direct seeding of natives (Manuka, Kanuka) in such sites, as recent experimental work using seeds progresses.

These species will accumulate carbon but will not sustain the C stock beyond 50 years. This consideration is not taken into account in our estimates as these only extend to 2050. However, we consider that focusing this Protocol on the RPL site is a good way to assess the potential to increase the carbon stock on northern aspect sites such as occur throughout the Queenstown Lakes District.

This Protocol applies to the Pathway by the same name in Table 2 in Section 4.3.

4.2.5 Protocol 5: Carbon Farming in Tussock Land

In this protocol we consider over-sowing tussock land up to 700m altitude with grey shrubs for carbon farming on an extensive (rather than intensive) basis. This would depend on the government evolving the non-ETS incentive programmes to include grey shrubland species in South Island high altitude tussock terrain. The LINZ managed Pastoral Lease land totals 298,600 ha in the Queenstown Lakes District.

The C stocks in tussock vegetation is very low but would be increased perhaps 2-3 fold over a few decades with grey shrub species, starting with Manuka/Kanuka and perhaps leading to tall-growing Matagouri in some zones, as recommended by a research ecologist. This could become an economically feasible land use if incentives matched the fairly low returns per hectare currently achieved by grazing tussock vegetation.

Establishment details outlined for Pathways 3 and 4 should also suffice for Pathway 5, but ecological advice should be sought regarding whether any carbon farming modification of higher altitude tussocks is likely to be accepted. One expert ecological view has been solicited to inform this Protocol. The advice received was that, given how much the natural landscape has already been altered, the clearest lesson is that no further changes in land use or management should proceed without an inventory (a botanical survey) in each site. This seems a very worthwhile suggestion, but may well limit the application of this protocol across some parts of the District.

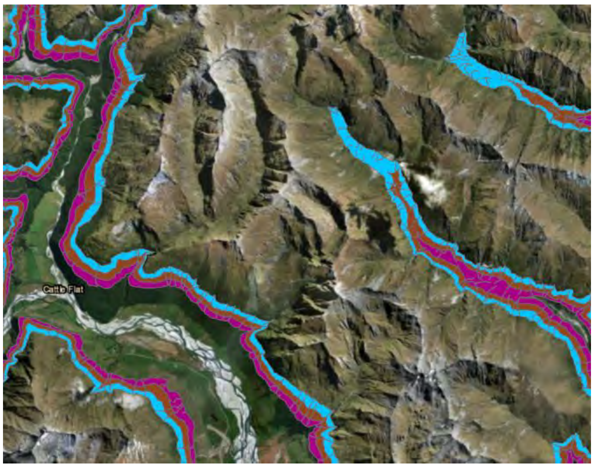

Figure 8: Image SW of Lake Wakatipu

The land area lying between 600 and 700m (the red band in the image from SW of Lake Wakatipu) is approximately 47,600ha across the whole QL District.

About half of this is in DOC Public Conservation Land, which may well exclude some uses, possibly this use included.

However, of the remaining 24,000 ha in LINZ pastoral leases about half, or 12,000 ha, could have the appropriate southern exposure.

In practical terms, therefore, related to planting logistics, it is likely that there will be sufficient lower elevation sites for carbon farming to be undertaken at an ambitious scale. The estimated 12,000 ha area of suitable land across the District defines the theoretical maximum land area this Protocol could be applied to for carbon sequestration. This is a large area, and further detail assessments would have to be done of land suitability, but the whole area would not be in use at one time.

Due to the short lifespans of grey shrubs (<50 years) new carbon sequestration plantings would be made on staggered planting dates. By 2050 the first cohort would still be growing and one or two more cohorts planted as well, perhaps a maximum of 40% of the 12,000 ha.

Alienated Lands. The QLDC has identified that there is a significant area of alienated lands, located between other administered lands such as DOC and LINZ leases. This land area should not be overlooked as much of it is likely to be similar to the land category described here. In terms of the Pathway/Protocol Descriptions (Section 4.4) we have combined the Alienated Lands category with this LINZ pastoral leases Land Type as indicative of the sort of intervention that might potentially be possible.

4.2.6 Protocol 6: Special Exotic Plantations

A future alternative means for the sequestration of carbon across the District is to allow exotic forest plantings involving tree species that do well in the drier parts of the District and which could in a decade or so be available in modified non-wilding (sterile) forms.

Although more 'outside the square' in nature than the above carbon sequestration protocols, research to achieve this in respect of the forestry species common to NZ is now advancing well (Porth and El Kassaby, 2014)[33], (Fritsche, et al. 2018)[34] (Porth, et al, 2018)[35]. Research on hardwood species like Populus or Eucalyptus indicates that these species are easier to achieve sterility (Strauss et al. 2017)[36], but advances are also progressing in softwoods such as Pinus radiata (Fritsche, et al, 2018); (Porth and El-Kassaby, 2015)[37].

There are other aspect of biotechnology research that will also be useful to take advice on over the coming decade that involve tree changes other than just sterility. These include improved biomass yield via greater wood density and/or improved growth rate; improved resistance to pathogens and insects which would both reduce management cost and improve crop yield; and wood with more cellulose to enable greater yields of liquid biofuels.

The protocol make use of more remote, scenically less sensitive parts of the District; including the large pastoral lease area as described in Protocol 5. It would make use of special forms of exotic tree species, which have demonstrated superior ability to NZ native species for producing high biomass (and C stock) in the harsh continental environment.

In our Pathway descriptions this option is shown as not starting for at least another decade, but it illustrates how different carbon stocking forests or bioenergy plantations are from a simple reliance on replanting with high country vegetation. The use of such exotic plantations would contribute products and economic activity local to the District: e.g. bioenergy to replace fossil fuels and the supply of timber for local construction. Such forestry would be carefully located and would be limited to ensure it did not compete with restoration of the District's natural vegetation.

The difference from the current wilding-prone exotic timber species is that such new plantings would be enabled by, and only allowed following, successful breeding of sterile plants which would be grown from tissue culture.

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[33] Porth, Ilga and YA El-Kassaby. 2014. Current status of the development of genetically modified (GM) forest trees worldwide: a comparison with other GM plants in agriculture. CAB Reviews 9: No. 008.
[34] Fritsche, Steffi, Amy L. Klocko, Agnieszka Boron, Amy M. Brunner and Glenn Thorlby. 2018. Strategies for Engineering Reproductive Sterility in Plantation Forests. Frontiers in Plant Science, 15 November 2018. doi: 10.3389/fpls.2018.01671
[35] Porth, Ilga, Gary Q. Bull, Julie Cool, Nancy Gelinas and Verena C. Griess. 2016. An economic assessment of genomics research and development initiative projects in forestry. CAB Reviews 2016:11, No. 016. doi: 10.1079/PAVSNNR201611016
[36] Strauss, Steven H, Kristin N. Jones, Haiwei Lu, Joshua D. Petit, Amy L. Klocko, Matthew G. Betts, Berry J. Brosi, Robert J. Fletcher Jr and Mark D. Needha. 2017. Reproductive modification in forest plantations: impacts on biodiversity and society. New Phytologist 213: 1000–1021. doi: 10.1111/nph.14374
[37] Porth, Ilga and Yousry A. El-Kassaby. 2015. Using Populus as a lignocellulosic feedstock for bioethanol. Biotechnology Journal 10, 510–524. doi: 10.1002/biot.201400194

We suggest two reasons to consider further this proposition. The first is that the success rate and supply of native seedings is likely to be low in the early years of any large-scale reforestation effort and thus the ability to augment native plantings with exotics offers higher stocking and thus faster C-sequestration rate. The second, is that the economic incentives that arise from commercial forestry activity also incentivises pest control and overall improved land management.

Ruminant methane emissions in the District would be reduced considerably in this Protocol. The land area converted would be determined by wood demand for bioenergy and timber in the District (but harvest would all be later than 2050).

This Protocol, Planting Special Exotic Plantations, applies to the Pathway by the same name in Table 2 in Section 4.3.

4.2.7 Protocol 7. Offset Forest Swaps

This protocol would involve forest 'swaps' with Southland sites, gaining offsets for local emissions. We do not consider this protocol further but suggest that a novel approach might be to consider a philanthropy-funded purchase of farmland in northern Southland, where tree growing conditions are more favourable both as permanent forest sinks and for biomass production to produce bioenergy.

This would make use of better soil/climatic attributes outside the District and trees that are acclimated there. While this pathway is hypothetical, actioning it would not require any technological advances. It would involve council and community assessment of its merits (a policy matter outside scope of this Action Analysis).

It would also provide an offset to the carbon footprint of other activities by the QLDC residents and visitors (a larger offset than is possible with native plant sequestration of C anywhere within the District).

4.3 Pathways Descriptions

The descriptions of our suggested Pathways to 2050 are a key construct to assess and document how the many categories of land type in the QLDC can be structured so some can be grouped into an appropriate pathway, both for future evaluation and possible action.

Pathways are not designed to bring the entire land area of each category into use for sequestration. Plantings of native trees or shrubs are not likely to succeed above 700m altitude. Realistic pathways need to allow for the time it takes to produce sufficient plants and manage the labour inputs. It is also necessary to see results from one planting before scaling up massively. The QLDC guidelines on plant species not allowed, such as wildings-prone, also limits new plantations since those species are the most productive for commercial forest companies.

These pathways are set out in Table 2 and include our estimates of potential stocking rates based on current known parameters and establishment capabilities. We advise that these pathways need to be further investigated in terms of the steps needed to deploy the various options depicted, and to address the key uncertainties described within the various outlined protocols.

In order to align Table 2 with the companion work undertaken for QLDC on emissions reduction we have in this report expressed the carbon stocks in terms of the units of CO_2e/ha/yr. However, our base metric is the dry matter yield and the carbon stored within the living biomass. The early stage nature of this work has precluded any detailed consideration of soil carbon.

In this instance the dry mass estimates of high country grazing land were estimated relative to a grazed ryegrass paddock in well rain fed areas. Multiple harvests to simulate grazing will yield up to 7tDM/ha/y. (if left to get dry with large stems the DM would be 10-12 tDM/ha in a single harvest per year).

It is assumed that tussock and small weeds would yield <2 tDM/ha/y or 1 tC/ha/y;

A grey shrubland planting on a northern exposure which is too dry for beech trees will have peak DM yield after about 30-40 years. On southern exposure grey shrubs will peak at 40-50 years, but site DM will keep increasing if beech and other large podocarp tree species are sufficiently present to provide forest canopies.

A beech plantation managed for a good start can build C stock up to 300 tDM/ha or 150 tC/ha after 300 years (we note that climate literature often uses units of CO_2e/ha, which would need to be divided by 3.67 to show carbon stock).

Conventional forestry dry matter yields are well described in the literature with a useful reference point the various studies undertaken by Scion[38] of carbon sequestration for different species and rotation ages in New Zealand. The values are relatively simple to calculate for commercial plantations, since models have been developed based on extensive empirical measurements.

The already referenced native forest planting/growing guides quite clearly set out the required steps for establishment of these protocols. Deployment steps for tree species to coppice are likely to be best determined by contacting one or more consultant or the CRIs. Deployment steps for a giant miscanthus plantings are described in some detail in the Protocol Report by Renquist (2014a).

In developing these pathways we also took a specific look at what was happening with existing forestry operations and also at the urban parks and reserves spaces owned and managed by QLDC. We have included QLDC forests in our pathways, combined into the Pathway 3, Southern Aspect Afforestation. That Pathway includes the QLDC forest, other forested land, and wildings removal areas.

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[38] Ford-Robertson J, Carbon balance calculations for the forest industries - a review, NZ. Forestry, May 1997

Table 2: Summary and establishment assumptions used for development of C Sequestration Plan

Pathways to 2050	**Expected Stocking out to 2050** **Annual plantings schedule**	**Estimated 2050 C Stock - as established over the period** **(tCO_2e/ha)**
P1.Use of nursery native plants, scaled up from 20,000 per year to >1,000,000 (50-fold) by 2030; Planted areas increase as directed by community groups and then assumed to expand greatly with government funding of nurseries and planting labour.	Nursery production up 10x by 2023, Planted area (At 10,000 plants/ha) = 20 ha/y; by 2026 At 25x current trees grown = 50 ha/y; by 2030 At full speed (50x current) the area = 100 ha/year until 2050; Average age at 2050 = 20 years = 17 y growth at 2 tDM/ha/y = 34 tDM/ha in 2050; total carbon = 17tC/ha Total area planted 2050 = 2,320 ha	50 (adjusted to take account of northern exposure sites)
P2.Fast growing eucalypts and miscanthus to give early and high rates of C sequestration; These use some of the current arable land and low hills; some of the 52,000 ha in LUC classes 3-5 is scattered and half of Class 5 (2,300 ha) is not suitable; However, there is still ample land to produce 100,000 tDM/y by 2035.	Use 20% of LUC classes 3, 4, 5 land (rolling farm land or flat with shallow soils) = 10,000 ha by 2050; Biomass trees and crops planted on 1000 ha by 2024, first harvests in 2027-8 (at 12 tDM/ha) = 12,000 tDM = 6,000 t Carbon; 5000 ha planted by 2030 (with average yield now 14 tDM/ha) =70,000 tDM = 35,000 t Carbon; Full production from 2035 only requires 100,000 tDM/y, which can be achieved using 12.5% of the of total land in these LUC classes.	Miscanthus 27.5 (annual crop) Eucalyptus 29.3 (annual crop) (full C stock re-grows every year; other values in this column are total growth to year 2050)
P3.Reforestation of these slopes near the Basin will follow the timeline of felling and clearance + 2 years on 500 ha; Other parts of the slopes (700 ha) are not forested so could be planted sooner. Total planted by 2030 = 1200 ha. Red beech is the aim for the future canopy, but will only contribute 0.5 tDM/ha/y by 2050. If grey shrubs are used ahead of beech they will contribute on average 1.2 tDM/ha/y	Beech trees planted in 2030 will contribute 0.5 tDM/ha/y by 2050. (but 4 tDM/ha if planted in 2020) If grey shrubs are used ahead of beech and have an average age of 20 years for all planting dates across 1200 ha, they will contribute 2.0 tDM/ha/y from ages 3 to 20; 17 yrs x 2 tDM/y = 34 tDM/ha total in 2050; total C = 17 tC/ha;	63
P4.Northern Aspect Enhanced Vegetation. includes 800 ha grazed land 800m on assumed site; Grey shrub species up to 700m planted to store carbon while	Grey shrub planting will grow more slowly, heat limited; in 2050 the average age will be 20 years for all planting dates across 1200 ha; they will contribute 1.2 tDM/ha/y	37

improving vegetation (assumes stock will not graze the grey shrubs and good pest control).	from ages 3 to 20; 17 yrs x 1.2 tDM/y = 20 tDM/ha total in 2050; total C = 10 tC/ha;	
Pathways to 2050	**Expected Stocking out to 2050** **Annual plantings schedule**	**Estimated 2050 C Stock - as established over the period (tCO_2e/ha)**
P5. Carbon farming in tussock land from 600-700m. Tests potential for widespread use of grey shrubs on southern aspect tussock land. Same general approach as P3 and P4.	Same aim and calculation as P3 and P4. Assume expected C stocking rate in 2050 to be an average of that for P3 and P4; avg forest age = 17yrs 17 yrs x 1.6 tDM/ha/y = 27 tDM/ha; Total C stock = 13.5 tC/ha	49.5
P6. Special Exotic Plantations. Lab development and scale up will take 10-15 years. 500 ha plantation will have no harvest before 2050. Tissue culture of Douglas has been tried for decades, but new genetic techniques may succeed. *P radiata* is a better bet to tissue culture. Breeding a sterile strain is a separate research procedure.	The area target is 1000 ha by 2050, starting planting by 2030. Assume average age in 2050 = 15; Average DM by 2050 = 19.6 tDM; Average carbon by 2050 = 9.8 tDM No harvest by 2050.	36
P7. Offset Forest Swaps. This Pathway is not related to QL District lands, but could be of interest given the difficult plant growth in most of the District	N/A	N/A

In these above pathways we have assumed that future wildings removals supported by government programmes will also involve replanting, likely to be a mix of protocols 3, 4 and 5. This is a future action that QLDC will need to address.

