Setting Better-Informed Climate Targets for New Zealand: The Influence of Value and Modeling Choices

Chandrakumar, Chanjief; Malik, Arunima; McLaren, Sarah J; Owsianiak, Mikoaj; Ramilan, Thiagarajah; Jayamaha, Nihal P; Lenzen, Manfred

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4 **Setting Better-Informed Climate Targets for New Zealand:**
5 **The Influence of Value and Modeling Choices**

6 Chanjief Chandrakumar^{a,b,*}, Arunima Malik^{c,d}, Sarah J McLaren^{a,b},
7 Mikołaj Owsianiak^e, Thiagarajah Ramilan^{b,f}, Nihal P Jayamaha^g, Manfred Lenzen^c

8 ^aNew Zealand Life Cycle Management Centre, c/o Massey University, Palmerston North 4442,
9 New Zealand

10 ^bSchool of Agriculture and Environment, Massey University, Palmerston North 4442, New
11 Zealand

12 ^cISA, School of Physics, The University of Sydney, Sydney, New South Wales 2006, Australia

13 ^dSydney Business School, The University of Sydney, Sydney, New South Wales 2006, Australia

14 ^eDivision for Quantitative Sustainability Assessment, Department of Management
15 Engineering, Technical University of Denmark, Produktionstorvet 424, 2800 Kgs. Lyngby,
16 Denmark

17 ^fSchool of Food and Advanced Technology, Massey University, Palmerston North 4442, New
18 Zealand

19 ^gSchool of Agriculture and Food, The University of Melbourne, Melbourne, Victoria 3010,
20 Australia

21 [*C.Chandrakumar@massey.ac.nz](mailto:C.Chandrakumar@massey.ac.nz)

22 **ABSTRACT**

23 Quantifying greenhouse gas (GHG) emissions and setting emissions budgets for
24 anthropogenic systems are influenced by several value and modeling choices. This study, for
25 the first time, quantified the influence of choice of GHG accounting approach, GHG metric,
26 time horizon, climate threshold, global emissions budget calculation method, and effort-
27 sharing approach, taking New Zealand (NZ) as a case study. First, NZ's production- and
28 consumption-based emissions were quantified using multi-regional input-output analysis and
29 applying different GHG metrics (global warming and temperature potentials) and time
30 horizons (20 and 100 years). Second, global emissions budgets for 1.5 °C, 2 °C, and 1 Wm⁻²
31 climate thresholds were estimated. Budget shares were then assigned to NZ using two effort-
32 sharing approaches (grandfathering and economic value), and emissions were benchmarked
33 against the assigned shares. Finally, the analysis was undertaken at the NZ sector level. The
34 results showed that, for each GHG accounting approach, NZ's total emissions exceeded their
35 budget shares, irrespective of the choices; the largest source of uncertainty was the choice of
36 global emissions budget calculation method, followed by GHG metric, climate threshold,
37 effort-sharing approach, and reference year for the grandfathering approach. The sector-level
38 analysis showed that, while most sectors exceeded their budget shares, some performed
39 within them. The ranking of uncertainty sources was quite different at the sector level, with
40 the choice of effort-sharing approach providing the largest source of uncertainty. Overall, the
41 study indicates the importance of handling value and modeling choices in a transparent way
42 when quantifying emissions and setting emissions budgets for anthropogenic systems.

43 **Keywords:** *science-based targets, absolute sustainability, value choice, modeling choice,*
44 *carbon budget, climate change, multi-regional input-output analysis, life cycle assessment,*
45 *New Zealand*

INTRODUCTION

Anthropogenic greenhouse gas (GHG) emissions increase the risk of transgressing global climate thresholds.^{1, 2} Existing climate change indicators based on different GHG emissions metrics such as global warming potential³ and global temperature change potential⁴ provide information about the climate change performance of an anthropogenic system (which can be either a product/process, service, company, sector, country or the entire Earth). However, they do not provide information about that system's performance relative to global climate thresholds.⁵ Therefore, they can be regarded as providing insufficient information to mitigate climate change globally.

Acknowledging the existence of global climate thresholds, researchers have started developing so-called *absolute environmental sustainability assessment* (AESA) methods.⁶⁻⁹ An AESA method, in general, quantifies the GHG emissions of an anthropogenic system using climate change indicators (based on GHG metrics) and provides information on that system's climate change performance relative to a chosen climate threshold.^{10, 11} Several value and modeling choices are made during this modeling process, which are potentially important sources of uncertainty. These choices include selection of:

- (i) A GHG accounting approach to calculate the GHG emissions (aka carbon footprint) of an anthropogenic system.
- (ii) A GHG metric and time horizon to estimate the aggregated impact of different GHGs associated with the chosen anthropogenic system.
- (iii) A global climate threshold.
- (iv) An estimated (GHG) emissions budget for the chosen global climate threshold.
- (v) An effort-sharing approach for assigning a share of the global emissions budget to the chosen anthropogenic system.

71 Regarding **selection of a GHG accounting approach**, these approaches can be either
72 production-based (also referred to as territorial in some studies) or consumption-based.¹²⁻¹⁴
73 Production-based accounting approaches, in general, account for the GHG emissions released
74 by the producer within a specific territory; hence, these approaches generally do not consider
75 the emissions associated with imported goods and services used by the producer.¹⁵ On the
76 other hand, consumption-based accounting approaches allocate all emissions of the
77 production of goods and services to the final consumer; these methods do not account for
78 the emissions associated with additional goods and services that are exported.^{12, 13} Each of
79 these approaches provides different insights to support climate change mitigation activities
80 and policymaking; hence, in general, both approaches are used in a complementary way.¹⁶⁻¹⁸

