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Absolute Sustainability-based Life Cycle Assessment: A Benchmarking Approach to Operate Agri-food Systems Within the 2°C Global Carbon Budget

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Summary

Given the increasing environmental impacts associated with global agri-food systems, operating and developing these systems within the so-called absolute environmental boundaries has become crucial, and hence the absolute environmental sustainability concept is particularly relevant. This study introduces an approach called Absolute Sustainability-based Life Cycle Assessment (ASLCA) that informs the climate impacts of an agri-food system (on any economic level) in absolute terms. Firstly, a global carbon budget was calculated which is sufficient to limit global warming to below 2°C. Next, a share of the carbon budget available to the global agri-food sector was estimated, and then it was shared between agri-food systems on multiple economic levels using four alternative methods. Thirdly, the climate impacts of those systems were calculated using Life Cycle Assessment methodology, and were benchmarked against those carbon budget shares. This approach was used to assess a number of New Zealand agri-food systems (agri-food sector, horticulture industries and products) to investigate how these systems operated relative to their carbon budget shares. The results showed that, in 2013, the New Zealand agri-food systems were within their carbon budget shares for one of the four methods, and illustrate the scale of change required for agri-food systems to perform within their carbon budget shares. This method can potentially be extended to consider other environmental impacts with global boundaries; however, further development of the ASLCA is necessary to account for other environmental impacts whose boundaries are only meaningful when defined at a regional or local level.

Keywords: absolute environmental sustainability; carbon budget; climate change; industrial ecology; life cycle assessment; agri-food

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Introduction

Increasing global challenges such as climate change, water scarcity, loss of biodiversity, resource depletion and air pollution have received the attention of multiple stakeholders, including academics, industries, government agencies and civil societies. To mitigate these challenges, attention has been focused on enhancing the existing environmental sustainability performance of economic and product systems at multiple economic levels, ranging from product/process, company, sector and country to the entire Earth. As of now, a number of quantitative Environmental Sustainability Assessment Methods (ESAMs) have been proposed, such as Life Cycle Assessment (LCA) and environmental footprints, which provide useful information to support decision-making about the environmental sustainability performance of these systems (Chandrakumar et al. 2017; Coelho and McLaren 2013; Moldan et al. 2012; Singh et al. 2009). Nevertheless, overall progress in mitigating global environmental challenges is inadequate and many environmental problems are continuing to intensify (ICSU and ISSC 2015; IUCN 2017; WWF 2017). One general criticism of ESAMs is that generally they do not evaluate the sustainability performance of a system against the so-called *absolute environmental boundaries*; instead, they only rank the system relative to another system that is relevant to the nature (or the function) of the examined system (Bjørn and Hauschild 2013; Bjørn et al. 2016). As a result, the contributions of any examined system to the overall

environmental impacts of production and consumption patterns of human societies are usually overlooked.

Scientists, therefore, have suggested adopting the concept of *absolute environmental sustainability* that focuses on how human societies can operate within the Earth's *carrying capacity* (Bjørn and Hauschild 2015; O'Neill et al. 2018). Achieving absolute environmental sustainability is, however, not straightforward as it involves addressing challenges such as prioritising key environmental impacts (hereinafter, impacts); defining appropriate indicators and boundaries; evaluating impacts at multiple economic levels (or scales) (from product/process to project, company, economic sector, country and the Earth); and understanding the interactions between various types of impacts (Chandrakumar and McLaren 2018b; Ryberg et al. 2016). Therefore, development of so-called *absolute environmental sustainability assessment* (AESA) methods is crucial in the pursuit of absolute environmental sustainability¹. In general, an AESA benchmarks the environmental impacts of a system against a set of environmental boundaries and classifies the system as absolutely sustainable if the impacts are within the boundaries (Bjørn et al. 2016).

Turning to the agri-food sector, today the sector is facing the huge challenge of meeting accelerating food demands due to growing population and changing dietary patterns (Garnett 2011; Godfray et al. 2010). Accelerating food demands are driving interventions like agricultural intensification and expansion, which have direct (and indirect) impacts on the environment, including in particular contributions to climate change, biodiversity loss, land-use change and water contamination (Campbell et al. 2017; Chobtang et al. 2016, 2017; Ericksen et al. 2009; Smith et al.