Wildings are defined by us as tracts of the wilding forest resource which has matured into a harvestable size and canopies are closed. They will have a large variation of ages and sizes of trees within the forest and thus basically have a lower C sequestration rate than managed plantation forests. Wildings have become such a damaging factor in the high country landscape that the government has allocated over $100m for a dramatically larger programme.

In addition, a large section of the 1200 ha area identified in the Pathway 3 site has exotic forest species too scattered for commercial management. This land is part of the reforestation plan but does not have to wait for the harvesting of existing plantations and any clearance of wildings forests.

With respect to total existing forestry we have made assumptions about removals as set out below. The carbon impacts arising from this activity is incorporated into the emissions reporting presented in the Emissions Reduction Pathway report.

The below table sets out our estimates of the total planted forest and wildings areas.

Total area =1,730 ha:

- Commercial forest = 360 ha removals start 2030 and completely gone by 2050 with replanting likely a mix of protocols including exotic plants (Protocol 6) and high carbon sequestration (Protocol 2)
- QLDC forests = 370 ha are assumed gone by 2030 with replanting in native (Protocols 3 and 4)
- Additional small woodlots = 500ha remain are presumed largely unchanged with an assumed clearance rates of 5% per year
- Wilding pines = 500 ha removed by 2040 with replanting likely to be a mix of protocols 3, 4 and 5.

Remaining details are described in Section 4.5 and Appendix C. Section 4.5 sets out in tabular form the finalised sequestration inputs for modelling whereas Appendix C provides a more detailed view of the various sequestration pathways drawing on the bio-sequestration protocols described above, and the relevant policy and regulatory settings described in Section 2.

4.4 Purpose Grown Species for Biomass Production

This section provides a brief overview of the underpinning principles of growing biomass for energy use. Plant biomass can be used for multiple forms of bioenergy, and as the above analyses suggests there is potential for significant supply, depending on assessment of the land area that could be made available for biomass production and determination of the most suitable plant species for the Queenstown Lakes District.

The subject most pertinent to actioning this QLDC aim was covered by Landcare Research (Giltrap, et al. 2009)[39]. Such an analysis requires better understanding of the opportunities, resource characteristics, agronomy and any land-use implications of different crop selections taking into account: species options available and local cropping, environmental conditions, biomass establishment / production / harvesting requirements, site selection and infrastructure[40].

The giant miscanthus research by Renquist included developing a detailed Protocol for growing the biomass and supplying it to a biomass processor (Renquist, 2014a)[41.] The

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[39] Giltrap, Donna, Anne-Gaelle Ausseil, Jagath Ekanayake, Steve M. Pawson, Peter Hall, Peter Newsome, John Dymond. 2009. Environmental impacts of large-scale forestry for bioenergy. Chapter pp 71-121 *in* ANALYSIS OF LARGE-SCALE BIOENERGY FROM FORESTRY: Productivity, Land use and Environmental & Economic Implications, BIOENERGY OPTIONS FOR NEW ZEALAND series.

[40] Kerckhoffs H, Renquist R, 2011. Literature review of biomass species

[41] Renquist, R, Kerckhoffs, H. 2014a. Protocol: growing giant miscanthus (Miscanthus × giganteus) biomass for gasification to biofuel. Report to the Biogas to Syngas to Liquids (BTSL) Project, University of Canterbury, by Bioenergy Cropping Solutions Ltd and Massey University.

same procedures were used as part of the research with Jerusalem artichoke (Helianthus tuberosus, cultivar 'Inulinz').

Renquist also carried out a New Zealand Life Cycle Assessment (Renquist, 2014b)[42], a procedure which is the gold standard for calculating the carbon dioxide footprint to compare it to other biomass species. An LCA was also done for Helianthus tuberosus and triticale (Renquist 2014c)[43]. The LUC classes 3 and 4 could also be used for biomass from hardwood tree species.

We examine here two species as indicative of what might be appropriate given climate and land area requirements: Eucalyptus, and Miscanthus.

Eucalyptus: Considerable investigation of growing Eucalyptus overseas and in NZ have demonstrated its solid ability to grow fast and give high log or dry mass yields, including in the South Island. That said, there have also been a number of unsuccessful ventures so that making the right decisions is necessary.

Grower handbooks (e.g. EU SRC[44]) and research reports provide the means to plan and execute a successful plantation. On LUC classes 5 and 6, Eucalyptus wood for fuel or feeding bioenergy technologies has a long history of successful R&D, including in New Zealand (Sims, et al, 2001)[45] .

The better adapted species for coppicing and hardiness are in the stringybark family of species and include E. *macrorhyncha,* E. *youmanii* and E. *viminalis* (as recommended to QLDC by the growers in or near the District). Marlborough research (van Ballekon[46]) favoured E. camaldulensis •E. *cladocalyx* •E. *eugenioides* •E. longifolia •E. *macrorhyncha* •*E. notabilis*. Several others species are also named in the NZ eucalyptus literature.

The average annual dry mass yield of eucalypts in NZ are quite similar to those of giant miscanthus (Sims and Venturi, 2004; van Ballekom, 2017).

Other well-researched hardwood species which coppice well for fuel or biomass are poplars and willows (Sims et al, 2001). These harvests on many LUC class 6 slopes would not require soil disturbance.

The likely best use of the wood grown within the QL District is to supply a bioenergy processing plant. The plantation type for this can use a standard tree spacing (2-4000

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[42] Renquist, R. 2014b. Life Cycle Assessment of Giant Miscanthus (Miscanthus × giganteus): a New Zealand 'Cradle to Farm Gate' assessment of net energy yield, global warming potential and eutrophication impacts of biomass crop production for bioenergy. Report to the University of Canterbury BTSL Project by Bioenergy Cropping Solutions Ltd.

[43] Renquist, R. 2014c. Life Cycle Assessment and Synchrony of Supply of Three Biomass Species: Giant Miscanthus (Miscanthus × giganteus), Triticale (× Triticosecale) and Jerusalem artichoke (Helianthus tuberosus). Report to the BTSL Project by Bioenergy Cropping Solutions Ltd.

[44] EU, 2017.

[45] Sims, Ralph E. H. and Piero Venturi. 2004. All-year-round harvesting of short rotation coppice eucalyptus compared with the delivered costs of biomass from more conventional short season, harvesting systems. Biomass and Bioenergy 26: 27 – 37.

[46] Marlborough research (van Ballekom, 2017).

trees/ha) and harvest to enable the stump to coppice (sprout multiple new shoots for the next harvest) at 5-6 year intervals, depending on species used. At close spacing (5-7000 trees/ha) harvest is more frequent.
Some special harvest equipment is necessary, requiring a large enough planting (or a cooperative with other growers) to justify the equipment cost. An equally important consideration is that a bioenergy processing plant would use the wood from at least 1000ha, but it could use other biomass sources along with eucalyptus wood.

Figure 9: A eucalyptus SRC plantation for biomass for energy after 6 years growth in New Zealand (Source: Dimitriou I.)

Giant miscanthus (*Miscanthus x giganteus*) is the non-woody species of choice for bioenergy feedstock. It has high biomass yield and several good properties. It is a sterile triploid and spreads very slowly from the plant crown, so it will not become a weed. A plantation is likely to live over 20 years in most parts of NZ and from the third year requires only harvesting, since the species needs little or no nitrogen fertiliser and no irrigation if the rainfall is >600mm per year and soil deep enough to store water.

A planting (in late spring) will produce a half crop in year 2 and a full crop from year 3. Year 1 is the only challenging period, since plants are small and require good weed control. From mid-year 2 it outgrows all weeds. Production can be achieved with very low energy consumption and environmental impacts.

The DM is at its peak in the late summer or early autumn, but cannot be harvested at that time without disrupting the future growth cycle.

Of the 36 tDM/ha in the planting shown in Figure 10, several tDM are transported into the large rhizome system to be recycled in rapid spring growth.

The Hawke's Bay yield of 23 tDM/ha in the trial planting converts to 19 t/ha on commercial scale and allowing for the first 2 years with low yield plus storage / handling losses.

Figure 10: Giant miscanthus in May 2013 in Hawke's Bay, with R Renquist.

Until trialled in the QL District a conservative yield figure of 12 tDM/ha is assumed for our base case assumptions.

The crop dries slowly standing in a Hawke's Bay winter (but could be faster in the drier local climate). It reaches harvest maturity (for baled storage, if needed) in July to August. If transported directly from field to energy processing plant harvest can be 1-2 months earlier, achieving a higher DM yield since some is lost in the field each month by weather impacts. Harvesting is with heavy maize forage type machinery. There is a market for miscanthus as bedding since stems are light and very absorptive. It is also a good shelter belt under centre pivot irrigation (tested by Fonterra near Ashburton), since the tops are flexible. The company Miscanthus NZ has experience and very detailed information on growing the crop and can also provide the planting material, although other sources may well be able to be obtained.

More information is provided on the management details for giant miscanthus is given in Appendix D.

4.5 Carbon Sequestration Estimates

As previously described the carbon sequestration calculation has required us to bring together both land category data as well as information on the various planting options that we have selected as a means of increasing carbon stocks.

Table 3 below sets out the various Land types that were finally settled upon to enable us to arrive at some indicative carbon sequestration potentials. These categories were derived from discussions with QLDC, and presents a range of land types and ownership classes that, together, were deemed to present the best potential regards biological carbon sequestration. This information was a key part in informing the development of the various Protocols and Pathways described in Section 4.4 above.

Table 3 sets out for reference the various Land Types used in the Pathway links (see Table 2) to establish the various planting areas and biomass vegetation combinations that constitute the developed Pathways. The table presents our estimates of the likely biomass vegetation present under current land use conditions. Again, the preferred metric is the derived dry matter. (DM).

Table 3: Description of the Land Use Categories used for the purposes of sequestration modelling

land class categories	name	Biomass Vegetation (tDM/ha)
1	ETS forests + wildings	500
2	Protected land – Outstanding Natural Landscape	<2
3	Grouped types on steep land (LUC 7,8)	<2
4	farms	4
5	steeper farms	4
6	urban parks and peri urban	300
7	QLT Forest	500
8	QLT Forest	500
9	Degraded lands	3
10	pastoral leases	3
11	Significant Natural Areas	100
12	Alienated parcels QLDC, DOC, LINZ	2

Table 4 shows the finalised input data for our base case analysis. The protocols adopted were intended to demonstrate what might be practically achievable based on current planting rates, a significantly accelerated nursery and establishment effort over current initiatives and the expected establishment periods. Again, we remind the reader that these pathways are merely hypothetical and intended as analogues as to what might be possible in the near-to medium-term given resource and regulatory constraints.

Not one pathway is favoured over the other. They merely allow us to arrive at an an estimated quantity of carbon sequestered above ground at the end of growing season 2050.

We acknowledge that natural forests such as occurs in a mixed beech forest have a much lower comparative growth and take a lot longer to reach maturity than other species, but our objective function in this work is to estimate and present the actual carbon stored in any one year, summed out to the year 2050 so that we can report a year-on-year sequestration total.

Table 4: Base data for carbon sequestration modelling

Base Data								
Pathway #	Pathway Name for Chart	Land categories:	Protocol Land contributions	Biomass Vegetation (tDM/ha)	Biomass Vegetation (tCO2e/ha)	Area under planting (ha)/year	Establishment time to full carbon stock - years	Carbon squestration at maturity and constant therafter (tCO2e/ha/y)
1	native forest restoration	4,5 6	20%, 30%, %50%	3	6	20 ha/y by 2026 50ha/y 2030 100ha/y until 2050	25 years for shrubs, beech 50 years dominat C carrier	7
2	high carbon sequestration	4,5,	60%, 40%	4	7	5000 ha by 2030 7,500 ha by 2035	3 y miscanthuis 4 years euclayptus	27.5 miscanthus 29.3 eucalyptus
3	southen aspect afforestation	5,10 (incl 1 post harvest)	30%, 30%, 40%	3	6	1200 ha by 2050	s-curve for beech 50 years	7
4	northen aspect - enhanced vegetation	5,10	30%,70%	3	6	100ha by 2030 500ha over the 20 hears	30y shrub	4
5	carbon farming in tussock land	5,10	30% 70%	3	6	100ha by 2030 500ha over the 20 hears	20y shrub	6
6	planting special exotics	5,10	30% 70%	3	6	commence 2030 1000ha over the next 20 year	full carbon with 4y	36
7	forest swaps	N/A	-	-	-	-	-	-

This data was then run out to the year 2050, summed over the period and expressed in terms of tCO_2e/ha. The output from the model run is as shown in the charts over.