81 Once the GHG accounting approach is chosen, the emissions of all GHGs (such as carbon
82 dioxide, methane, nitrous oxide, chlorofluorocarbons, and hydrofluorocarbons) associated
83 with the chosen system are quantified using methods such as carbon footprinting¹⁹ and
84 environmentally-extended input-output analysis.^{20, 21} The **measured GHGs** are then
85 **aggregated** into so-called **carbon dioxide-equivalent** (CO₂-eq) emissions, using a **GHG metric**
86 and a **time horizon** which assign a weighting (referred to as a characterisation factor in Life
87 Cycle Assessment) to the emission of each individual GHG. Global warming potential (GWP)
88 and global temperature potential (GTP) are the commonly used metrics;^{22, 23} the former
89 represents the heat absorbed over a given time horizon due to a GHG emission, whereas the
90 latter expresses the change in the atmospheric global mean temperature at the end of the
91 time horizon.²⁴ GWP calculated for a 100-year time horizon (GWP100) is commonly used in
92 carbon footprinting methodologies as well as in the United Nations Framework Convention
93 on Climate Change (UNFCCC) and its Kyoto Protocol,^{19, 25} although alternatives such as GWP
94 20 and GTPs at 100, 50, and 20 years (GTP100, GTP 50, and GTP 20 respectively) exist.^{4, 26, 27}

95 Once the GHG emissions are assessed, the aggregated result is benchmarked against an
96 assigned share of the global emissions budget, which requires choosing an appropriate **global**
97 **climate threshold** (hereafter, climate threshold). There are several climate thresholds
98 proposed in the literature.^{25, 28, 29} For example, the international policies of the UNFCCC were
99 centred on limiting the global mean temperature increase to 2 degree Celsius (°C) above pre-
100 industrial levels.³⁰ This long-term goal was lately revised under the Paris Agreement to holding
101 the increase well below 2 °C and pursuing efforts to limit it to 1.5 °C.^{28, 31} At the same time,
102 the planetary boundaries framework has defined more ambitious (two) climate thresholds
103 that should not be transgressed: a global average atmospheric CO₂ concentration of 350 parts
104 per million (ppm) CO₂ and an increase in radiative forcing of 1 watt per square metre
105 (Wm⁻²).²⁹ However, staying within these climate thresholds seems ambitious as it requires
106 rapid and dramatic changes in how governments, businesses, and societies currently operate.

107 The chosen climate threshold should then be translated into a measurable **global**
108 **emissions budget**; different methods exist for this purpose.³²⁻³⁴ For example, Bjørn and
109 Hauschild³³ proposed a method to estimate a global emissions budget using the GEOCARB
110 model for CO₂ and the model of Shine et al.⁴ for other GHGs. Using this method, they
111 estimated the global emissions budgets for the 1 Wm⁻² and 2 °C climate thresholds (and using
112 the GWP100 metrics)- 3.6 and 6.8 gigatonnes carbon dioxide equivalent per year
113 (GtCO₂-eq·yr⁻¹), respectively (see Methods, Supplementary Information (SI) 1 for details). At
114 the same time, Doka³² proposed an alternative method to translate the increase in radiative
115 forcing into a global emissions budget using so-called absolute GWPs of different GHGs. By
116 applying this method, Doka³² estimated the global emissions budget for the 1 Wm⁻² climate
117 threshold (10.9 GtCO₂-eq·yr⁻¹ for the GWP100 metric) (see Methods). Thus, the budget

118 calculated using the method of Doka³³ (for GWP 100) is three times higher than the budget
119 calculated using the method of Bjørn and Hauschild.³³ There are additional methods that
120 propose different global emissions budgets for the same climate thresholds^{34, 35} (see SI 1
121 section 1).

122 Finally, to **assign a share** of the global emissions budget to a chosen anthropogenic system
123 (e.g., an economic sector of a country), there are a wide range of effort-sharing approaches
124 based on different equity principles such as grandfathering (aka historical responsibility),
125 population, territorial area, economic output (or value addition), and final consumption
126 expenditure.³⁶⁻³⁹ Each effort-sharing approach has its own benefits and limitations. For
127 example, the grandfathering approach effectively rewards the larger emitters with larger
128 emissions budget shares, while leaving smaller emitters with smaller (or even zero) emissions
129 budget shares.^{36, 40} And the population-based approach equally shares the global emissions
130 budget between all the individuals in the world; this means that countries with lower
131 populations get smaller shares of the budget even if they have economic activities whose
132 outputs benefit other countries.^{36, 41} Given each effort-sharing approach effectively rewards
133 some countries and/or sectors, the choice of effort-sharing approach to assign a share of the
134 global emissions budget is generally considered normative and non-scientific.^{36, 38-40}

135 It is therefore evident that value and modeling choices need to be made when quantifying
136 the GHG emissions and defining emissions budgets for anthropogenic systems. To that end,
137 recent studies have started addressing the influence of these value and modeling choices;
138 however, those efforts are limited to one^{36, 40-42} or two^{33, 38, 43, 44} choices. While the effort-
139 sharing approach is the commonly assessed choice,^{36, 38, 40, 41} some studies have focused on
140 other choices such as GHG accounting approach,⁴³⁻⁴⁵ GHG metric (including time horizon),^{4, 24,}

⁴⁶ and global climate threshold.^{33, 38} However, the influence of the choice of method for calculating the global emissions budget has not been assessed yet. More importantly, no study to date has assessed the influence of all these choices together in a single study.

This study, therefore, for the first time, assessed the influence of all the above-mentioned value and modeling choices on the overall climate change performance of an anthropogenic system- using a case study of New Zealand. New Zealand is a relatively complex, developed economy which recently passed a Zero Carbon Bill, with the aim of reducing net GHG emissions to zero by 2050.^{47, 48} To make progress towards achieving the aim of the Bill, it is necessary to define an emissions budget (based on a chosen climate threshold) for New Zealand's economic activities, and implement climate action programs with the goal of performing within this emissions budget as soon as possible. Economic sector-level emissions budgets provide a pragmatic basis upon which to develop these climate action programs. In this context, using both production- and consumption-based accounting approaches, the GHG emissions of the New Zealand economy for the reference year 2011 (i.e. the latest year available on the Eora26 multi-regional input-output database^{49, 50} at the time of this study) were calculated at a sector level and benchmarked against a range of scenarios developed using the identified value and modeling choices.

METHODS

This section provides an overview of the assessment methodology. It then describes the procedure for calculating production- and consumption-based GHG emissions, and the selected climate thresholds, global emissions budgets, and methods for assigning shares of the global emissions budget to New Zealand and finally to its economic sectors.