¹ In some literature, an AESA method is referred to as an absolute sustainability assessment method (ASAM) (e.g. Chandrakumar and McLaren 2018a, 2018b).

2013). For example, it was calculated that the global agri-food sector contributes 19-29% of global climate impacts (Vermeulen et al. 2012). In turn, these impacts threaten food security through changing patterns of agricultural production that affect food prices and food quality (Garnett et al. 2017). It is, therefore, crucial to investigate how current and future agri-food systems can operate and develop within absolute environmental boundaries including the ones proposed for climate change (Campbell et al. 2017; McLaren 2017; Repar et al. 2017; Smith et al. 2013; Wolff et al. 2017).

To that end, this study proposes the development of an innovative AESA method called Absolute Sustainability-based Life Cycle Assessment (ASLCA) to benchmark the climate impacts of agri-food systems against their shares of the 2°C global carbon budget at multiple economic levels. Firstly, a short literature review establishes that there is a gap regarding this type of assessment. Then use of ASLCA is illustrated through a case study of the New Zealand agri-food sector, and the horticulture industry in particular. Finally, the results of the case study, limitations and future work required to develop ASLCA are discussed.

A review of studies on absolute environmental sustainability assessment methods

Rockström et al. (2009a, 2009b) introduced the planetary boundaries (PBs) concept and illustrated how current human society is operating in terms of nine critical Earth system boundaries. Since then, scientists have been investigating how to apply the PBs to address absolute environmental sustainability on a sub-global level (Clift et al. 2017; Häyhä et al. 2016; Muñoz and Sabag 2017; Sim et al. 2016). A selection of

AESA studies known to the authors of this article is presented in Table 1, classified according to key research areas; the most relevant ones are discussed below.

Although the PBs provide a scientific basis for addressing absolute environmental sustainability, there are a number of outstanding challenges in achieving absolute environmental sustainability, and in development and use of AESA methods in pursuit of this objective (e.g. Laurent and Owsianiak 2017; Ryberg et al. 2016).

Regarding AESA methods, Chandrakumar and McLaren (2018b) advocated that an AESA should: quantitatively assess a comprehensive range of environmental impacts in absolute terms; inform the impacts at an early stage in impact pathways; and be capable of benchmarking the impacts at multiple economic levels. They identified twelve key environmental impacts (including the ones listed in the PBs) for inclusion in an AESA.

Regarding assessment at multiple economic levels, methodologies such as LCA (ISO 2006a, 2006b) and environmental footprints (ISO 2013, 2014) can be used to calculate the impacts associated with a chosen system. However, research on developing environmental boundaries has only emerged recently. According to Häyhä et al. (2016), when developing boundaries at multiple economic levels, three key dimensions should be considered. The first dimension is biophysical which characterises a particular environmental impact as a *systemic* process with global boundaries (e.g. climate change, ozone depletion) or an *aggregated* process with regional/local global boundaries (e.g. biogeochemical flows, land-system change). The second dimension is socio-economic that evaluates the interactions between socio-economic activities and environmental impacts (e.g. use of a production- or consumption-based approach for impact assessment). The third dimension is ethical which addresses the challenge of downscaling global boundaries (particularly,

systemic processes) to other sub-global levels (e.g. country, sector, company, product) and what ethical principles (or rationales) should guide this process. Some researchers have already started addressing these dimensions in proposed methods to downscale the global boundaries of systemic processes to sub-global levels (e.g. Bjørn 2015; Sandin et al. 2015), while others are developing regional (or local) boundaries for aggregated processes (e.g. Dearing et al. 2014; Teah et al. 2016).