The total contribution to carbon sequestration for the period out to 2050 based on these pathways and areas planted (total establishment, 17,320ha – see Table 4) is estimated at approximately 9.5 million tonnes CO_2e. Annual sequestration rates at the end of the period are determined to reach around 420,000 tonnes CO_2e / year.

It should be noted that these quantities simply reflect the pathways assumed and the assumptions as to their deployment over time. As such, the numbers themselves should not be taken as specific sequestration targets, rather it is the protocols underpinning the different pathways that are important as they have enabled different options to be tested and gaps in our knowledge base to be identified.

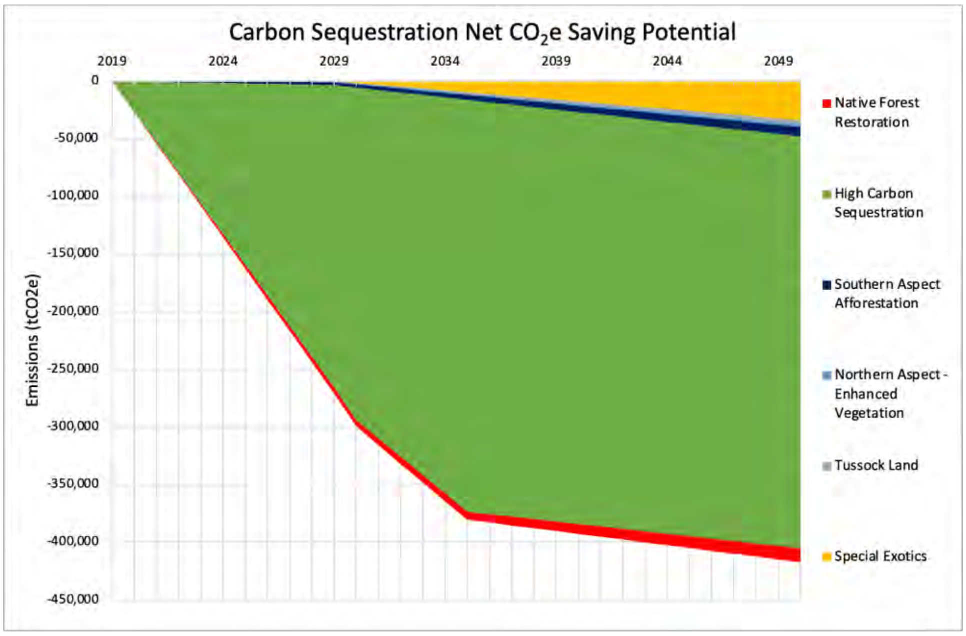

Figure 11: Base Case annual Carbon (CO_2) Sequestration quantities Queenstown Lakes District, 2020-2050

It is very obvious from the above chart that the high carbon sequestration pathway involving the planting of 12,500 ha in a mixed miscanthus / eucalyptus regime dominates the amounts of sequestration ascribed. The second most important category are the plantings of special exotics, even at the very low assumed planting rate of just 1000 ha. The contributions from the plantings of natural forests are very much less.

Of particular interest is the relatively small contributions from the other Pathways 1, 3, 4 and 5. These pathways anticipate native forest restoration supplemented at the higher altitudes by the planting of grey shrub species to store carbon while improving the overall vegetation (assuming stock control and good pest control). The planted areas for the high-country pathways (3, 4 and 5) combine to a total area of 2,400 ha, which is relatively small when compared to the total land area available.

Our understanding of the likely carbon sequestration potential of the high-country protocols adopted here is still quite limited due to the early stage nature of this work but it would seem that extension of the areas planted may well offer good prospect for further growth. However, before one can reach such a conclusion it would require that more detailed ecological and establishment studies be undertaken. Continued investment in native forest reforestation will help improve our learnings.

The net contributions from the sequestration activity assumed is set out in Figure 12. This chart shows the annual quantities sequestered over each five-year interval. As can be seen, in the absence of continued plantings over the period, the quantities of carbon sequestered begin to plateau out. Of course, in the real world one might expect continued gains in knowledge of C sequestration plantings, with establishment success rates improving as a result.

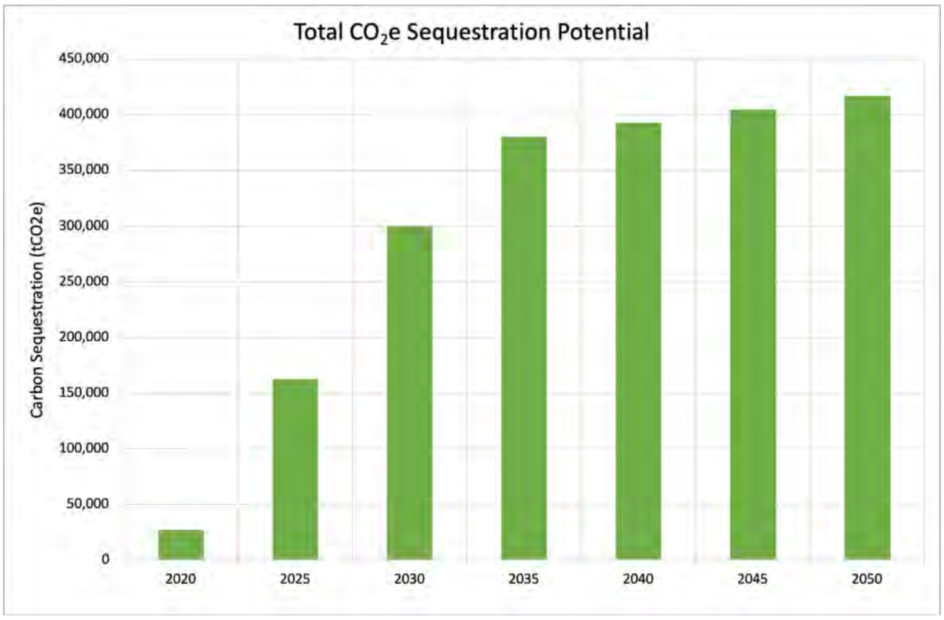

Figure 12: Total CO_2e Sequestration Potential for the Base Case pathway analysis

Finally, we present statistics which detail the individual contributions from each of the pathways assumed. This is shown in Table 5. As can be seen, this simply reinforces the contributions made by a high carbon sequestration pathway. Whilst we have not explicitly looked at the science involved, we note that Southern Aspect Afforestation would appear to generally offer better plant growth than the other equivalent native forest restoration efforts. With further science and agronomy trials the improved knowledge that will thus derive will likely be expressed in increased sequestration rates.

Table 5: Individual pathway contributions to Carbon Stocks out to 2050

Pathway #	Stacked Area Chart	Total Area Established	Cumulative (tCO_2e total)
1	Native Forest Restoration (by community)	2320	207,000
2	High Carbon Sequestration	12500	8,739,000
3	Southern Aspect Afforestation	1200	134,000
4	Northern Aspect - Enhanced Vegetation	600	32,000
5	Tussock Land	600	49,000
6	Special Exotics	100	372,000
	Total	**17320**	**9,533,000**

We comment that looking at these pathways our assumption on both yield (Pathway 2) and planted areas (Pathway 3 and 4) could be seen as being quite conservative. The inclusion of Pathway 6 (Special Exotics) could be argued against but is included as an indication of the carbon values that can be ascribed to plantation forestry activity.

The various pathways outlined above are all valid, albeit hypothetical, options worthy of further consideration and development.

Pathway 1 is already under way via the activities of proactive community projects, the scale of effort considered here may well be on the high side, but that could change dramatically should further investment or Government support eventuate. Also these findings could change if longer time horizons were considered.

In undertaking this study we have made a first attempt to categorised the potential of the different land types in the Queenstown Lakes District. Much more work needs to be done in this area, however, one key distinction among the land areas considered is the Land Use Capability classes, developed for farming and forestry land uses. The use of farm land in Land Use Capability (LUC) classes 3, 4, 5 and 6 (which is not a very large land area within the Queenstown Lakes District) should, in our view, be the focus of investigation for producing high yields of biomass for use in bioenergy (substituting for fossil fuel energy). These were identified under Pathway 2.

The relevant crop species to use may be either non-woody perennials or trees that re-grow when harvested every few years. If for example we assumed a more typical yield for Miscanthus of 36 tCO_2e/ha/y, equivalent to a biomass yield of 20 tDM/ha (and similar values for coppiced Eucalyptus) then the total quantities of CO_2e stored over the 30-year analysis period would, increase from 9.5 million tonnes to 11.8 million tonnes - an addition of 2.3 million tonnes.

Whilst we do not make any recommendations on what pathways should be followed it seems reasonable to observe that with very little incremental planting one can quickly see measurable additions of carbon being sequestered. The use of high-country land currently in pastoral leases (LUC classes 6 and 7 on sloping land) in our view also merits further investigation for carbon farming as permanent shrubland or forests.

This becomes more important when looked at in conjunction with the technical carbon sequestration options, as biomass supply for uses such as firewood, biofuels and biochar will significantly enhance the overall C sequestration outcome, and thus considerably strengthen the District's climate change mitigation efforts.

4.6 Findings and Recommendations

This technical analysis of biological sequestration opportunities with the Queenstown Lakes District land areas has sought to frame the identified opportunities in terms of land types land use capability and land use change. This has not previously been done from the perspective of growing plants for C storage, but doing so offers a coherent science and land management platform to guide the QLDC in achieving a realistic carbon sequestration plan as part of its Climate Action Plan.

Pathways 2,3,4,5, and 6 all have land use change as a central feature. Several analyses of this issue that involve comparisons between pastoral farming and tree crops have been cited. There is, however, one best methodology to make comparisons between different land uses, as postulated here, or even for species selection and proposed new plantings – and that is Life Cycle Assessment (LCA). Whilst outside the scope of this work we recommend this methodology be adopted in any future comparisons. We also comment that the productivity of research-based specialised commercial plantations of bioenergy crops will be dramatically higher than traditional farm crops and high country pastoral vegetation, or companion plantings of natives as part of community reforestation efforts.

The carbon stock comparisons presented in this report are not intended to belittle those other land uses, which all have multiple values other than carbon stocking, but simply identify where immediate gains may be made. It is anticipated that significant further analysis, science effort and policy evaluation would be undertaken to inform decision-making going forward. Considerable more work is required to identify the optimal policy levers and regulatory paths to enable emissions offsets via carbon sequestration.

In summary, our major findings in respect of bio-sequestration are:

- Amongst the various land areas canvassed, the use of farm land in Land Use Capability (LUC) classes 3, 4, 5 and 6 should be the focus of investigation for producing high yields of biomass for use in bioenergy and / or biochar and thereby maximising carbon sequestration potentials.
- The pastoral lease lands managed by LINZ are the most pertinent land category for considering any long-term management interventions designed to sequester carbon in vegetation. In arriving at this conclusion we have also taken into account altitude and land use factors and scale.
- Integrating a professional ecologist's point of view on any afforestation efforts however will be essential when proposing land management regime with the objective of carbon sequestration. The high altitude NZ vegetation is rare and will present risks if modified to any great extent. At the very least, it is necessary to do a botanical survey of species that are present at a site before seeking to modifying it.
- We note that globally, increasing attention is also be given to the use of purpose-grown species to both enhance carbon storage and also provide

opportunity to supply biomass as a renewable energy source or a means of fixing carbon from the atmosphere. In the Queenstown Lakes District the availability of land areas suitable for biomass cropping is quite restrictive and will also be subject to competition from other land uses, as well as likely constraints regarding water and Regional Planning Policy.

- However, land use change from existing pastoral/grazing use to more intensive cropping regimes presents opportunities for both reducing ruminant methane emissions and improving carbon stocks on the land. This would provide a double win.
- The greatest potential for carbon storage is with development at a commercial scale of tree/crop management regimes on existing farmland for biomass production (coppice-capable tree species, mainly Eucalyptus, and long-lived non-woody species, such as Miscanthus x giganteus). It has been shown that this pathway has a ready potential to sequester up to 70,000 tonnes of carbon per year, The 70,000 tonne scale involves the utilisation of about 12,500 ha of farming land.
- Other useful additions are likely to be provided by over-sowing tussock land up to 700m altitude with grey shrubs for carbon farming on an extensive (rather than intensive) basis as well as the introduction of sterile clones of exotic tree species grown from tissue culture, in the more remote, less environmentally sensitive parts of the District, including the large pastoral lease areas. These species are capable of producing high biomass (and C stock) in the harsh continental environment. Our analysis indicates a potential to sequester up to 3,100 tonnes of carbon per year using the protocols assumed. These approaches would involve 1,200 ha of high country lands.
- Existing policies to reduce old age forests and wilding pines will have an immediate negative impact on total carbon stocks. However, replanting of these areas with native forest and grey shrubland native vegetation (such as *manuka, kanuka, Pittosporum spp*. and *kowhai*) will have long term benefit and enable the natural reinstatement of beech and other vegetative cover; thereby accelerating establishment rates, and carbon stocks over current approaches.
- Whilst offering strong ecological and biodiversity benefits, the current and projected local programmes for native forest restoration offer a limited carbon sequestration benefit in the near term. The rates of establishment and low biomass per plant simply means a very limited storage over the time frame out to 2050. Our analysis indicates a potential to sequester up to 6,200 tonnes of carbon /year at 30 years average growth, from the planting out of 2,320 ha. This may be scalable but much will depend on the success rate achieved with current community-led and QEII afforestation initiatives.
- An encouraging note regarding natural forest planting is that climate change mitigation will likely need to go on all of this century and maybe the next one. Any native plantings that go on to become established permanent forests of

beech and other large trees will sequester much greater amounts of carbon over the next two to four centuries.

It should be reinforced that the above conclusions are largely based on a series of hypothetical constructs that will require further development and analysis before firm estimates can be provided. These current estimates and the methodologies underpinning them were simply intended to inform and not to be taken as specific achievable targets or even as desirable outcomes. Simply, they are intended to be looked at as C sequestration potentials when the objective is to maximise C stocks. There are many other considerations that will need to be taken into account before any final decisions are made.