Overall Assessment Methodology

The assigned shares of the global emissions budget (SoGEB) for New Zealand and its economic sectors were calculated using eq 1.

$$\text{SoGEB}_{X,\text{ESA}} = \text{GEB} \times aS_{\text{ESA}} \quad (1)$$

Where $\text{SoGEB}_{X,\text{ESA}}$ is the SoGEB assigned to anthropogenic system X (which can be either New Zealand or its economic sector), using the selected effort-sharing approach (ESA), GEB is the global emissions budget related to a given climate threshold, and aS_{ESA} [%] is the percentage share assigned to X, using the chosen ESA. The climate change performance of X is given as an occupied share of the global emissions budget, as represented in eq 2.

$$\text{occSoGEB}_{X,\text{ESA}} = \frac{\text{GHG}_X}{\text{SoGEB}_{X,\text{ESA}}} \times 100\% \quad (2)$$

Where $\text{occSoGEB}_{X,\text{ESA}}$ is the SoGEB occupied by X using the chosen ESA. GHG_X is the GHG emissions of X. $\text{SoGEB}_{X,\text{ESA}}$ is the SoGEB assigned to X. If $\text{occSoGEB}_{X,\text{ESA}}$ is greater than 100%, X can be considered as unsustainable with regards to the chosen global climate threshold.

Calculation of GHG Emissions of New Zealand and Economic Sectors

To calculate the production- and consumption-based GHG emissions of New Zealand, a global environmentally extended multi-regional input-output (MRIO) analysis was undertaken using a global MRIO database called Eora26. Eora26 provides a time series of input-output and trade tables with matching environmental (including climate change) and social satellite accounts for 26 economic sectors of 186 countries.^{49, 50} The climate change

satellite of Eora26 accounts for 24 GHGs including CO₂, methane (CH₄), nitrous oxide (N₂O), chlorofluorocarbons, hydrochlorofluorocarbons, hydrofluorocarbons, chlorocarbons, and halons (a full list is available in SI2). For the methodology of the Eora-based MRIO analysis, see Lan et al.⁵¹ and Malik and Lan.⁵² Given some of the 26 sectors are similar in terms of their activities, they were combined together (after calculating the GHG emissions of each of those 26 sectors) in order to more easily interpret the results, following the approach used in a previous study.¹⁷ Transport, and transport equipment were combined and named 'transport and equipment'. Likewise, service-providing sectors were aggregated as (i) 'financial and trade-related services'; and (ii) 'other services'. Finally, the 'others' and 'private households' sectors were aggregated and named 'miscellaneous'. A detailed description is available in SI2.

Selection of GHG Metrics and Time Horizons

To weight and aggregate the GHGs of each sector (both production- and consumption-based), three alternative GHG metrics were used: GWP100, GWP20, and GTP 100. As discussed in the Introduction, GWP represents the heat absorbed over a given time horizon due to a GHG emission (i.e. change in radiative forcing) and GTP expresses the change in the atmospheric global mean temperature at the end of the time horizon due to the emission.²⁴ ²⁵ The different time horizons were chosen in order to capture the differences in climate change impacts of long- and short-lived GHGs; for example, the GWP100 and GWP 20 weightings of CH₄ are 28 and 84 respectively.²⁵

Selection of Global Climate Thresholds and Global Emissions budgets

To understand the influence of the choice of global climate threshold, the following thresholds were chosen: (i) the 1.5 °C Paris climate target;²⁸ (ii) the 2 °C UNFCCC climate target;³⁰ and the 1 Wm⁻² radiative forcing threshold in the planetary boundaries.²⁹

To translate the chosen climate thresholds into global emissions budgets, the method proposed by Bjørn and Hauschild³³ was first applied. As described in the Introduction, Bjørn and Hauschild³³ estimated global emissions budgets for the 1 Wm⁻² and 2 °C climate thresholds and using the GWP100 metric. For this analysis, the 1.5 °C global emissions budget (for GWP100) was obtained by taking the sustained emissions of each GHG that lead to a steady state temperature increase of 2 °C, scaling them down to represent a steady state temperature increase of 1.5 °C, and then multiplying those emissions with their respective GWP100 weightings. This resulted a 1.5 °C global emissions budget (for GWP100) of 5.1 GtCO₂-eq·yr⁻¹. Subsequently, the global emissions budgets for all three climate thresholds, using alternative GHG metrics (GWP20 and GTP100), were estimated (SI1 sections 2-10).

The same budgets were then quantified using Doka's method.³² As described in the Introduction, Doka³² estimated the 1 Wm⁻² global emissions budget by translating the increase in radiative forcing using absolute GWPs of different GHGs. Following Doka's method³² and using relevant radiative forcing values,^{31, 53} the global emissions budgets (using absolute GWP100) for the 1.5 and 2 °C climate thresholds were estimated as 20.7 and 28.4 GtCO₂-eq·yr⁻¹ respectively. Likewise, the global emissions budgets for all three climate thresholds, applying alternative GHG metrics, can be quantified (see SI1 section 11).

Assigning a Share of the Global Emissions budget

In this study, two commonly used effort-sharing approaches were chosen to assign a share of the global emissions budget (SoGEB) to different New Zealand sectors. One of them was the grandfathering approach which assigns a SoGEB to a sector based on its relative contribution to the global GHG emissions that occurred in a chosen reference year.^{36, 41} The other one was the economic value approach which assigns a SoGEB to a sector using economic indicators such as gross value added (GVA) and final consumption expenditure (FCE). The GVA

method is applied in studies based on a production-based accounting approach in which a SoGEB is assigned to a sector based on its relative contribution to the gross value-added globally.^{44, 54} The FCE method is applied in studies that use a consumption-based accounting approach; a SoGEB is assigned to a system based on its relative share of the global final consumption expenditure.^{38, 44} While the former (i.e. GVA) associates responsibility for GHG emissions from production activities with the economic benefits (e.g., employment, earning foreign exchange, and tax revenues) obtained by different supply chain actors, the latter (FCE) represents consumer preferences for different products and services that are driving the increase in GHG emissions globally.^{38, 44} Variants of these methods have already been applied in other studies.^{40, 55, 56}

Table 1 here

Scenarios

The different value and modeling choices (two GHG accounting approaches, three GHG metrics (and respective global emissions budgets), and two effort-sharing approaches) were used to develop a set of 12 (2×3×2) scenarios for each of the three climate thresholds (i.e. a total of 36 scenarios). Table 2 shows the six production-based and six consumption-based scenarios developed for the 1.5°C climate threshold (chosen as a baseline); similar scenarios were developed for the remaining climate thresholds (see SI5 and SI6).