Regarding the ethical dimension, several methods are available in the literature, which guide downscaling the global boundaries in proportion to past environmental impacts, population, mass, economic value, and relative contribution to human well-being (e.g. Liu and Bakshi accepted; Ryberg et al. 2018a). A detailed discussion is available in Bjørn (2015). Additionally, in the Science Based Targets (SBT 2017) initiative, methods like the Greenhouse Gas Emissions per unit of Value-Added (GEVA) and the Sectoral Decarbonization Approach (SDA) have been proposed to guide companies to set greenhouse gas (GHG) emissions reduction targets. The GEVA recommends a carbon intensity reduction rate of 5% per year for all economic sectors and their companies, stating that it is sufficient to achieve a 50% reduction in GHG emissions globally in 2050. The method, however, fails to account for heterogeneities between regions, countries, sectors or companies (e.g. current environmental and economic performances, mitigation potentials, costs). This limitation was later addressed through the SDA, which translated the sectoral emission pathways² of the International Energy Authority (IEA 2014) into sectoral intensity pathways³ using physical (e.g. tonne of cement manufactured) or economic (e.g. value added) indicators, and then translated them into individual company

² Emission pathways provide information on how emissions are likely to develop in future by accounting for the past emissions and future economic and technological developments.

³ Intensity pathway = emission pathway/activity projections; here, an activity can be either physical or economic activity.

intensity pathways. However, the SDA fails to address all economic sectors, activities, or types of GHG emissions. Hence, it is best suited for companies in the *homogeneous sectors* (e.g. power generation, iron and steel, cement), and further research is necessary to develop methods for companies belonging to *heterogeneous sectors*⁴ (e.g. agriculture, forestry, construction) (Clift et al. 2017; Gieseke et al. 2018).

Overall, then, the studies undertaken to date propose a number of methods (centred on various ethical principles) to benchmark the absolute environmental sustainability performance of countries, economic sectors and individual companies. However, they primarily focus on the homogeneous sectors and overlook heterogeneous sectors such as agriculture and forestry. In fact, to date, there is no specific study that has investigated the absolute environmental sustainability performance of agri-food systems at multiple economic levels.

As a step forward, this article presents an AESA method to downscale the environmental boundaries proposed for systemic processes in the context of agri-food systems (at multiple economic levels), and then to use these downscaled environmental boundaries (or budgets) to benchmark the environmental impacts of those agri-food systems. The method is elaborated for assessment of climate change where sufficient data are currently available to enable the calculations.

⁴ A sector that cannot be represented using a single physical indicator due to the uniqueness of the characteristics of the sector or the difficulties in comparing them (SBT 2017).

Table 1 Key topics and related publications in absolute environmental sustainability research

Topics	References
Defining indicators and boundaries for environmental impacts	<p>Carpenter and Bennett (2011)</p> <p>Clift et al. (2017)</p> <p>Cole et al. (2014)</p> <p>de Vries et al. (2013)</p> <p>Dearing et al. (2014)</p> <p>Gerten et al. (2013)</p> <p>Mace et al. (2014)</p> <p>Meyer and Newman (accepted)</p> <p>Rockström et al. (2009a)</p> <p>Rockström et al. (2009b)</p> <p>Steffen et al. (2015)</p> <p>Teah et al. (2016)</p>
Downscaling the global environmental boundaries into sub-global levels	<p>Alcorn (2010)</p> <p>Bjørn (2015)</p> <p>Bjørn et al. (2015)</p> <p>Brejnrod et al. (2017)</p> <p>Dao et al. (2015)</p>

	<p>Dao et al. (2018)</p> <p>Fanning and O'Neill (2016)</p> <p>Häyhä et al. (2016)</p> <p>Hoff et al. (2017)</p> <p>Krabbe et al. (2015)</p> <p>Nykvist (2013)</p> <p>O'Neill et al. (2018)</p> <p>Randers (2012)</p> <p>Ryberg et al. (2016)</p> <p>Ryberg et al. (2018a)</p> <p>Ryberg et al. (2018c)</p> <p>Sandin et al. (2015)</p> <p>SBT (2017)</p>
<p>Exploring the complementary linkages between ESAMs to develop AESA methods</p>	<p>Bjørn and Hauschild (2015)</p> <p>Bjørn et al. (2016)</p> <p>Chandrakumar and McLaren (2018a)</p> <p>Chandrakumar and McLaren (2018b)</p> <p>Doka (2015)</p> <p>Doka (2016)</p> <p>Dong and Hauschild (2017)</p> <p>Fang et al. (2015a)</p>