Finally, we comment that looking at these pathways and their underlying assumptions offers opportunity for a wider discussion on the values and trade-offs that are implicit in any carbon sequestration action. We hope the community feels sufficiently encouraged from these results to engage in such a conversation. We present below considerations that QLDC may wish to take into account going forward.

Action Plan Recommendations:

QLDC transition pathway decisions on carbon sequestration (aims and values) should in the first instance focus on confirming the values that can be ascribed to biological sequestration and the investment that will be needed to support/finance community led or private initiatives to increase carbon stocks. Coming to terms with land use change, which would be necessary for most Pathways, will be an essential element of this conversation.

There should also be a re-think about working with landowners, Otago Regional Council and other stakeholders in trying to identify the key policy and regulatory levers required for transition to a viable carbon farming regime. A key aspect of this is whether it is simply desired to adhere to 2050 targets or, instead, seek action to achieve the maximum long-term carbon capture potential. An important component of that dialogue should be to catalogue the wider economic opportunities that might derive from such a strategy. What are the pathways that would achieve the greatest offset of carbon emissions? How does this play out over time? What is the value proposition?

Quick wins could involve replanting wilding control sites, the upscaling of nurseries already engaged in native species propagation, improved pest control and expansion of community planting initiatives and some early stage assessments of the value chain synergies and opportunities.

In the near term we suggest QLDC could;

- Develop the business case for scale up of current community plantings 50 to 100-fold (using eco-sourced seed or not?).
- Examine further the potential for biomass production for bioenergy and permanent carbon farming forests, and how this might best achieved on current farm land in areas such as Hawea Flat and surrounding low hills. Under what

scenarios would those options be of interest to land owners? Are there potential synergies with the mooted Hawea Flat Food Forest? What other synergies might reside?

- Establish the appropriate science/ university links to examine the business case for the suggested development (perhaps in partnership with private interests) of a commercial scale demonstration site at the QLDC owned Hawea Flat reserve.
- Examine further the potential for land use change for those high country sites with favourable altitudes on southern exposed slopes, with large native tree (beech) potential; many will likely fall within grazing lease land (Land Information NZ administered); prepare details protocols to support such conversions, where identified as suitable. Give further consideration to other demonstration / research sites in order to validate protocols for beech establishment and grey shrubland plantings.
- Instigate a review of alienated lands currently held by QLDC, DOC, LINZ and other administrations with a view to combining these into an Alienated Lands category so as to formulate a suitable carbon management protocol as indicative of the sort of interventions that might potentially be possible.
- Where appropriate, formalise a generalised Life Cycle Assessment (LCA) analysis approach suitable for future comparisons and policy assessment of all land use change proposals.
- Finally, sourcing local knowledge of adapted NZ native species and acceptable exotic species; combined with expert ecological advice and soil and plant science investigations will be critical elements going forward.

5. Options Assessment - Technical Sequestration

5.1 Overview

QLDC is characterised by its landscape and natural values. It has limited agricultural and industrial activity and a quite low permanent population. The opportunities for significant technological sequestration of CO_2 to reduce carbon footprints is thus somewhat limited as adoption of such technology is very much reliant on having available for sequestration point sources of relatively pure CO_2 at scale. Whilst this is not necessary a limiting condition and, as will be described in our later analysis, there are opportunities available that may offer useful contributions it is important to make the point that technological sequestration needs to be looked at in terms of its ability to augment and maximise carbon reduction via biological sequestration pathways; rather than as a stand-alone pathway acting on its own merits.

This Section, therefore, focusses on providing an overview of current technological sequestration pathways, the technical readiness of the different technologies that underpin these pathways and their potential for uptake within the near- to medium-term. Our starting point for comparison is the extent to which the direct capture and use of carbon dioxide might lower the net costs of reducing emissions or offset some of the costs of climate change mitigation.

As previously described, we define technological sequestration for the purposes of this study as being the capture and storage of carbon that would otherwise be emitted to or remain in the atmosphere through technological means. This includes techniques such as the direct removal of CO_2 from air, the separation of CO_2 from combustion gases and process streams, the utilisation of CO_2 as a feedstock for manufacture of chemicals and fuels, chemical looping for hydrogen production, biochar production and other technological uses of CO_2.

Excluded from consideration is geological sequestration which involves the storage of captured CO_2 in deep geological formations such as; depleted petroleum reservoirs, deep coal and shale deposits, saline aquifers, salt caverns, basalt formations and the like. Without any obvious suitable geological settings, and in the absence of scale, these techniques are not seen as likely to be of interest going forward.

None of the above, of course, avoid the need for low-emission technologies and reduced fossil-fuel consumption. But, the realisation that CO_2 is an important chemical feedstock and CO_2 can be cycled to either produce value-add products or reduce the climate change impact of other processes is essential to improved climate change outcomes.

In order to arrive at a view of the potential for technical sequestration we have examined a non-exhaustive selection of nine different CO_2 utilization pathways; (1) CO_2-based chemical products; (2) CO_2-based fuels; (3) mineralisation including concrete building materials; (4) conversion to graphite/graphene; (5) bioenergy with carbon looping; (6) land management via soil carbon in the form of biochar; (7) biotechnological conversion to microalgae fuels and/or other microalgae products; (8) the direct use of CO_2, and; (9) hybrid opportunities from the uptake of CO_2 based on existing sources.

A technical review of these nine CO_2 utilization pathways is provided in Appendix E. This technical review shows that whilst the utilization of CO_2 could contribute to carbon cycling or otherwise help reduce climate change through direct capture and sequestration, the opportunities are in fact quite limited. This is largely due to the early stage development of many of the pathways canvased and/or technical complexity. In addition, the avoided cost of carbon in many instances is very high and it is unlikely that the price point for commercial investment will be reached in the near-to-medium future.

It is also important to consider the storage potential of the various options canvassed. Sequestration pathways can be characterized as being 'cycling', 'closed' or 'open' utilization pathways[47]. For instance, conventional industrial utilization pathways - such as CO_2-based fuels and chemicals - tend to be 'cycling' in that the carbon moves through industrial systems reducing carbon footprints over a short to medium timeframe, whereas 'closed' pathways - such as mineralisation - involves utilization and near permanent CO_2 storage. 'Open' pathways tend to be based in biological systems, which are characterized by large removal potentials but with the risk of large-scale flux back to the atmosphere.

From a sequestration perspective 'closed' systems are clearly more desirable, but where there is opportunity to utilise a renewable energy source (as in biomass cropping) then open cycle system can have advantage because of the volumes of carbon removal.

5.2 Commercial Readiness of the Various Technical Sequestration Options

For this study we have undertaken our own preliminary assessment of the different pathways. Our findings are shown in Table 6 over. As can be seen technical complexity, completion and price risk are showstoppers for most options, although scalability also is a significant factor. Simply put, in the absence of scale chemicals, many of the options examined are simply not feasible. This particularly applies to the manufacture of alternative fuels, chemicals manufacture and direct mineralisation.

[47] Hepburn C *et al "The technological and economic prospects for CO_2 utilization and removal" Nature* Vol 575 ,7 November 2019, *https://doi.org/10.1038/s41586-019-1681-6*

Of the options canvased, biochar and the direct utilisation of CO_2 offer the least risk, subject to market and CO_2 sources being properly delineated. There are also integration options that may be worthy of further evaluation; should a suitable CO_2 source be identified commensurate with, say, horticulture use in glasshouses or combined with a small-scale biofuel's opportunity. The two most obvious candidates are anaerobic digestion or biomass gasification with carbon looping to produce either bio-methane or hydrogen with CO_2 recovered as a separate product stream. The pyrolysis of purpose grown biomass to biochar where developed in association with a waste-to-energy plant is also of potential interest.

It has not been possible within the bounds of this study to explore these options further or properly assess the carbon sequestration potential that could arise. Instead, we present two case studies that seek to quantify the potential energy opportunity and the quantities of CO_2 that might become available for domestic use locally. These are set out in Section 5.3.

Table 6: Options Assessment - Technological Sequestration Pathways

Technology option	Chemical pathway	Utilisation pathway	Storage potential	Technical readiness	Commercial readiness	QLDC opportunities / synergies	Highest risks
Direct Air Capture DAC	Using a chemical absorbent or engineered molecules to produce a pure CO2 stream.	CO2 stream for storage or direct use.	N/A	TRL 4/5 technical development - pilot scale	CRL 2 commercial trial	N/A	technical risk cost
CO2 utilisation - chemicals	Catalytic chemical conversion of CO2 into chemical products	CO2-derived platform chemicals such as methanol, urea and plastics	large volumes but open cycle and thus temporary storage - decades?	TRL 8/9 validated performance	CRL 5/6 Bankable where firm supply and offtake agreements	N/A	scalability
CO2 utilisation - fuels	Catalytic hydrogenation processes to convert CO2 from into fuels	CO2-derived fuels such as methanol, methane and Fischer–Tropsch derived	large volumes but open cycle and thus temporary storage - weeks?	TRL 6/7 technology demonstration	CRL 3/4 commercial scale up	N/A	scalability
Mineralisation	storage of CO2 as calcium and magnesium carbonate minerals	CO2 can be used to "cure" cement, or in the manufacture of aggregates.	permanent with low likelihood of release	TRL 4/5 technical development - pilot scale	CRL 2 commercial trial accelerated curing early stage commercial	low but possibly?	route to market
Graphite / Graphene	high temperature condensation of CO2 to produce carbon nanoparticles	various material/device applications, including solar cells, light-emitting diodes (LED), touch panels,etc.	permanent with low likelihood of release	TRL4 technical research	CRL 2 commercial trial	synergies with bio sequestration and biogas	technical risk cost
Bioenergy and carbon looping	Biomass gasification and separation of the CO2	production of bio-hydrogen, with CO2 as a by-product	requirements moderate to high	TRL 4/5 technical development - pilot scale	CRL 2 commercial trial	synergies with bio sequestration and biogas /biomethane / hydrogen	technical risk cost
Biocarbon	pyrolysis or torrefaction of biomass or waste materials for the production of char or other carbon products	Biochar application to agricultural soils carbon black	long term with significant likelihood of release - years?	TRL 8/9 validated performance	CRL 3/4 commercial scale up	waste plastics end of life opportunity synergies with bio sequestration and biogas	environmental / airshed
Microalgae	industrial bioreactors CO2 dissolved in water or under a gas phase concentration up to 5–10%,	Biofuels, animal feed, or bioproducts such as aquaculture feed	Probably fairly low - product dependent	TRL 4/5 technical development - pilot scale	CRL 2 commercial trial	integration opportunity for biogas	climatic / yields costs
sc-CO2 / CO2 gas	direct use with recovery/recycle	sc-CO2; solvent extraction nutraceuticals etc. industrial gas - existing market	SC-CO2 low volumes moderate risk of release - years? Specialist gas market - high	TRL 8/9 validated performance	CRL 5/6 Bankable where firm supply and offtake agreements	economic development / synergies with wine industry	market (?)
Integration opportunities	Uptake of CO2 from other sources above	Greenhouse cultivation under a CO2 concentration of ca. 600 ppm	N/A ? Crops short life span. Biomethane - substitute fossil fuels	TRL 8/9 validated performance	CRL 5/6 Bankable where firm supply and offtake agreements	synergistic opportunities with waste treatment (AD especially putrescibles) and bioenergy	complexity route to market

Note: *in the above matrix red is used to identify potential showstoppers where completion / technological risk is deemed to make any such project unbankable; green suggests that risks are likely within an acceptable bound, with yellow suggesting risks that will require mitigation interventions. The boxes in grey require further consideration or are simply not applicable, dark grey means less certainty.*

5.3 Case Studies

5.3.1 Biochar via Pyrolysis

Biochar is the solid residue remaining from the pyrolysis of any biomass substrate. The biochar product is a form of black carbon. It is a stable solid material with chemical and physical properties similar to that of graphite, charcoal, and biocoal (roasted biomass). Biochar has a high carbon content, low density, low volatile matter continent and high porosity. Where desired, biochars can be transformed into different forms (such as pellets, briquettes) to enable easy transportation and/or packing[48,49]. As previously described biochar has an increasing use in the enhancement of soil fertility through improved nutrient retention, promoting soil biology, and improved water retention and /or drainage

In many jurisdictions biochar is considered as a renewable, low-carbon fuel because, rather than introducing more carbon to the atmosphere (c.f. burning fossil fuels), as it simply releases carbon that had been absorbed from atmosphere via photosynthesis and that would otherwise have been emitted if the biological feedstock had been allowed to naturally degrade. Where biochar replaces existing fossil fuel use then a direct GHG benefit ensures.

Industrial scale installations producing biochar are common through the world including Europe, Nth America, and elsewhere. A typical biochar production scheme is as outlined in Fig 13 (from ref 24). Once the biomass is collected, it is transported to the pyrolysis facility, where it is hogged or crushed, to reduce piece size, and (where necessary) dried before being fed to the pyrolysis reactor. The generated gases and vapours from the pyrolysis unit, as well as the oils, are either burned on-site for heat or recovered for sale. In the pyrolysis step the biomass is first degasified at high temperature. Volatiles are released from the parent biomass and under continued heating the dry and devolatilized material is then carbonised into char, cooled and removed from the reactor.

For biomass pyrolysis, a wide range of different reactor configurations can be adopted. For this case study we assume an entrained flow, rotating kiln, intermediate pyrolysis system operating at temperatures of between 400 – 600°C. The liquid, gaseous, and solid product yields from the assumed mixed biomass feedstock will have the approximate proportions of 35, 32, and 33%, respectively.

The process itself requires about 15% of the energy in the feed which is assumed in this case study to be provided by the produced pyrolysis gas. The bio-oil is assumed used as

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[48] Pacific Institute for Climate Solutions Industrial and Market Development of Biochar in British Columbia, February 2014

[49] Khaira B., et al, Biomass Derived Chars for Energy Applications", Renewable and Sustainable Energy Reviews 108 (2019) 253–273

a fuel for electricity generation via a reciprocating engine (diesel) generation set, with the char going to soil remediation.