Table 2 here

RESULTS AND DISCUSSION

New Zealand's GHG Emissions

In 2011, New Zealand's GHG emissions calculated using production- and consumption-based accounting approaches were 84,192 and 81,505 kilotonnes (kt) CO₂-eq, respectively, using GWP100 metrics (calculations are in SI2 and SI3). Since the production-based emissions were slightly (=2,687 ktCO₂-eq) higher than the consumption-based emissions, the country was a net GHG exporter in the given year.

Figure 1 presents New Zealand's production- and consumption-based emissions at sector level. According to the figure, for GWP100, half of New Zealand's production-based emissions were from agriculture; the contributions of other sectors were small when compared to agriculture, e.g., transport and equipment (17%), electricity, gas and water (12%), petroleum, chemical and non-metallic mineral products (4.5%), and other services (5.1%). These results clearly demonstrate that New Zealand has an unusual climate change profile compared with most other developed countries. Generally, energy production and/or energy-intensive sectors, and transport dominate the production-based GHG emissions of developed countries, while agriculture makes a relatively small contribution.^{9, 13, 16} However, New Zealand is one of the largest food producing countries and exports around 85% of its total food production to the rest of the world.^{17, 57}

According to the consumption-based accounting approach (for GWP100), food and beverage was the largest contributor, representing a quarter (i.e. 26%) of New Zealand's consumption-based emissions, followed by financial and trade-related services (20%), other services (16%), construction (8.5%), transport and equipment (7.9%), agriculture (5.5%), and electricity, gas and waste (5.4%). The seven sectors together contributed approximately 90% of New Zealand's consumption-based emissions in 2011. These consumption-based emissions

were comparable (in terms of the emissions composition) to some other developed countries such as Australia and the Netherlands.¹³

New Zealand's climate change results varied significantly, however, when an alternative GHG metric and/or time horizon were selected, as shown in Figure 1. Using GWP20, New Zealand's production- and consumption-based emissions were 159,804 and 140,660 ktCO₂-eq respectively; these values are 73 and 90% higher than the results calculated using GWP100. The increased results arise mainly due to the greater weighting given to the short-lived CH₄ gas in GWP20 rather than long-lived GHGs (compared with GWP100). A contrasting outcome was observed when GTP100, which gives a greater weighting to the long-lived CO₂ gas, was used instead; according to Figure 1, New Zealand was a net GHG importer in 2011, given the production and consumption-based emissions were 32 to 40% lower than the emissions calculated using GWP100. Calculations are presented in the sections 4-6 of SI 2 and SI3.

In addition to the changes in total emissions when using different GHG metrics, notable changes were observed in terms of the relative contributions of some sectors to New Zealand's total emissions. For example, if GWP20 is used instead of GWP100, agriculture's contribution is 66% rather than 50%, and transport and equipment's contribution is 9% rather than 17%. The opposite occurs if GTP100 is applied as opposed to GWP100: agriculture's contribution is halved to 27% from 50%, while transport and equipment's contribution is increased to 27% from 17%. However, the total aggregated emissions for some of the other sectors remain (nearly) the same across the different GHG metrics (e.g., transport and equipment, electricity, gas and water, and metal products) for both production- and consumption-based accounting approaches. These results are explained by the quantities of

295 individual GHG emissions associated with different sectors, and the weightings assigned to
296 different GHGs under each of the GHG metrics. Most of the GHG emissions of the transport
297 and equipment sector are CO₂, and non-CO₂ GHG emissions are negligible. However, in
298 contrast, agriculture's GHG emissions are primarily non-CO₂ gases such as CH₄ and N₂O (for
299 individual GHG emissions for each sector, see the section 7 of SI2 and SI3).

300 *Figure 1 here*

New Zealand's Emissions Budgets: Influence of Choice of GHG Accounting Approach, GHG Metric and Effort-Sharing Approach

Table 3 presents the influence of the value and modeling choices in terms of the (1.5 °C) SoGEBs for New Zealand and its economic sectors. New Zealand's total production- and consumption-based SoGEBs (calculated using the GWP 100 metric and grandfathering approach) were 12,189 and 10,272 ktCO₂-eq·yr⁻¹ respectively.

The SoGEBs of New Zealand and its economic sectors differed when an alternative GHG metric and/or effort-sharing approach were chosen. When the GHG metric was changed to GWP20, New Zealand's total production- and consumption-based SoGEBs increased by a factor 3.4 and 3.2 respectively. When the GHG metric was changed to GTP100, New Zealand's total production- and consumption-based SoGEBs varied by a factor 0.20 and 0.21 respectively. These notable variations are due to the different weightings assigned to different GHGs (under each GHG metric) when calculating the global emissions budget using the method of Bjørn and Hauschild.³³ Alternatively, when the effort-sharing approach was changed (from grandfathering to economic value), New Zealand's total production- and consumption-based SoGEBs varied by a factor 0.77 and 0.99, 0.61 and 0.84, and 0.98 and 1.2 for GWP 100, GWP20, and GTP100, respectively. These outcomes are explained by the underlying equity principle of each of the two effort-sharing approaches: the grandfathering approach assigns a SoGEB to a country based on the country's relative contribution to the global GHG emissions in a reference year, whereas the economic value-based approach assigns a SoGEB based on the country's economic contribution/expenditure.^{36, 44}

From a sector perspective, half of New Zealand's production-based SoGEB (for GWP100 and grandfathering, scenario S1) was assigned to the agriculture sector, and the SoGEBs assigned to other sectors were small (17% or less). The largest share of New Zealand's consumption-based SoGEB (for GWP100 and grandfathering, S7) was assigned to the food

326 and beverage sector (26%), and the SoGEBs assigned to other sectors were small (18% or less).
327 In scenarios where the GHG metric was changed to GWP20, sector SoGEBs varied by a factor
328 (up to) 5.1 (mining and quarrying in S2) and 4.3 (agriculture in S8), for the production- and
329 consumption-based accounting approaches, respectively. When the GHG metric was changed
330 to GTP100, sector SoGEBs varied by a factor of 0.07 (mining and quarrying in S3) to 0.32 (metal
331 products in S3), and 0.12 (agriculture in S9) to 0.31 (electricity, gas and water in S9)
332 respectively. In scenarios where the effort-sharing approach was changed, sector SoGEBs
333 showed significant variations; for example, sector SoGEBs in S5 (as opposed to S1) differed by
334 a factor of 0.091 (agriculture) to 34 (miscellaneous).