	<p>Laurent and Owsianiak (2017)</p> <p>Liu and Bakshi (accepted)</p> <p>Muñoz and Sabag (2017)</p> <p>Repar et al. (2017)</p> <p>Ryberg et al. (2018b)</p>
<p>Supporting environmental sustainability-related policy- and decision-making</p>	<p>Barbier and Burgess (2017)</p> <p>Bendewald and Zhai (2013)</p> <p>Chandrakumar et al. (submitted)</p> <p>Dao et al. (2015)</p> <p>Fang et al. (2015b)</p> <p>Galaz et al. (2012)</p> <p>Giesekam et al. (2018)</p> <p>Heijungs et al. (2014)</p> <p>Kara et al. (2018)</p> <p>Lucas and Wilting (2018)</p> <p>Nykvist (2013)</p> <p>Raworth (2012)</p> <p>Roos et al. (2016)</p> <p>Sandin et al. (2015)</p> <p>Sim et al. (2016)</p>

Methods

Benchmarking the climate impacts of any economic system requires the definition of a share of the carbon budget associated with a global climate boundary (Fanning and O'Neill 2016; Hoff et al. 2017). In the planetary boundaries (PBs), Steffen et al. (2015) proposed two global boundaries (i.e. a global average of CO₂ concentration of 350ppm CO₂ (or GHG concentration of 400ppm CO₂eq)⁵ and a radiative forcing of 1Wm⁻²) based on the scientific evidence, which are sufficient to limit global warming to below 1.5°C. However, others have suggested that the global climate boundary “...should be in the middle of the PB range at 450 ppm CO₂eq...” (Clift et al. 2017), which would potentially limit global warming to below 2°C (Clift et al. 2017; Renaud and Matthews 2015)⁶. It should also be noted the 2°C target has already been ratified internationally and strategized within business activities (Clift et al. 2017; SBT 2017). This study, therefore, applied the 2°C target as the global climate boundary. Subsequently, using the method of Doka (2015, 2016), an annual global carbon budget (CB_{Glo}) related to this target was calculated (=29.9 gigatonnes CO₂ equivalent (GtCO₂eq/yr). The particular method calculates an annual carbon budget associated with a radiative forcing value (i.e. 2.6 Wm⁻² in this context) by dividing the radiative forcing value by the absolute global warming potential of CO₂eq⁷. However, note that the calculated annual carbon budget is constant over time and does not shrink, such as in the case of the methods available in the SBT (2017). Calculations are in Table S1.3 in supporting information S1 available on the Journal’s website.

⁵ Note that the uncertainty zone for the CO₂ and GHG concentration are 350-450 ppm CO₂ (Steffen et al. 2015), 400-500 ppm CO₂eq (Clift et al. 2017), respectively.

⁶ The 2°C target is also equivalent to a radiative forcing of 2.6 Wm⁻² (Renaud and Matthews 2015).

⁷ The absolute global warming potential of CO₂eq is 8.69E-14 (W·yr)/(m²·kg GWP_{100yr} CO₂eq) (Doka 2015, 2016).

Regarding downscaling the 2°C carbon budget to sub-global levels, the share of the budget available for the global agri-food sector ($CB_{Glo,AgFd}$) was calculated based on the relative contribution of the global agri-food sector to global climate impacts, using the grandfathering principle, as suggested by Alcorn (2010, p.147). According to this principle, the share of the carbon budget available for a sector is calculated based on its relative contribution to the total GHG emissions in a reference year (Bjørn et al. 2016; Ryberg et al. 2018a). This is the same as the approach used in the Sectoral Decarbonization Approach (SDA) method to calculate GHG emissions reduction targets on a (global) sector-level (Krabbe et al. 2015, SBT 2017)⁸.

The GHG emissions from the global agri-food sector in 2013 were calculated based on the study by Vermeulen et al. (2012). Vermeulen et al. (2012) calculated the GHG emissions from the global agri-food sector in 2008 using the 100-year time horizon global warming potential (GWP_{100}) indicator, which included GHG emissions from a range of pre-production⁹, production¹⁰ and post-production¹¹ activities. These emissions were then adjusted to exclude catering, domestic food management and waste disposal, acknowledging the uncertainties associated with different practices undertaken in individual countries (Vermeulen et al. 2012). The adjusted climate impacts of the global agri-food sector were 13.1 GtCO₂eq, which was 23.6% of the global climate impacts in 2008 (see Table S1.3 in supporting information S1 on the Web for calculations). Assuming that this percentage contribution remained unchanged in 2013, $CB_{Glo,AgFd}$ was calculated as 7.1 GtCO₂eq i.e. 23.6% of the CB_{Glo} .