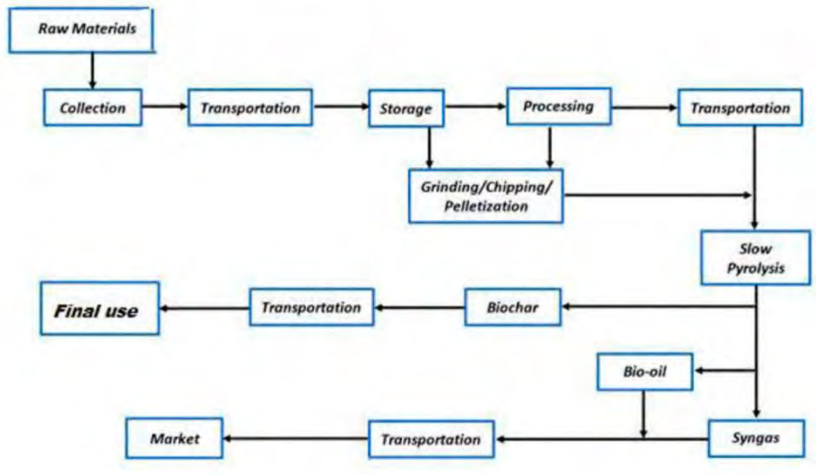

Figure 13: Schematic of Industrial biochar process - from reference[24]

Based on total feedstock of organics, paper, textiles and untreated timber (as projected, 2040 landfill) we arrive at a sizing of 20,000 tonnes per year; equivalent to 5x12 tonnes per day batch units operating at 330 days per year. This is equivalent to a typical minimum sized commercial plant. With additional biomass supply (say from a biomass cropping regime) the facility could be readily replicated.

The assumed basis of design and CAPEX, OPEX estimates for the case study are as provided below:

Pyrolysis plant feedstock	Food waste, green waste, paper, textiles and untreated timber
Pyrolysis plant capacity	20,000 t/year
Pyrolysis plant batch units	5 x 12 t/day batch units operating 330 days per year
Bio-oil produced	4,100 t/year (dry basis)
Bio-gas produced	3,700 t/year (dry basis)
Bio-char produced	3,900 t/year (dry basis)
Carbon stored in the bio-char	3, 315 t/year
Installed engine generator capacity	1.5 MW
Electricity generated from the bio-oil	8.5 GWh/year

Pyrolysis Plant Capex	$NZ 5.8 million
Engine Generator Capex	$NZ 1.5 million
OPEX	$NZ 0.4 million p.a.
NPV[50]	$NZ 7,780,000
IRR[51]	18%

The photograph below shows a typical configuration for an equivalent facility courtesy of Shangqiu Jinpeng Industrial Co., Ltd, China.

[50] Assumes an economic life of 20 years and WACC of 6%

[51] We note that an alternative sensitivity case based on a solely purpose grown biomass feed gives a reduced financial performance as a result of lower rates of bio-char production (2,800 tpy). For this case the derived IRR is 10% and NPV $NZ 2.54 million

5.3.2 Anaerobic Digestion

Anaerobic digester technology for the production of biogas or biomethane has achieved significant advances over the last 25 years. This is largely due to the development of industry capability through providing solutions to environmental issues facing primary producers (dairy and pig farmer effluent processing), agriculture (crop residues), sewage treatment and the diversion of food waste and other organics from land fill.

In New Zealand, large sewage treatment wastewater processing facilities have led the way in uptake of anaerobic digestion technology, using biogas produced from the processed waste to power the treatment plant, and with excess energy exported into the electricity network. Of more importance, however, is the recent announcement from Ecogas Limited of a first reference utility scale facility to be built at Reporoa, Central North Island which will be capable of processing up to 75,000 tonnes per annum of food waste and processing organics into both biogas and biofertilizer products. This site is located adjacent to horticultural growers T&G Global who will utilise the biogas for renewable heating, power and use of CO_2 for enhanced plant growth and glasshouse production yields. This $30m+ facility will be the largest private biogas facility in the country[52].

The biomethane industry on the other hand has been rarely looked at. Globally, however, there is a significant growing interest in several countries for the potential of biomethane to deliver clean energy to a wide array of end users; especially when this can be done using existing infrastructure. Currently around 3.5 Mtoe of biomethane are produced worldwide. The vast majority of production lies in European and North American markets, with some countries such as Denmark and Sweden boasting more than 10% shares of biogas/biomethane in total gas sales.

The rising interest in biomethane means that the number of operating plants worldwide is increasing rapidly. Around 60% of plants currently online and in development inject biomethane into the gas distribution network, with a further 20% providing vehicle fuel. The remainder provides methane for a variety of local end uses[53].

In addition to the above obvious renewable energy benefits, anaerobic digestion is also been seen as an answer to soil degradation and as a way of sustaining agricultural capacity. Digestate, the residue of organic matter left once the biogas is extracted, is rich in key nutrients that are returned to the soil as an organic nutrient-rich fertiliser .

In this case study we assume the use of AD for either biogas / CHP or bio-methane from putrescibles / organics wastes from within Queenstown, or alternatively using a mixed organic feed including purpose-grown biomass crops (lucerne or maize silage). We

[52] Ecogas, personal communication, 2020. Also see https://www.ecogas.co.nz

[53] IEA *Outlook for biogas and Prospects for organic growth*, World Energy Outlook Special Report, Biomethane, IEA 2020

assess the likely quantities in the near term for Queenstown to be of the order of 10,000 t/y for food waste plus other organics and, say, 30,000 t/y for a mixed organic feed comprising purpose-grown from a local bio-sequestration project. We are not looking at other feedstocks at this preliminary stage.

We assume for this case study dry digestion technology. Dry Digestion involves anaerobic digestion at temperatures of between 50-58 °C in either batch or continuous flow systems. The system is capable of processing a range of mixed waste streams with solids contents of up to 50%. It is also ideally suited for the digestion of energy crops such as maize, lucerne and other crops without further processing (apart from size reduction) or water addition.

Essentially the process replicates the natural processes that occur in situ within a landfill but accelerated many-fold, with retention times being of the order of 20-30 days rather than years. An advantage of dry digestion over wet digestion processes is that the technology enables acceptance of more waste containing impurities and avoids problems with flotation and sedimentation. Water demand is thus significantly reduced.

With the addition of post digestion treatment, a clean compost - similar in quality as compost from source separate collection- can be produced from mixed residual waste; thereby achieving high diversion rates.

Typical process properties for a dry digestion plant are given in the table below - extracted from reference[54]:

Table 2 – The Dranco Process: Key Features

Property	Value
Wet or dry process, solids content (%)	Dry, TS = 20 to 50 %
Number of Stages	single stage
Hydraulic Retention Time (HRT)	13 to 30 days
Type of Reactor	vertical, input stream by the top
Biogas production ($Nm^3.t^{-1}$ MSW)	100 to 120
Use of biogas produced by the plant (%)	-
Mixing the residue inside the reactor system	Recirculation of the solid mass in anaerobic digestion.
Temperature	Thermophilic

Reference: adapted from Angelidaki, Ellegaard & Ahring (2003), Deublein & Steinhauser (2010).

[54] de Lima H Q, *Anaerobic digestion AD of municipal solid waste in Santo Andre-SP – Review,* conference paper https://www.researchgate.net/publication/291334691,

The assumed basis of design and CAPEX, OPEX estimates for the Anaerobic Digestion plant are provided below. Value-add options could involve further treatments to allow for liquid CO_2 and biomethane supply. These have not been considered here.

Anaerobic digester plant feedstock	Food waste, green waste and other organics
Anaerobic digester plant capacity	30,000 t/year
Biogas production rate	100 m3/t feedstock
Biogas production	3,000,000 m3/year
Methane content in biogas	60%
Methane production	1,800,000 m3/year
Methane energy	68,400 GJ/year
CHP electrical efficiency	35%
Electricity generated	6.7 GWh/year
Engine generator size	1 MW
Thermal energy output	12.35 GWh/year
Thermal power output	1.5 MW
Compost produced	8,300 t/year

Plant Capex	$NZ 8.1 million
Opex	$NZ 0.34 million/year
NPV[55]	$NZ 11,130,000
IRR	23%

An example plant in Belgium is shown below. This plant processes 30,000 tonnes per year of food and garden waste from 4 digestors to produce both biogas for electricity generation using gas engine as well as a by-product compost.

General view of a 30,000t/y dry AD plant, Belgium – DRANCO technology

[55] Assumes an economic life of 20 years and WACC of 6%

6. Conclusions and Sequestration Roadmap

This study has been predicated upon the view that NZ is well placed to mitigate climate change through land use change, the growth of forests that hold C and through other direct carbon sequestration action. The QLDC has thus sought to develop a preliminary sequestration plan for the District that assesses options for sequestering carbon and to outline scenarios for future action; covering both biological sequestration opportunities and emerging approaches using technical means to capture and store carbon.

Key considerations for the QLDC were alignment with current policy and planning frameworks, the ability to sequester carbon on QLDC controlled land, and the requirement that any pathways suggested adhere to the biodiversity commitment of the District's Climate Action Plan. This study has sought to address these concerns alongside the wider national policy imperatives that that drive NZ (and global) action on Climate Change.

This study begins with a review of the NZ policy and regulatory context for sequestration activities, including an assessment of the implications that Regional and District Planning objective, policies and rules will have on any sequestration activity pursues. What is clear from this review is that Rules pertaining to the conservation of natural values, and water access rights are likely to dominate any future biological sequestration activities. The concept of Mātauranga Māori will be also an important future inclusion to ensure a wider understanding of the relevant issues and risks associated with any climate change adaptation proposed.

We also comment that integrating an ecological point of view on forest restoration will be essential when proposing any new land management regime having the objective of carbon sequestration. The issues of The NZ high altitude vegetation is rare and modification of these environments will inevitably present risks if modified to any great extent. It is also worth remembering that the continental climate of the Queenstown Lakes District combined with a high proportion of high altitude sloping ground and not very deep soils, makes the District one of the more challenging areas in the country to grow plants with high C storage, since that requires high plant growth (dry mass).

Our major findings in respect of bio-sequestration are outlined in Section 4.6 and are not repeated here, except to note that globally, increasing attention is being given to the use of purpose-grown species to both enhance carbon storage and also provide opportunity to supply biomass as a renewable energy source or as a means of fixing carbon dioxide from the atmosphere.

We have identified this area as being particularly worthy of further consideration. In addition to these lands other useful additions to increased Carbon Stocks could be provided by over-sowing tussock land up to 700m altitude with grey shrubs for carbon farming on an extensive (rather than intensive) basis as well as the introduction of sterile exotic tree species grown from tissue culture, in the more remote, less sensitive parts of the District.

We did not have sufficient time or data to consider in detail the ability to sequester carbon on QLDC controlled land. We address this in part through examining (Protocol 2) the option of developing the QLDC-owned Hawea Flat 40ha reserve, located south of Lake Hawea, as a possible commercial scale demonstration of how to maximise carbon sequestration through growth of exotic species on the better land in the District. This would include testing of different tree/crop management protocols and periodic harvest systems for biomass production. Consideration will need to be given to water and zoning requirements.

This case study we further extended in our analysis of the potential to use purpose grown biomass as feed to a biomass pyrolysis plant producing a bio-char product for use as a soil-enhancer and as a carbon sink. This option shows considerable promise. We note also the possible synergies that might arise with the currently moted Hawea Flat Food Forest planting initiative.

With respect to other QLDC lands we comment that parcels of land are generally small, constrained by the urban communities they support, the recreational needs of both locals and visitors, and a strong adherence to the landscape values that support there establishment. We do not see much further potential for increasing carbon planting areas and believe any likely Carbon Stock contributions will be negligible.

It should be reinforced that the above conclusions are based on preliminary analysis and discussions with QLDC staff and people associated with existing voluntary tree planting initiatives. Our work was simply intended to looked at C sequestration potentials with an objective to maximise C stocks. There are many other considerations that would need to be taken into account before any final decisions were made.

In the wider context, QLDC transition pathway decisions on carbon sequestration should in the first instance focus on confirming the values that can be ascribed to biological sequestration and the investment that will be needed to support/finance community led or private initiatives to increase carbon stocks. Coming to terms with land use change would be necessary for most Pathways

Quick wins could involve replanting wilding control sites, the upscaling of nurseries already engaged in native species propagation, improved pest control and expansion of community planting initiatives.

In the near term we suggest QLDC could give further consideration to the development of demonstration / research sites in order to validate protocols for native forest establishment and grey shrubland planting on high country lands. Sourcing local knowledge of adapted NZ native species and acceptable exotic species, combined with expert ecological advice will be essential to that.

Our report then moves on to discuss technical sequestration and the means by which CO_2 can be captured and either directly storied, or utilised as a feedstock for manufacture of chemicals and fuels, chemical looping for hydrogen production, biochar production and other technological uses.

At a macro level there is a paucity of opportunity for the adoption of the techniques within the District. This is largely due to the early stage development of many of the pathways canvased and/or the complexity of the underpinning science and technology. In addition, the avoided cost of carbon in many instances was determined to be very high and it is unlikely that the price point for commercial investment will be reached in the near-to-medium future.

Of the options canvased, the production of biochar for soil enhancement and the direct utilisation of CO_2 as an industrial gas / working fluid offer the least risk, subject to markets and CO_2 sources being properly delineated. There are also integration options worthy of further evaluation should a suitable CO_2 source be identified, and a local biomass source be established.

The two most obvious candidates for further examination identified were anaerobic digestion to biogas or biomass gasification with carbon looping to produce either bio-methane or hydrogen; with CO_2 recovered as a separate product stream. The pyrolysis of purpose grown biomass to biochar where developed in association with a waste-to-energy plant is also of potential interest.

Case studies were prepared to better establish the costs and benefits of these latter two opportunities. The results show that a 20,000 tonne per year biomass pyrolysis plant producing 3,900 t/y of biochar will have a capital cost of the order of $NZ 7.3 million and offers an IRR of approximately 18%, at a WACC of 6%. Based on the carbon embedded in the char such a facility would return to the soil for permanent storage some 3,300 t/y of carbon.