New Zealand's Emissions Budgets: Influence of Additional Value and Modeling Choices

In addition to the above-discussed choices, the influence of the choice of global climate threshold, method for calculating the global emissions budget, and reference year for the grandfathering approach, were also evaluated.

Regarding the choice of global climate threshold, if 2°C was used as opposed to 1.5°C, New Zealand's total production- and consumption-based SoGEBs increased by a factor 1.3. Alternatively, if 1 Wm⁻² planetary boundary threshold was used instead, New Zealand's total production- and consumption-based SoGEBs varied by a factor 0.53.

The sector-level analysis showed the same variations when an alternative climate threshold was chosen (for 2°C and 1 Wm⁻² results, see SI5 and SI6, respectively). These variations are explained by the notable differences between the global emissions budgets calculated for each climate threshold, e.g., 3.6, 5.1, and 6.8 GtCO₂-eq·yr⁻¹ for 1 Wm⁻², 1.5, and 2 °C climate thresholds, respectively (using GWP100).

To calculate the global emissions budget, the method proposed by Bjørn and Hauschild³³ was used in this study. If Doka's³² method was applied to calculate the global emissions budget, the 1.5° C global emissions budget was a factor 4.1 higher than the budget used in our analysis. Therefore, the SoGEBs of New Zealand and its sectors increased by a factor 4.1 (see the section 5 of SI7).

Lastly, the influence of the choice of reference year for the grandfathering approach was examined by re-running the analysis for the year 2011 based on an alternative reference year (2005 instead of 2000). The analysis showed a moderate influence at the country level; New Zealand's total production- and consumption-based SoGEBs varied by a factor of 0.91 (scenario S2) to 0.93 (S3) and 1.07 (S8) to 1.14 (S9), respectively. The sector-level analysis, however, showed significant variations in terms of the SoGEBs; they varied by a factor of 0.79

359 to 5.1 and 0.85 to 1.5 for production- and consumption-based approaches (see the sections
360 4 and 5 of SI4). These outcomes are due to the differences in the climate change profile of
361 New Zealand in the years 2000 and 2005.

New Zealand's Occupied Shares of the Emissions Budgets

Tables 4 and 5 show the influence of the value and modeling choices in terms of occupied shares of the 1.5 °C global emissions budget for all the economic sectors of New Zealand, for production and consumption-based accounting approaches respectively. These outcomes provide (at least) five key insights.

Firstly, New Zealand exceeded its SoGEBs in all scenarios, irrespective of the choice of GHG accounting approach. The exceedances varied by a factor of 3.9 to 21 and 4.2 to 24, across the production- and consumption-based approaches respectively.

Secondly, all the economic sectors exceeded their SoGEBs in the grandfathering approach (for both production and consumption). Exceedances, however, varied significantly with regard to the choice of GHG metric. For example, when production-based emissions (using GWP100, scenario S1 in Table 4) were compared with the respective SoGEBs, the exceedances varied by a factor of 5.7 (petroleum, chemical and non-metallic mineral products) to 19 (fishing). When GWP20 was applied instead (S2), the exceedances varied by a factor of 3.4 (petroleum, chemical and non-metallic mineral products) to 19 (fishing). In contrast, when GTP100 was applied (S3), the exceedances varied by a factor of 17 (petroleum, chemical and non-metallic mineral products) to 34 (fishing). These large variations are explained by the influence of the choice of GHG metric in calculating the GHG emissions of New Zealand's sectors and the global emissions budget (whose shares were subsequently assigned to each sector).

Thirdly, although all 16 sectors exceeded their SoGEBs under the grandfathering approach (for both production and consumption), some sectors were within their SoGEBs when using the economic value-based sharing approach. According to Tables 4 and 5, three sectors were within their SoGEBs for the production-based accounting approach (financial

and trade services, miscellaneous, and fishing), while no sector was within its SoGEB for the consumption-based accounting approach. Furthermore, unlike the grandfathering approach, the exceedances in the economic value sharing approach varied remarkably; they were in the range of factor 1.1 (wood and paper in S5) to 149 (electricity, gas and water in S6) and 2.0 (electrical and machinery in S11) to 666 (fishing in S12), for the production- and consumption-based accounting approaches, respectively. These large variations are due to the widely different GHG emissions and economic contributions (and expenditures) of these sectors. For example, in 2011, the production-based GHG emissions of agriculture were 41,913 ktCO₂-eq, which was approximately 25 times the emissions of the financial and trade services sector. On the other hand, the economic contribution of the agriculture sector was equivalent to US\$14 billion, which was approximately a quarter of the economic contribution of the financial and trade services sector (US\$54 billion, see Table 4). As a result, the financial and trade services sector was effectively assigned a four times larger SoGEB than the agriculture sector (see Table 3), and the agriculture sector was unsustainable for all the economic value-based scenarios.

Fourthly, when 2°C was chosen as opposed to 1.5°C, the exceedances of each sector in all 12 scenarios varied by a factor 0.25 (see the section 4 of SI8). As a result, one more sector (i.e. wood and paper in S5) performed within its SoGEB for the production-based accounting approach, in addition to financial and trade services, miscellaneous, and fishing. Similarly, if the 1 Wm⁻² planetary boundary threshold was applied instead of 1.5°C, exceedances of each sector across the 12 scenarios differed by a factor 0.42, resulting in one more sector (fishing in S5) being unsustainable for the production-based accounting approach (see the section 1 of SI8). These variations in the exceedances are due to the notable differences between the global emissions budgets estimated for each climate threshold.

410 Lastly, when the choice of reference year for the grandfathering approach was examined,
411 the analysis showed a moderate influence at the country level: the production- and
412 consumption-based exceedances varied by a factor of 1.08 (scenario S3) to 1.10 (S2) and 0.88
413 (S9) to 0.94 (S8) respectively. The sector-level analysis, however, showed significant variations
414 in exceedances: the production-based exceedances differed by a factor of 0.20 (fishing in S2)
415 to 1.27 (petroleum, chemical and non-metallic mineral products in S3), whereas
416 consumption-based exceedances varied by a factor of 0.67 (miscellaneous in S9) to 1.18
417 (agriculture in S8) (see the section 2 of SI8). These outcomes are primarily due to the
418 differences in the climate change profile of New Zealand in 2000 and 2005.