An alternative AD plant based on dry digestion technology and sized for 30,000 tonnes per year mixed landfill waste/biomass feed, would be capable of supplying up 1,800,000 m^3/year (68,400 GJ/year) biomethane to the Queenstown District (either as pipeline gas or as feed to renewable electricity generation). The estimated capital cost of the precursor biogas/ electricity plant (without methanation) was estimated at $NZ 8.1 million with an IRR of 23% at 6% WACC.

Clearly what these two case studies show is that biological and technical sequestration are not mutually exclusive, but instead offer synergies that will act to enhance QLDC carbon reduction initiatives; a double wins as it were. We suggest these opportunities are examined in more detail and further assessment be undertaken to establish whether there is a sufficient business case for further investment; either by the District itself or through some form of public / private partnership.

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MfE reporting of soil C stock: MfE website

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https://www.tekakano.org.nz/

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Treespace: Mt Dewar development video: https://treespace.co.nz/#projects

Appendix A: Restrictions on *Pinus radiata*

Rules around the discretionary plantation of Pinus radiata involve:

- Planting and management must avoid adverse effects of the spread of wilding trees and degradation to the landscape
- Proposals for planting and management must consider
    - The location and potential for wilding take-off, having specific regards to the slope and exposure to wind
    - The surrounding land uses and whether these would reduce the potential for wilding spread
    - The ownership of the surrounding land and whether this would constrain the ability to manage wilding spread
    - Whether management plans are proposes for the avoidance or containment of wilding spread
    - Whether a risk assessment has been complete and the results are favourable to the proposal.

Planting of Pinus radiata is prohibited in rural areas (p.5-10 in (QLDC, 2018c))

Appendix B: Vegetation photos by Michael Sly and related materials

Overview of wildings along the Motutapu Valley.

Shrub regeneration at lower altitude (Lake Wakatipu) 15 years after fire – 4 photos

Grey Shrub species, 10 years growth in Chinaman's Bluff area

An example of secondary tree species (Stunted Trees species) showing Celery Pine and Mountain Totara - mixed with Manuka, and the grey shrubland species

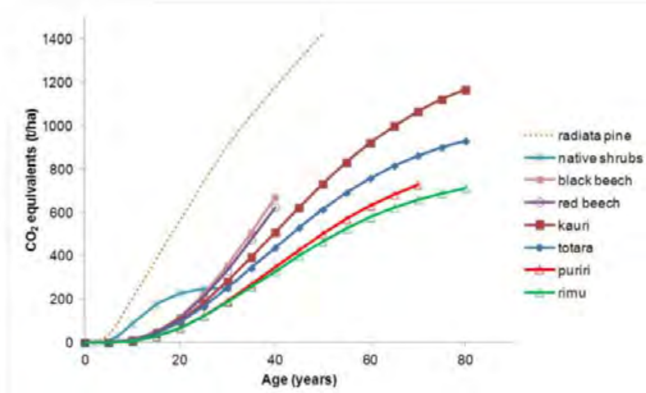

Figure for native plantations, mostly North Island climate.
Courtesy of Tane's Tree Trust

Total number of plants planted	Trees	Shrubs & grasses	% shrubs	Total surface planted in m^2
1,714	960	754	44%	2914
3,714	2,266	1,448	39%	6546
4,148	2,738	1,410	34%	7570
4,681	3,043	1,638	35%	8484
3,255	2,344	911	28%	6185
3,124	1,906	1,218	39%	5506
3,558	2,313	1,245	35%	6449
3,519	2,287	1,232	35%	6378
4,063	3,007	1,056	26%	7821
4,976	2,588	2,388	48%	8210
1,341	831	510	38%	2380
38,093	**24,281**	**13,812**	36%	**68444**

Appendix in A. Information from Te Kakano Aotearoa Trust (who plant many of the native plants in the Upper Clutha):

Over the last 10 years, they have planted about 6.8ha of land in QLDC district (that includes QLDC land and DoC land).

Appendix C: Summary of sequestration pathways

Table B1 – Summary of sequestration scenarios and pathways

Land type	Ownership	Biomass vegetation (tDM/ha)	Scenario high-level approach
Forests with ETS deforestation liabilities	Private ownership and QLDC owned	>200	We assume that all pre-1990 forests will be felled as they are source of wildings. We assume accelerated felling of the QLDC forests such that these are cleared by 2030. Private forests are harvested and cleared linearly after that. Cleared land is replanted with native forest capable of greater management to maximise C sequestration using selected species. Some land may be replanted with (e.g planting with eucalyptus).
Farmlands – flat to rolling (LUC classes 3,4)	Private ownership	Pastures: 3 – 6; biomass crops much higher	<u>Moderate and severe limitations for arable use</u> Land Use Capability classes 3 & 4 (moderate & severe limitations for arable use, but no limitations for trees and pasture). The best use of the above ground biomass would be on-going harvests for use in production of renewable biomethane or potentially biochar. The greenhouse gas emissions per ha of land would also be significantly reduced if the land used for new plantings was previously used for ruminant livestock (with methane emissions). <u>Most accessible rolling land</u> The most accessible rolling arable land (LUC classes 3 & 4) is best used to maximise C sequestration in below ground parts of trees/bioenergy crops and maximise dry mass growth rate above ground for periodic harvest.

Land type	Ownership	Biomass vegetation (tDM/ha)	Scenario high-level approach
			We assume that the proposed changes to water permitting in the Otago region is conducive to conversion of land to biomass plantations, as we are choosing species that do not require water, and are able to operate in the harsh environment. Eligibility of such plantations to qualify as forest offsets would further support such conversions, although this issue should be investigated further. We assume that the rate of biomass conversion of farmland follows a similar pattern as that of private plantation removals, i.e. a linear progression to 2050.
Farmlands -steeper lands (LUC classes 5, 6,7)	Private ownership	>20	New plantings would mostly be permanent native forest, but other regimes to be considered. Biomass production using tree or bioenergy crop species would have the greatest impact to reduce the greenhouse gas emissions. Long-term C sequestration would be in below ground plant structures. The most accessible parts of land in non-arable LUC classes 5 & 6 can be used for trees that are able to be coppiced (i.e., will grow new shoots below the cut tree trunk), done about every 5 years. We assume that the rate of biomass conversion of farmland follows a similar pattern as that of private plantation removals, i.e. a linear progression to 2050.
Urban park lands and holdings (include alienated land)	QLDC	>100	Small parcels Small parcels < 5ha and not conducive to harvesting wood could be planted to a typical native forest species mix but may also be good for larger exotic trees that grow fast and store C well. species could include *Sequoia giganteum, Thuja plicata, Acer Platanoides, Quercus ilex* and some *Leyland cypress* varieties. Larger parcels

Land type	Ownership	Biomass vegetation (tDM/ha)	Scenario high-level approach
			Larger parcels, such as the 40ha reserve near Hawea Flat, have good potential for biomass production (both coppiced trees and long-lived perennial crops), however we understand that these parcels cannot be planted to due to the current zoning rules. We understand that most of park land areas are within urban and per-urban boundaries, which means that activities other than decorative planting are restricted. We assume that 40h are planted in 2026, which is doubled by 2050 through incidental plantings (decorative/specialist/ educational species).
Grouped types on steep land (LUC 7,8)	Pastoral leases, DOC various	<2	The planting option for all land in this category is permanent native forest or restored tussock. Land above 700m unlikely to be addressed within the timeframe of this study.
Reserve land, excluding national parks	DOC	<7	From discussion with officials, we note that a significant proportion of this land is deemed to be degraded. Our treatment of this land, although requiring further development, is based on our treatments applied to pastoral lease land: Management via over-sow weedy ex-grazed land with highly competitive (but non-weedy) species (see list). while increasing conservation value of land.[56] Tussock land restoration or replanting with native grey shrub species and competitive pioneer species for several years, then transition to native species with greater C sequestration.

[56] "nature conservation means the preservation and protection of the natural resources of New Zealand, having regard to their intrinsic values and having special regard to indigenous flora and fauna, natural ecosystems, and landscape" (Conservation Act 1987)

Land type	Ownership	Biomass vegetation (tDM/ha)	Scenario high-level approach
			The rate of conversion above is linear from 2020 to 2050. Land above 700m unlikely to be addressed within the timeframe of this study.
Pastoral Crown Lease, sheep & beef land	LINZ (CCL) shows ownership	3	South-facing sites Plant most into native grey shrubland (pioneer species) and beech on better south-facing sites after several years with nurse species. Focus on below 700m, but allow for higher altitudes. North-facing sites • Restrictions apply on what can be planted on the north facing site (see **Table 1**), we therefore assume planting of beech. Growth rate follows an S-curve, a lag phase followed by a an exponential growth, then linear sequestration. Beech: exponential carbon sequestration accounting for a lag phase, linear after the lag phase which lasts 30 years (follows S-curve). Exponential 20 2050, and linear after that Grey shrubland is necessary to create environment for beech. It is planted on north-facing site. We assume a lag phase of 10 years, then linear carbon sequestration.
Pastural lease land	Private ownership, but	3 degraded >100 where conversion	New plantings would all or mostly be permanent native forest, but should be capable of greater management to maximise C sequestration using selected species, compared to similar land outside of farms. Assume beech planting, following an S-curve as above.

Land type	Ownership	Biomass vegetation (tDM/ha)	Scenario high-level approach
	managed by QEII Trust[57]		
Protected land – Significant Natural Areas	DOC – includes National Parks	>100	We simply assume that the carbon stock increases by 1% per annum, accounting for pest control activities.

[57] "The QEII Trust works with private land owners who wish to have some or all of their land legally protected. A covenant is registered on the title to the land, providing legal protection that binds the current and all subsequent landowners. The Trust generally contributes to the establishment of the covenant and regularly monitors the land to ensure it is managed in accordance with the covenant conditions" https://www.mfe.govt.nz/sites/default/files/media/legally-protected-conservation-land-snapshot.pdf

Appendix D: Use of Giant Miscanthus

Use of Giant Miscanthus (*Miscanthus x giganteus*) for Biomass Production and Bioenergy Use

The perennial grass giant miscanthus (Miscanthus × giganteus) is a sterile triploid natural hybrid of M. × sinensis and M. × sacchariflorus and is abbreviated as Mxg. New shoots grow 3-4 metres tall each year and a planting has a life expectancy that can exceed 20 years. It also has a massive rhizome system, much of it in the upper 30 cm of soil, where it stores large amounts of energy and mineral nutrients in the autumn and re-uses this source for rapid early shoot growth in the following spring (Himken et al, 1997; Heaton et al, 2009; Dohleman et al, 2012). Plants develop in clumps, with 30-130 stems per plant annually from the second or third year of the plantation. Rattans (new shoots) emerge in spring, including some a few cm outside the clump, gradually widening it each year.

The farming inputs required are very low (CIRAIG, 2013; Teagasc, 2010; Dohleman et al, 2012). As a result, the use of Mxg biomass for bioenergy has been calculated to offer substantial reduction in global warming potential (Clifton-Brown et al, 2007; Godard et al, 2013). A principal reason is the low requirement for N fertiliser due, in part, to a soil ecological feature shared with sugar cane. N is fixed in the Mxg rhizosphere by both associative and endophytic soil microbes (Davis et al, 2011).

The highest commercial DM yield is likely to be achieved by harvesting as soon as all harvest timing criteria have been met, before there are further impacts of weather on stems.

Mxg was included in field trials that included arable crops already present in NZ such as forage maize (Zea mays) and a promising NZ clone ('Inulinz') of Jerusalem artichoke (Helianthus tuberosus). Mxg was studied during four years of field experiments and was also the subject of a Life Cycle Assessment (LCA) spanning 'cradle to farm gate' stages (Renquist, 2014). The research was on biomass crops for gasification feedstock as part of the project Biomass to Syngas to Liquids at the University of Canterbury, Christchurch (Pang et al, 2015).

Mxg in NZ reached its full yield potential in year 3. The excellent third year yield during the 2012–13 season occurred despite the region having the driest season since records began in 1960 (Clothier et al, 2014). The good growth was apparently due to access to the water table (at a depth of about 2 m) by the well-developed root and rhizome system.

In addition to Mxg having a small environmental footprint to grow is the very positive impact of growing Mxg on climate change due to sequestration of soil organic carbon. If proven, Mxg production (in place of other arable crop species) would be environmentally beneficial even before the biomass is to substitute for fossil fuel.

Appendix E: Technical sequestration options - overview of the technology

This appendix provides a technical review of a non-exhaustive selection of nine different CO_2 utilization pathways; (1) CO_2-based chemical products; (2) CO_2-based fuels; (3) mineralisation including concrete building materials; (4) conversion to graphite/graphene; (5) bioenergy with carbon looping; (6) land management via soil carbon in the form of biochar; (7) biotechnological conversion to microalgae fuels and/or other microalgae products; (8) the direct use of CO_2, and; (9) hybrid opportunities from the uptake of CO_2 based on existing sources.

The review focusses on known technology and emergent technology at early stage commercialisation. Particular focus is given to the likely utilisation pathways and overall technical readiness. Whilst not directly applicable to this study an analysis by Hepburn *et al* of the prospects for CO_2 sequestration reinforces the marginal nature of some of the activities examined and the likely required very high carbon price for deployment. A number of the options described below, especially chemicals and fuels, may appear at first glance to offer some potential for deployment, however, in the absence of a point source of CO_2 these options are not viable.

Pathway	Removal potential in 2050 (Mt CO_2 removed per year)	Utilization potential in 2050 (Mt CO_2 utilized per year)	Breakeven cost of CO_2 utilization (2015 US$ per tonne CO_2 utilized)
Conventional utilization			
Chemicals	Around 10 to 30	300 to 600	–$80 to $320
Fuels	0	1,000 to 4,200	$0 to $670
Microalgae	0	200 to 900	$230 to $920
Concrete building materials	100 to 1,400	100 to 1,400	–$30 to $70
Enhanced oil recovery	100 to 1,800	100 to 1,800	–$60 to –$45
Non-conventional utilization			
BECCS	500 to 5,000	500 to 5,000	$60 to $160
Enhanced weathering	2,000 to 4,000	n.d.	Less than $200*
Forestry techniques	500 to 3,600	70 to 1,100	–$40 to $10
Land management	2,300 to 5,300	900 to 1,900	–$90 to –$20
Biochar	300 to 2,000	170 to 1,000	–$70 to –$60

n.d., not determined.

The breakeven cost is the cost in 2015 US$ per tonne of CO_2 adjusted for revenues, by-products, and any CO_2 credits or fees. A breakeven cost of zero represents the point at which the pathway is economically viable without governmental CO_2 pricing (for example, a subsidy for CO_2 utilization). Breakeven costs presented as a range represent either (for conventional pathways with the exception of EOR) 25th and 75th percentile estimates as calculated via the scoping review of the academic literature (in which the magnitude of the difference reflects the diversity of technological and economic assumptions available within and across each sub-pathway) or (for land-based pathways) top-down estimates of revenues that may accrue (when the uncertainty of the accuracy of the estimation is high). Breakeven costs presented with an asterisk are calculated unadjusted for revenues and by-product credits. To obtain the global gross utilization potential high and low values for conventional pathways, we averaged the interpolated expert opinions with an author group estimate. For non-conventional utilization pathways, estimated utilization potential ranges are based on estimates of additional realized yield of carbon in vegetation (for soil carbon sequestration and biochar, additional yield approximates to net primary productivity, and for afforestation/reforestation, it approximates to wood products). These are first rough estimates based on preliminary but sparse published research reporting relationships between carbon storage and additional carbon that can be utilized.

Figure 1: Range estimates of the potential for CO_2 utilization and present-day breakeven cost *(from reference* [21]) (BECCS refers to bioenergy with carbon capture and sequestration – in this report the term carbon looping is used)

The below summary begins with a technical review of Carbon Capture or the direct removal of CO_2 from air or flue gas:

Carbon Capture

The removal of CO_2 from a gas mixture containing other chemical species is not a new challenge for chemical engineers or industry. In NZ for example the CO_2-rich Kapuni gas is stripped of most of its CO_2 at the Kapuni gas treatment plant before it enters the natural gas pipeline system. In addition the produced CO_2 is used as a feedstock for urea manufacture at the adjacent Ballance Agri-Nutrients urea plant or distributed as a pure gas for direct use throughout the North Island Excess CO_2 is currently vented to atmosphere; although geological sequestration or even enhanced oil recovery could be options for future consideration.

There are several pathways for CO_2 separation, including among others absorption (preferential dissolution of a species into a liquid) and adsorption (preferential adherence of a species onto a solid). At Kapuni the Benfield process is used to strip out the CO_2, which involves a gas absorption step with potassium carbonate followed by a carbonate regeneration step.

Other examples of CO_2 removal from process gas streams include the production of hydrogen from synthesis gas; produced via steam reforming of methane (or natural gas). Here, the produced mixture of carbon dioxide, carbon monoxide and hydrogen undergoes first a shift reaction to maximise the hydrogen content of the gas with residual CO_2 removed via amine-based solvent absorption or, on a smaller scale, membrane technology. These technologies are all quite mature and relatively simple.

More recently the application of these technologies has been extended to include the capture of CO_2 from power stations or from combustion flue gases. The below schematic describes a typical monoethanolamine (MEA) CO_2 absorption configuration that one might see in any industrial plant. The carbon dioxide stream exits from the top of the stripper and is cooled to remove solvent and water vapours, which are returned to the regeneration column. CO_2 that is captured is normally at a high purity and is then compressed, dehydrated and liquefied.

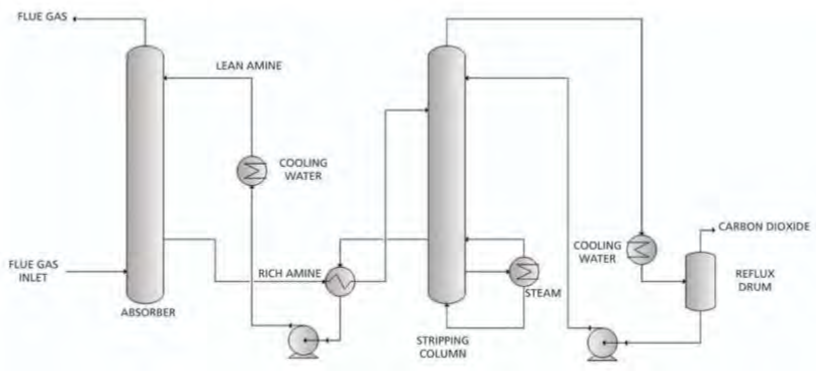

Figure 2: Example Chemical Absorption Process (from Energy Institute, Reference 32)

One of the key issues that has to be addressed when removing CO_2 from a combustion or flue gas is the overall thermodynamic efficiency of the process and also the scale of the plant due to, typically, the relatively low concentrations of CO_2 and the presence of nitrogen plus other impurities in the flue gas – nitrogen is introduced when using air as the combustion gas. There is a significant research and development effort globally to improve these processes, and to improve overall efficiencies and recoveries. Essentially, from a theoretical basis the amount of energy required to remove CO_2 from a typical power station flue gas containing 12% CO_2 is 172 kJ/kg CO_2. This, in turn, becomes a parasitic load on the power station reducing overall electrical generation efficiency.

Work done for the NZ CCS Group by Transfield Worley[58] showed that the parasitic load for a conventional NGCC power station was of the order of 27 percent and that retrofitting a power station to enable CO_2 capture was unlikely to be economic; requiring a carbon price of between $NZ 83 - 128/tonne of CO_2. The Transfield Worley work concluded that the only viable CCS sequestration option for NZ was from single large point sources of CO_2 , as exists at the Kapuni Benfield Plant.

These inefficiencies are even greater when one looks at Direct Air Capture (DAC) of CO_2 from air. The thermodynamic minimum energy required to remove CO_2 from a mixture where its initial concentration is 0.04% (characteristic of air) is about three times larger than the corresponding minimum energy when the initial CO_2 concentration is 12% (characteristic of a flue gas). Whilst there are several reported developments of the technology at pilot / semi-commercial scale, DAC is largely at research and conceptual engineering level. It is also worth noting that to have any significant effect on global CO_2 concentrations, DAC would need to be rolled out on a vast scale, raising serious questions about the energy required and the levels of water usage for particular technologies; let alone its commercial readiness.

Thus, whilst a large DAC facility could conceivably be built today, the capital cots would be enormous with some estimates giving a final avoided cost of around $US600/t$CO_2$. This is not an option for QLDC, or NZ for that matter. There are better ways of dealing with this issue. For example the above "post-combustion capture" (PCC) retrofit of a NGCC power plant.

However, there is significant work and investment internationally in this technology. Examples of commercial initiatives include the US company Carbon Engineering which constructed a CAD$8 million pilot plant in British Columbia in 2015. This pilot plant was sized to extract about a tonne of carbon dioxide a day using an aqueous KOH sorbent coupled to a calcium caustic recovery loop. The company currently proposes a "first-of-of-a-kind" commercial plant capable of removing 1 million tonnes per year CO_2 and claims a levelized cost per tonne of CO_2 captured of between 94 to 232 $/t-$CO_2$[59].

In another initiative the Swiss company Climeworks, in 2016, built a "first commercial plant" to capture CO_2 directly from air. Their technology is based on physical adsorption via a geomaterial filter. Currently the company has partnered with Reykjavik Energy at the Hellisheidi geothermal plant in Iceland where they have a 50 tonnes of CO_2 per year air capture unit. The recovered CO_2 is then sequestered via injection into basalt formations.

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[58] Transfield Worley Ltd., "Potential for CCS in New Zealand", A study for the NZCCS Partnership, November 2011

[59] Keith W D et al, *A Process for Capturing CO_2 from the Atmosphere,* Joule 2, 1573–1594, August 15, 2018

This project, CarbFix2, has received funding from the European Union's Horizon 2020 research and innovation programme[60]. However, the cost of storage in the pilot scale plant is estimated at around \$US600/tCO_2 compared with a require breakeven price at current carbon prices of around \$US 30-40/tCO_2[61]

In NZ, Hot Lime Labs[62] is offering its own variant of the above technology, but based on the recovery of CO_2 from synthesis gas produced via biomass gasification. Their technology uses a patented lime pellet absorption process. The pellets have very high CO_2 capture capacity and act like a sponge within the system. These pellets have the capacity to absorb up to 30% of their volume in CO_2. After absorption hot air is applied to the system causing a reaction that releases the CO_2 as a carbon source for hydroponic greenhouse (~700ppm CO_2) operations.

Carbon Dioxide as a feedstock for Chemicals and Fuels

CO_2 is an important chemical feed stock and globally the uses of carbon dioxide for these purposes is huge. The use of CO_2 as a building block in organic syntheses to obtain valuable chemicals fuels and materials has been discussed in many reports and review articles (See, Aresta[63], Centi[64], Styring[65]). Some estimates but the total sequestration potential from these routes at about 2-4 Gtonne/y CO_2. The various possibilities are shown diagrammatically below.

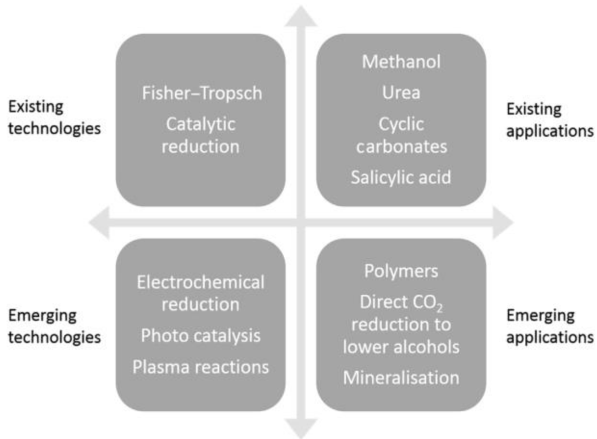

Figure 3: Existing and emerging CO_2 utilisation technologies and applications. (From Chapter 13 of *Carbon Dioxide Utilisation: Closing the Carbon Cycle.* Editors; Styring, P., Quadrelli, E. A., & Armstrong, K., 2014)

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[60] *https://www.carbfix.com/carbfix2*

[61] Ragnheidardottir E *et al*, "Opportunities *and challenges for CarbFix: An evaluation of capacities and costs for the pilot scale mineralization sequestration project at Hellisheidi, Iceland and beyond"* International Journal of Greenhouse Gas Control Volume 5, Issue 4, July 2011,

[62] *https://hotlimelabs.com/increasing-yield/*

[63] Aresta M, Carbon Dioxide Utilzation, Utilization of Greenhouse Gases , ACS Symposium Series; American Chemical Society: Washington, DC, 2003.

[64] Centi G, Siglinda P. "*Opportunities and prospects in the chemical recycling of carbon dioxide to fuels*" Catalysis Today 148 (2009) 191–205.

[65] Styring, P, Chapter 13 of *Carbon Dioxide Utilisation: Closing the Carbon Cycle, 2014*

Bulk chemicals at present being produced from the capture of CO_2 include methanol, urea, salicylic acid, and polycarbonate-based plastics. In the NZ context methanol and urea are important commodities with production capacity in Taranaki based on natural gas as feedstock. Methanol occupies a key position in the chemical industry as a highly versatile globally traded intermediary for the manufacture of countless everyday products. The largest scale application in terms of volume is its processing into formaldehyde, which is further treated to form resins, glues and various plastics. Other important uses include the production of acetic acid (used for the production of polyester fibres and PET plastics), methanol-to-olefins and also in the manufacture of methylamines used in pesticide manufacture.

Currently the largest scale chemical utilization pathway for CO_2 is that of urea production. Urea is produced from ammonia according to the rection $2NH_3 + CO_2 \rightleftharpoons CO(NH2)_2 + H_2O$; with coal or natural gas typically providing the necessary chemical energy required for the reaction. The potential availability of renewable hydrogen based on the electrolysis of water thus opens up the long-term possibility of producing urea from renewable sources.

Fuels derived from CO_2 are argued to be an attractive option in the decarbonization process because they can be deployed within existing transport infrastructure. There are many different pathways to convert CO_2 to fuels. However, the hydrogenation of CO_2 to form oxygenates and/or hydrocarbons is the most intensively investigated area of CO_2 conversion.

Hydrogen sources for the chemical recycling of CO_2 could be generated by a variety of means such as biomass gasification to the electrolysis of water. Fuels produced include methanol, methane, dimethyl ether, Fischer–Tropsch fuels and FAME. All of these products are potential CO_2 energy carriers for transport use, are proven fuels in modern internal combustion engines, and can be readily stored and transported. A useful summary of the chemistry involved can be found in Samedi et al[66]. This review paper describes the different routes for conversion to hydrocarbons, the catalyst systems employed and the various process configurations available.

At industrial scale, Carbon Recycling International, founded in 2006 in Reykjavik, has developed the world's first commercial scale CO_2 to liquid fuel production facility near Grindavik, Iceland, with capacity of 5 million litres/year at full scale. The plant started supplying methanol to the domestic market in 2011. CO_2 feedstock to the plant and renewable energy required for H_2 production comes from the Svartsengi geothermal power plant. It is estimated that as much as 340 million/litre per year methanol could be manufactured in Iceland based on the country's available geothermal capacity[67]. Most notably, the use of the renewable methanol from the plant releases 90% less CO_2 in comparison to the use of a comparable amount of energy from fossil fuels.

The solar dissociation of CO_2 and H_2O to synthesis gas is also a possible synthesis route. Whilst still at the development stage companies such as NewCO2Fuels Ltd (Israel) have successfully

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[66] Saeidi S, *"Hydrogenation of CO_2 value -added products – A review and potential future developments"* Journal of CO_2 Utilization 5 (2014) 66–81

[67] Carbon Recycling International Technology Overview. https://www.carbonrecycling.is/technology-and-services (accessed 10-02-2020).

completed trials to dissociate CO_2 into CO and oxygen, where the heat required for the process is generated by concentrated solar radiation[68]. The oxygen produced in the process can be used in the combustion of the clean fuel, for example, using advanced-combustion methods, such as oxy-fuel combustion in power plants. Considerable research continues in this area but has not been reviewed here.