419 *Tables 4 and 5 here*

Research Implications for Setting Emissions Budgets for Anthropogenic Systems

For both GHG accounting approaches, the largest source of uncertainty in New Zealand's SoGEBs arose from the choice of method for calculating the global emissions budget (a factor 4.1), followed by the choice of GHG metric (0.20 to 3.4), the choice of climate threshold (0.53 to 1.3), the choice of effort-sharing approach (0.61 to 1.2), and the choice of reference year for the grandfathering approach (0.91 to 1.1).

The influence of these choices, however, varied notably with regard to New Zealand's sector SoGEBs. For each GHG accounting approach, the largest source of uncertainty arose from the choice of effort-sharing approach (0.031 to 34), followed by the choice of GHG metric (0.072 to 5.1), the choice of reference year for the grandfathering approach (0.79 to 5.1), the choice of method for calculating the global emissions budget (4.1), and the choice of climate threshold (0.53 to 1.3).

Taken together, the results at both national and sector level indicate, in contrast to the current focus on choosing either a 1.5 or 2 °C climate threshold, the importance of considering other value and modeling choices when setting emissions budgets for anthropogenic systems.

Regarding the choice of GHG metric, the International Life Cycle Initiative recommends to carry out a sensitivity analysis with the GWP20 and GTP100 metrics (in addition to GWP100) to ensure that the conclusions about the ranking of different anthropogenic systems are robust regardless of the choice of GHG metric.^{22-24, 58} The results of our analysis emphasise the relevance of this guidance. However, until recently, no similar agreement has been reached regarding the choice of effort-sharing approach; while some recommend sharing the global emissions budget equally among the world population, others suggest using the grandfathering or economic value-based approaches.^{36, 38, 40} Our results suggest that guidance on this choice should be a priority, given it is the largest source of uncertainty in the

sector SoGEBs. The reference year for the grandfathering approach and method for calculating the global emissions budget are also both significant sources of uncertainty. Therefore, a consensus should be developed regarding these choices.

The study has additional implications for research on method development for setting GHG emissions budgets and policymaking. The proposed methodological framework can be considered as a complementary approach to the sectoral decarbonization approach (SDA) developed under the Science Based Targets initiative.^{59, 60} SDA transforms the sectoral emission pathways of the International Energy Agency into sectoral intensity pathways using economic or physical indicators, and then translates these into individual company intensity pathways. Although SDA is currently being used mostly for setting emissions (only CO₂) budgets for homogenous economic sectors (and companies) such as power generation, metal production, and cement production, it is not suited for heterogeneous sectors such as agriculture and construction whose GHGs and product categories are quite diverse.⁶⁰ These limitations are, however, addressed by the proposed framework which accounts for all GHGs (a total of 24), assigns a share of the global emission budget to each sector and subsequently, informs the required levels of emission reduction for all the sectors of a country.

While setting production-based emissions budgets for all the sectors of a country could potentially catalyse innovation and support investment in low-emissions activities and technologies,^{16, 61, 62} it could also have perverse consequences. For example, New Zealand's agriculture is recognized as relatively carbon-efficient compared with many other countries.^{24, 57} A requirement for costly mitigation efforts could result in the shifting of agricultural production to some other countries with poor agricultural practices and higher GHG emissions per unit of production, leading to a global increase in GHG emissions. It may be preferable, instead, to offset New Zealand's agricultural GHG emissions by imposing more

stringent targets on other sectors where mitigation efforts may be easier to implement and more cost-effective (e.g., electricity, gas and water, and transport and equipment). This could be facilitated by the adaptation of the existing New Zealand emissions trading scheme, which currently excludes agricultural CH₄ emissions until 2025, by including all the GHGs of all economic sectors.^{63, 64}

To mitigate both production- and consumption-based emissions, a range of climate policies have already been proposed and are being deployed across the world,^{16, 61, 62, 65} including policies that focus on fuel efficiency improvements in passenger cars, uptake of public transport, energy retrofits in buildings, and change of dietary patterns.⁶⁶⁻⁶⁹ However, many of these policies have turned out to be less effective than predicted due to rebound effects where consumers substitute decreased consumption of one good or service by increased consumption of other goods and/or services.^{61, 67, 68} To be effective, setting a comprehensive range of consumption-based emissions budgets at national level, as well as per capita emissions budgets for different product consumption categories, could provide a better basis to deal with rebound effects.

Research Limitations and Future Work

This study, for the first time, examined the influence of alternative value or modeling choices on setting emissions budgets for anthropogenic systems, taking New Zealand's economic sectors as a case study. The choices included: two GHG accounting approaches, three GHG metrics, three global climate thresholds, two methods for calculating the global carbon budget, two effort-sharing approaches, and two reference years for the grandfathering approach. There are additional alternatives for each of these choices^{5, 36, 38, 70} that were not examined but whose influence on the final results could be investigated in future analyses.

There is interest amongst policymakers in setting emissions budgets for individual GHGs (such as CO₂, CH₄, and N₂O budgets).^{48, 71, 72} Future work could explore how these individual emission budgets can be assigned to different economic sectors given that a CO₂ budget is relevant for sectors like transport and equipment, and metal products, while CH₄ and N₂O budgets are more relevant for agriculture.

Another topic for future research concerns how the proposed methodological framework presented in this study can be adapted to set emissions budgets that also account for discrete future activities in economic sectors. In that context, it is crucial to understand the differences between static and dynamic approaches to estimating global emissions budgets. In this study, a static approach was applied; as a result, the global emissions budget for any given year throughout the 21st century is the same. However, this approach does not represent the time-specific societal transitions to a low-carbon society that could take place in the future. On the other hand, dynamic approaches, such as the IPCC's Representative Concentration Pathways²⁵ and the latest Shared Socio-economic Pathways³¹ represent these time-specific changes. For example, these scenarios project that the global CO₂ emissions involve a sharp

507 decrease to net zero by around 2050 and 2075, for the 1.5 and 2 °C climate thresholds,
508 respectively.³¹

509 To that end, using a dynamic approach,⁷³ Chandrakumar et al. have proposed a method
510 for setting emissions budgets that accounts for both the current New Zealand residential
511 housing stock and time-specific construction of additional buildings up to 2050.^{56, 74} This type
512 of study is likely to be particularly relevant for long-lived products and services whose GHG
513 emissions during use are largely “locked-in” at the design or manufacturing stage, and where
514 significant modifications are difficult once the product or service has entered its use stage.
515 Examples include vehicles, energy generation facilities, and waste management
516 infrastructure.

517 Table 1. Overview of effort-sharing approaches, underlying equity principles and equations for calculating the share of the global emissions budget available for each
518 economic sector

Effort-sharing approach	GHG Accounting approach	Equity principle ³⁶	Equation
Grandfathering (GF)	Production	Sovereignty	$aS_{ESA} = \frac{GHG_{Pro,X}}{GHG_{World}}$ <p>Where aS_{ESA} is the share of the global emissions budget assigned to the studied sector X of a country. $GHG_{Pro,X}$ is the production-based GHG emissions of sector X, whereas GHG_{World} is the global GHG emissions.</p>
Economic value: gross value added (GVA)	Production	Capability	$aS_{ESA} = \frac{GVA_X}{GVA_{World}}$ <p>Where GVA_X is gross value added by sector X, and GVA_{World} is the total gross value added in the world.</p>
Grandfathering (GF)	Consumption	Sovereignty	$aS_{ESA} = \frac{GHG_{Con,X}}{CF_{World}}$ <p>Where $GHG_{Con,X}$ is the consumption-based GHG emissions of sector X.</p>
Economic value: final consumption expenditure (FCE)	Consumption	Need	$aS_{ESA} = \frac{FCE_X}{FCE_{World}}$ <p>Where FCE_X is the money spent by consumers on sector X, and FCE_{World} is the total final expenditure of the world.</p>

519 Table 2. Underlying value choices and parameters for the 12 scenarios proposed for the 1.5°C climate threshold

520

GHG accounting approach	Scenarios ^a	Value choices		
		Effort-sharing approach	GHG metric	Global emissions budget ^a (GtCO ₂ -eq·yr ⁻¹)
Production	S1-1.5DC,GWP100,GF	Grandfathering ^b	GWP100	5.1
	S2-1.5DC,GWP20,GF		GWP20	13.8
	S3-1.5DC,GTP100,GF		GTP100	1.3
	S4-1.5DC,GWP100,GVA	Economic value: gross value added ^c	GWP100	5.1
	S5-1.5DC,GWP20,GVA		GWP20	13.8
	S6-1.5DC,GTP100,GVA		GTP100	1.3
Consumption	S7-1.5DC,GWP100,GF	Grandfathering ^b	GWP100	5.1
	S8-1.5DC,GWP20,GF		GWP20	13.8
	S9-1.5DC,GTP100,GF		GTP100	1.3
	S10-1.5DC,GWP100,GVA	Economic value: final consumption expenditure ^c	GWP100	5.1
	S11-1.5DC,GWP20,GVA		GWP20	13.8
	S12-1.5DC,GTP100,GVA		GTP100	1.3

^a The 1.5 °C global emissions budgets calculated for each of the three GHG metrics, according to the method proposed by Bjørn and Hauschild.³³

^b For the grandfathering approach, the year 2000 was chosen as the reference year. The GHG emissions of the New Zealand economic sectors in 2000 were calculated using the Eora-based environmentally-extended MRIO analysis⁵² and all 24 GHGs were aggregated using the three GHG metrics respectively, as was already done for 2011. The uncertainty related to this choice was assessed by re-running the analysis based on an alternative reference year (i.e. 2005) (results are in the SI).

^c Economic indicator values (for gross value added and final consumption expenditure) of New Zealand and the entire world were sourced from the Eora26 MRIO database.^{49, 50}

521 Table 3. The influence of the value and modeling choices in terms of the 1.5 °C global emissions budget shares for New Zealand and its economic sectors

Sectors	Production-based emissions budget shares ^a (ktCO ₂ -eq·yr ⁻¹)						Consumption-based emissions budget shares ^a (ktCO ₂ -eq·yr ⁻¹)					
	S1-1.5 DC, GWP100, GF	S2-1.5 DC, GWP20, GF	S3-1.5 DC, GTP100, GF	S4-1.5 DC, GWP100, GVA	S5-1.5 DC, GWP20, GVA	S6-1.5 DC, GTP100, GVA	S7-1.5 DC, GWP100, GF	S8-1.5 DC, GWP20, GF	S9-1.5 DC, GTP100, GF	S10-1.5 DC, GWP100, FCE	S11-1.5 DC, GWP20, FCE	S12-1.5 DC, GTP100, FCE
Agriculture	6079	27981	629	944	2542	236	811	3529	100	86	232	22
Transport & equipment	2111	3912	661	627	1689	157	873	1900	252	796	2142	199
Electricity, Gas & Water	1473	2709	464	270	726	67	536	1042	164	158	426	40
Petroleum, Chemical & Non-Metallic Mineral Products	669	1333	202	237	637	59	312	854	77	282	760	71
Services: Others	536	2323	70	2014	5421	503	1530	5047	314	2816	7579	704
Metal Products	363	644	117	141	379	35	43	102	12	28	74	6.9
Food & Beverages	235	436	74	340	916	85	2736	10309	458	720	1937	180
Mining & Quarrying	205	1056	15	121	327	30	32	99	7.2	17	45	4.1
Construction	153	283	48	459	1236	115	882	2389	219	1069	2877	267
Services: Financial & Trade	158	306	48	3561	9586	890	1954	5855	443	3273	8811	818
Wood & Paper	95	177	30	301	811	75	157	531	31	127	343	32
Electrical & Machinery	64	127	19	144	386	36	350	924	89	670	1803	167
Textiles & Wearing Apparel	29	54	9.2	95	256	24	194	618	41	201	542	50
Other Manufacturing	14	26	4.3	49	131	12	102	279	25	132	354	33
Miscellaneous	3.2	6.2	1.0	78	209	19	44	125	11	110	297	28
Fishing	2.2	4.4	0.68	35	94	8.8	14	41	3.5	0.47	1.3	0.12
Total-New Zealand	12189	41378	2392	9417	25347	2353	10572	33645	2246	10485	28221	2620

^aDescription of the scenarios is given in Table 2. The results are rounded to two significant digits. Calculations are available in the sections 1 and 2 of SI4.