Syngas fermentation also offers an alternative route to methanol from biomass[69] but, again, remains largely at developmental stage. A potential advantage over traditional thermochemical conversion routes is that that the derived biofuels include; hydrogen, ethanol, butanol, acetic acid and butyric acid. Worldwide there is significant ongoing research and development with the literature suggesting some five demonstration or semi-commercial plants either operating or planned. Known commercial syngas fermentation plants include Indian River (INEO) and Lighthouse in Pennsylvania (Coskata).

LanzaTech (formerly Range Fuels) has operated a waste gas fermentation demonstration plant at Bluescope Steel and are report to be developing two additional demonstration plants in partnership with Baosteel and Capital Steel in China. However, the current status of these plants is unknown.

Other Technological Uses of CO_2

Specialist Chemicals

In addition to the traditional catalytic conversion routes to chemicals and fuels there are a variety of electrochemical, biological and other technological options for the utilisation of CO_2. For example, the carboxylation of alkenes may well offer novel new synthesis routes for the production of acetates, cyclic carbonates and other chemicals.

Aresta refers to a number of new processes for the synthesis of polycarbonates using new synthetic strategies based either on the direct use of CO_2 (copolymerization of CO_2 with olefin-oxides: mainly to make propene-polycarbonate) or on the use of CO_2 substitutes (organic carbonates). Polycarbonates are used in several different applications; from building materials to car manufacture, CDs, and specialty optics. The market has seen steady growth in the past years, with 2012 global demand reported at over 4 million tonnes.

Centi comments that important advances have been made in the electro-catalytic reduction of CO_2 in recent times. Substantial advances in electrodes, electrolyte, and reactor design have been reported but still require further advance to permit the development of commercial processes. He suggests that the integration of bio- and solar-refineries in order to create greater synergies will be important to valorize the CO_2 produced in biorefineries as well as to integrate renewable energy sources in biorefinery production (solar biorefineries).

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[68] Greenearth Energy Ltd: ASX announcement and media release 28 May 2014, (http://www.newco2fuels.co.il/).
[69] Daniell J., *et al* Commercial Biomass Syngas Fermentation, Energies 2012, 5, 5372-5417; doi:10.3390/en5125372

Biochar

Biochar is a co-product or by-product of pyrolysis-based biofuel production. There has been a significant interest in biochar, both as a waste minimisation/disposal option because of the reduced volumes and increased stability in landfills, but also as a carbon sequestration material where it acts as:

- A soil fertility enhancer - enhancing nutrient retention, promoting soil biology, increasing productivity/yields, increasing efficiency of fertilisers, improved water retention and/or drainage
- A soil remediation tool - contaminated site clean-up, mine site restorations, etc.

In particular, chars produced at higher temperatures have a well-developed carbon nanostructure which provides good porosity, high surface areas, and electrical conductivity which is believed to provide extra space for air and water storage in the soil along with shelter/habitat for fungi and bacteria[70]. Research studies have observed with the application of biochar short-term positive yield and growth impacts (Spokas et. al. 2012[71]) and an increase in crop productivity of around 15~18% across many crops and application rates (Jeffery et. al. 2015[72]). Use of biochar as an additive for compost making has also been reported as improving nitrogen retention (Schmidt et.al. 2014[73]).

Graphene

In other applications carbon dioxide can be used as a raw material to produce both graphite and graphene. Graphene is an advanced carbon material used to create screens for smart phones and other devices. The reduction process is done at atmospheric pressure and high temperatures of up to 1,000°C over copper-palladium catalysts[74]. Graphene production is limited to specific industries but is an example of how carbon dioxide can be used as both as a resource and as a solution in reducing CO_2 footprints.

The use of graphene in high-performance membranes to specifically pick out CO_2 from a mix of gases is considered as one of the most energy-efficient routes for reducing CO_2 emissions. The membranes are based on single-layer graphene with a selective layer thinner than 20 nm, and

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[70] McDonald-Wharry J, *Potential applications for chars, biochar and other carbonaceous materials;* paper to Biomass Conference Rotorua, 2015.
[71] Spokas, K.A., et al., *"Biochar: A Synthesis of Its Agronomic Impact beyond Carbon Sequestration",* Journal of Environmental Quality, 2012. 41(4): p. 973-89.
[72] Jeffery, S., et al., *"Biochar effects on crop yield, in Biochar for environmental management: science and technology",* J. Lehmann and S. Joseph, Editors. 2015, Routledge: New York.
[73] Schmidt, H.-P., et al., *"Biochar and biochar-compost as soil amendments to a vineyard soil: Influences on plant growth, nutrient uptake, plant health and grape quality".* Agriculture, Ecosystems & Environment, 2014. 191: p. 117-123
[74] Molina-Jiron C, *"Direct Conversion of CO_2 to Multi-Layer Graphene using Cu–Pd Alloys"*, ChemSusChem 2019, 12,3509 –3514

have highly tunable chemistry, meaning that they can pave the way for next-generation high-performance membranes for several critical separations.

Mineral Carbonisation and Concrete Building Materials

In mineral carbonation, CO_2 is reacted with minerals (mostly calcium or magnesium basic silicates, such as serpentine $Mg_3Si_2O_5(OH)_4$, olivine, Mg_2SiO_4, and wollastonite, $CaSiO_3$) to form (Ca or Mg) carbonates. Breakeven costs are relatively low when compared to other sequestration options and thus this pathway is of considerable interest to those countries that lack the land for geological or deep ocean storage of CO_2[75]. Additionally, carbon sequestration via mineralization is suggested as the safest and most stable way of locking away large amounts of CO_2.

The process itself takes CO_2 from a point source and reacts the CO_2 over the silicate minerals. These minerals are readily accessible, and the feasibility of the reaction pathways is reasonably assured. Life cycle costing suggests sequestration of around are 105 – 127 USD/tonne CO_2 avoided. However, there still remains various engineering challenges related to recovery of the heat produced by the carbonation reaction that have to be overcome and, as well, account must be taken of the energy penalties associated with the front-end CO_2 recovery step.

In addition to the above there is significant interest worldwide in replacing lime-based ordinary Portland cement with alternative binders such as steel-slag based systems or geopolymers made from aluminosilicates. Whist technically feasible this is an unlikely an option for Queenstown given the lack of mineral industries or the like. An alternative that might offer limited sequestration opportunity is the CO_2 curing of concrete. This technology uses the CO_2 emitted from industrial operations and embeds the carbon dioxide permanently within concrete. Used widely in Nth America in the precast concrete and concrete block industries the technique is used to accelerate early strength, improve long-term durability and reduce both energy requirements and overall emission.

The theoretical maximum possible carbon uptake in concrete is around 29% based on cement mass in the product. Indicated costs are of the order of \$US10/tCO_2[76]

Direct use of CO_2

Carbon dioxide, either as compressed CO_2 or liquid CO_2 is routinely supplied to industry, hospitals and for many other uses; including food and beverage, dairy and horticulture. CO_2 is produced both at Kapuni and at NZ Refining in Marsden Point. The Marsden Point refinery CO_2 separation plant produces some 50,000 tonnes of CO_2 a year whereas the Kapuni Benfield plant capacity is around 2,000 t/day, with much of that going to urea manufacture.

In addition to the above conventional uses supercritical CO_2 is becoming an important commercial and industrial solvent in chemical extraction due to its low toxicity and relative ease of recovery. At supercritical conditions (above 31°C and 73.8 bar) the CO_2 gas behaves like a

[75] Khoo H et al, *"Carbon capture and utilization: preliminary life cycle CO_2, energy, and cost results of potential mineral carbonation"*, Energy Procedia 4 (2011) 2494–2501

[76] *Shao Y, "Beneficial Use of Carbon Dioxide in Precast Concrete Production". McGill University report to U.S. Department of Energy, March 2014*

dense fluid with strong extractive properties. Typical uses include the decaffeinating of coffee, the extraction of essential oils and other herbal distillates, as well as in crystallisation and a range of pharmaceutical uses.

In NZ there are a number of small pilot-scale facilities that offer batch processing operations to industry partners for the production of high value, natural bio-actives from biologically based raw materials and other extractives. Whether these technologies might potentially offer benefit to QLDC requires further investigation, however, the direct use of CO_2 as a technological fluid is a potentially useful contribution to the reduction of the impact of climate change.

Biological Conversion of CO_2

It is important also to comment on the biological conversion of CO_2. The conversion of C1's into organics can occur either under natural conditions (i.e., up-take of CO_2 from the atmosphere) or under "enhanced" or "industrial" conditions, that are much different from natural ones. Typical examples of "enhanced" biological fixation are (i) the cultivation of terrestrial biomass (plants, vegetables etc.) in greenhouses under a CO_2 concentration in the gas phase of ca. 600-700 ppm and (ii) the farming of aquatic biomass by dissolving CO_2 in water or under a gas phase concentration of up to 5−10%, i.e., 130−260 times natural levels.

A small but growing industry for the cultivation and industrial scale production of microalgae and aquatic species has evolved over the last fifty or so years. Whilst these techniques are seen as "solar factories" the other, equally important, feedstock is carbon. For example, C represents about 50 percent of the total dry weight of algae.

Micro-algae have the ability to fix CO_2 directly from waste streams such as flue gas as well as using nitrogen from the gas as a nutrient. Cultivation of microalgae can be carried out in open raceway ponds and photo-bioreactors (flat-plate, annular or tubular). The former requires a large land area and process control is difficult, limiting productivity. Generally, in natural systems the efficiency of CO_2 uptake is limited. Also, since the pumping of CO_2 to the cultivation system represents a parasitic energy loss, efficient use of CO_2 is desired.

Photo-bioreactors are better in that respect but are more expensive than open-pond systems. From an engineering perspective, CO_2 supply becomes a key issue in the design of algae production systems. The design of the photobioreactors to increase organic carbon loadings and thus algae cultivation is an important aspect in the production of the selective algae species used for nutraceutical purposes.

Algae is often touted as an ideal feedstock for the production of aviation fuels. The conversion into fuels can be carried out through thermochemical or biochemical conversion. The former uses heat to produce first syngas and then fuels as well as heat and electricity. Some examples of thermochemical conversion processes include gasification, liquefaction and pyrolysis[77].

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[77] Rosa *M, Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts*" Journal of CO_2 Utilization 9 (2015) 82–102

Biochemical conversion relies on biological and chemical processes, such as anaerobic digestion, fermentation and esterification. At small scale the digestion of algae to biomethane may offer some fuel substitution opportunities, however, at large-scale the production of biofuels from microalgae is currently not available because of the high production costs, mainly owing to the high energy requirements[78].

[78] Lundquist T *et al, "A Realistic Technology and Engineering Assessment of Algae Biofuel Production",* Energy Biosciences Institute, University of California, October 2010

Appendix F: About Us

About Sapere

Sapere Research Group is one of the largest expert consulting firms in Australasia, and a leader in the provision of independent economic, forensic accounting and public policy services. We provide independent expert testimony, strategic advisory services, data analytics and other advice to Australasia's private sector corporate clients, major law firms, government agencies, and regulatory bodies.

'Sapere' comes from Latin (to be wise) and the phrase 'sapere aude' (dare to be wise). The phrase is associated with German philosopher Immanuel Kant, who promoted the use of reason as a tool of thought; an approach that underpins all Sapere's practice groups.

We build and maintain effective relationships as demonstrated by the volume of repeat work. Many of our experts have held leadership and senior management positions and are experienced in navigating complex relationships in government, industry, and academic settings.

We adopt a collaborative approach to our work and routinely partner with specialist firms in other fields, such as social research, IT design and architecture, and survey design. This enables us to deliver a comprehensive product and to ensure value for money.

About DETA

DETA Consulting (DETA) is a New Zealand owned and managed consultancy specialising in identifying, developing, and delivering efficiency projects. Our expertise in energy efficiency is second to none across Australasia and has led to our strong growth to a team of 20 staff across three offices in New Zealand, one in Australia, and work across the Asia Pacific region.

We work to improve our clients' business by helping identify, scope and deliver optimization projects. We always analyse the impacts of our solutions on the client as a whole, considering practicality, health and safety, business and environmental concerns. We ensure our analysis is "real" and that clients can make informed decisions.

Our customers are broad and far reaching and include large industrial processors in the dairy, meat, wood and food production areas, commercial and governmental agencies, healthcare providers, and small SME businesses. We are at the forefront of technology in our industries – we have rolled out several 'first in country' projects in the refrigeration and energy generation space and are working closely with several of our customers to deliver significant market leading automation projects. Our recent project at Hanmer Springs thermal resort, completed in 2018, won several innovation awards for its application of new technology.

About Maidstone

Maidstone Associates is a private consulting firm led by George Hooper offering expert advisory and consulting services to clients within the technology and resources sectors, with a primary focus on industry strategy and operational support, technology commercialisation, and technical due diligence.

This includes a strong interface role between the university and research sectors of NZ and industry research investments.

A core competency of the firm is in front-end conceptual engineering. Assignments have included evaluations of emerging technologies, specific project investigations and feasibility assessments of commercial resource development proposals, plus the evaluation of new business opportunities in the renewable energy sector. In this capacity, the company plays a key role in scoping and identifying project opportunities, and in the formulation of deployment pathways.

In respect of this assignment specific projects include expert contributions to a range of industry studies assessing future energy supply options, biomass gasification studies, appointment as Technical Advisor to the New Zealand CCS Partnership, stage gate risk analysis for new technology investments across a range of biofuel and non-conventional energy options, plus expert review of the carbon default emissions factors for gas mining and processing.

For more information, please contact:

Name: Toby Stevenson
Phone: 04 915 7616
Mobile: 021 666 822
Email: tstevenson@thinkSapere.com

Wellington	**Auckland**	**Sydney**	**Melbourne**	**Canberra**
Level 9 1 Willeston Street PO Box 587 Wellington 6140	Level 8 203 Queen Street PO Box 2475 Shortland Street Auckland 1140	Level 18 135 King Street Sydney NSW 2000	Level 2 161 Collins Street GPO Box 3179 Melbourne 3001	PO Box 252 Canberra City ACT 2601
P +64 4 915 7590 F +64 4 915 7596	P +64 9 909 5810 F +64 9 909 5828	P +61 2 9234 0200 F +61 2 9234 0201	P +61 3 9005 1454 F +61 2 9234 0201 (Syd)	P +61 2 6100 6363 F +61 2 9234 0201 (Syd)

www.thinkSapere.com

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