Figure 1. Contributions of 16 economic sectors to New Zealand's production- and consumption-based GHG emissions for the year 2011, calculated using three different GHG metrics (GWP100, GWP20, and GTP100).

524 Table 4. The occupied shares of the 1.5 °C global emissions budget (SoGEB) by each sector for twelve scenarios (in %) for the production-based accounting approach. If
525 occupied share of the global emissions budget by a sector for a chosen effort-sharing approach ($\text{occSoGEB}_{X,\text{ESA}}$) is greater than 100%, sector X is unsustainable in absolute
526 terms for the climate change impact category. The values in the figure are rounded off to the first decimal point. See the SI for the actual values. Description of the
527 scenarios is given in Table 2. Colors indicate scenarios where the $\text{occSoGEB}_{X,\text{ESA}}$ is less than 100% (green), $\geq 100\%$ (yellow), $>1500\%$ (orange), and $>4000\%$ (red). The reader
528 is referred to the online version of the article for the interpretation of the references to color in the table.

Sector	Production-based GHG emissions (ktCO ₂ eq)			Gross value added (×1000 US\$)	Occupied share of the global emissions budget (%)					
					Scenarios					
	GWP100	GWP20	GTP100		S1-1.5 DC,GWP100,GF	S2-1.5 DC,GWP20,GF	S3-1.5 DC,GTP100,GF	S4-1.5 DC,GWP100,GVA	S5-1.5 DC,GWP20,GVA	S6-1.5 DC,GTP100,GVA
Agriculture	41913	105089	13717	25395000	689	376	2182	4439	4135	5813
Transport & equipment	13934	14338	13712	19730900	660	366	2074	2221	849	8745
Electricity, Gas & Water	10183	10398	10076	9764300	692	384	2173	3773	1431	14938
Petroleum, Chemical & Non-Metallic Mineral Products	4256	10141	1658	11647000	566	337	1698	1599	704	5790
Services: Others	3782	4485	3423	64104360	794	436	2373	211	187	329
Metal Products	2409	2408	2435	7624400	664	374	2073	1709	635	6913
Food & Beverages	1702	2820	1143	28457000	707	463	2019	490	220	1752
Mining & Quarrying	1666	2015	1490	3649700	706	385	2137	1194	1245	1042
Construction	1449	4069	316	24574000	764	555	2019	254	127	845
Services: Financial & Trade	1168	1571	969	113114200	1076	921	2369	48	29	128
Wood & Paper	699	890	603	14791000	732	504	2017	232	110	801
Electrical & Machinery	513	720	401	7159600	799	566	2112	358	186	1117
Textiles & Wearing Apparel	277	435	198	4536500	942	799	2154	292	170	836
Other Manufacturing	154	260	102	2460400	1116	1018	2346	317	199	836
Miscellaneous	43	83	24	2790188	1372	1339	2486	56	40	123
Fishing	42	82	23	1591000	1894	1864	3351	121	87	261
Total-New Zealand	84192	159804	50290	341389548	691	386	2103	894	630	2137

530 Table 5. The occupied shares of the 1.5 °C global emissions budget (SoGEB) by each sector for twelve scenarios (in %) for the consumption-based accounting approach. If
531 occupied share of the global emissions budget by a sector for a chosen effort-sharing approach ($\text{occSoGEB}_{X, \text{ESA}}$) is greater than 100%, sector X is unsustainable in absolute
532 terms for the climate change impact category. The values in the figure are rounded off to the first decimal point. See the SI for the actual values. Description of the
533 scenarios is given in Table 2. Colors indicate scenarios where the $\text{occSoGEB}_{X, \text{ESA}}$ is less than 100% (green), $\geq 100\%$ (yellow), $>1500\%$ (orange), and $>4000\%$ (red). The reader
534 is referred to the online version of the article for the interpretation of the references to color in the table.

Sector	Consumption-based GHG emissions (ktCO ₂ eq)			Final consumption expenditure (×1000 US\$)	Occupied share of the global emissions budget (%)					
					Scenarios					
	GWP100	GWP20	GTP100		S7-1.5 DC,GWP100,GF	S8-1.5 DC,GWP20,GF	S9-1.5 DC,GTP100,GF	S10-1.5 DC,GWP100,FCE	S11-1.5 DC,GWP20,FCE	S12-1.5 DC,GTP100,FCE
Agriculture	4482	10706	1703	1365343	552	303	1708	5204	4618	7910
Transport & equipment	6440	7699	5859	12614298	738	405	2324	809	359	2946
Electricity, Gas & Water	4426	4709	4295	2506447	826	452	2611	2799	1107	10870
Petroleum, Chemical & Non-Metallic Mineral Products	2182	3367	1647	4473072	700	394	2146	773	443	2335
Services: Others	13080	22801	8745	44636098	855	452	2788	465	301	1243
Metal Products	314	404	274	436961	721	395	2273	1137	545	3980
Food & Beverages	20989	43623	10859	11406966	767	423	2371	2917	2252	6038
Mining & Quarrying	228	417	146	262621	709	420	2035	1377	936	3515
Construction	6919	10461	5315	16944539	785	438	2424	647	364	1990
Services: Financial & Trade	15953	26032	11408	51891302	816	445	2575	487	295	1394
Wood & Paper	1236	2256	779	2017834	786	425	2510	971	658	2449
Electrical & Machinery	2496	3657	1967	10620564	713	396	2218	373	203	1175
Textiles & Wearing Apparel	1356	2372	898	3189208	699	384	2185	674	438	1786
Other Manufacturing	841	1281	642	2085443	827	460	2562	640	362	1953
Miscellaneous	458	709	344	1749190	1031	566	3225	415	239	1247
Fishing	106	166	79	7502	735	408	2276	22374	13001	66590
Total-New Zealand	81505	140660	54960	166207389	771	418	2447	777	498	2097

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SUPPORTING INFORMATION

Global emissions budget calculation methods and emissions budgets for three different climate thresholds; production- and consumption-based GHG emissions of New Zealand calculated at a sector level using different GHG metrics; global emissions budget shares assigned to each of the New Zealand sectors; influence of each of the value/modeling choices considered in this study.

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