⁸ Note that the SDA method uses the data from the IEA 2°C scenario to break down the the carbon budget in the future (IEA 2014), whereas, an equal annual cabon budget is applied in this study.

⁹ Pre-production: fertiliser manufacture, energy use in animal feed production, pesiticide production

¹⁰ Production: direct and indirect emissions from agriculture

¹¹ Post-production: primary and secondary processing, storage, packaging and transport, refrigeration, retail activities, catering and domestic food management and waste disposal

Once the $CB_{Glo,AgFd}$ is calculated, it can be downscaled to sub-global levels and several methods are already available. However, considering the objective of the study (i.e. benchmarking the production-based climate impacts of different agri-food systems at multiple economic levels), four alternative methods were chosen for this particular study (described below). For each method, the $CB_{Glo,AgFd}$ was shared among the countries that produce agri-food products, and then among the agri-food industries of that country. Afterwards, the share of the carbon budget for each agri-food product was determined by dividing the carbon budget share of the agri-food industry by the total production volume of that particular agri-food product.

The first method is based on the grandfathering principle (hereafter called the **grandfathering method**) (Bjørn et al. 2016; Ryberg et al. 2018a). According to this method, the carbon budget is shared among emitters in terms of their climate impact shares in a reference year. The second method is centred on the idea that economic value can be considered a proxy for societal value creation (hereafter called the **economic method**) (Clift and Wright 2000), and sharing is based on the emitters' economic contribution to gross domestic product (GDP) (Bjørn et al. 2016).

The other two methods are (only) relevant to agri-food systems. The third method (hereafter called the **agri-land method**) represents the idea that agri-food systems require agricultural land (Smith et al. 2013); therefore, the carbon budget can be shared according to the territorial share of agricultural land of the emitter. A similar method has already been applied for downscaling the biogeochemical flows and land-system change PBs to sub-global levels (see Fanning and O'Neill 2016).

The final method is based on the calorie content of different foods (called the **calorific content method**). It uses calories as a proxy to represent the fact that the primary purpose of agri-food production is to feed people (Smith et al. 2013). Firstly, the total calories produced globally was calculated based on the production volume and calorific content (FAO 2018b; Roe et al. 2015) of a range of agri-food products listed in (FAO 2018b), for example, vegetables, fruits, nuts, livestock products and beverages (see SI2 for a complete list). Thereafter, the total calories available for human consumption was estimated by subtracting the loss of calories during agricultural production, livestock production (including animal feed), handling, storage and transportation, and processing (see SI2). The $CB_{Glo,AgFd}$ was shared among the agri-food products, according to their calorific contribution to the total calories available for human consumption. The carbon budget share for each agri-food system was then calculated with regard to the total production volume of that particular agri-food product.

An industry-level application of ASLCA

The agri-food sector is one of the largest economic sectors in New Zealand (NZ), making up more than 50% of the value of exported goods annually (Plant & Food Research 2016). In 2016, the horticulture industries contributed 10.3% of NZ's merchandise exports (equal to NZ\$5 billion); of them, the exports from kiwifruit, apple and wine industries were dominant (Plant & Food Research 2016). Given the significance of NZ's "clean and green" image (OECD 2017; Seidel-Sterzik et al. 2018), it is interesting to investigate how NZ's dominant horticulture product categories perform relative to their 2°C carbon budget shares.

The following sub-sections discuss and present the calculation of (i) the climate impacts of the NZ agri-food sector, NZ horticulture industries (kiwifruit, apple and wine), and their products; (ii) the associated carbon budget shares; and (iii) the ASLCA results. Note that the study benchmarks the climate impacts in 2013 and, therefore, the data used for the analysis were based on that year unless specified otherwise.

Climate impacts of the NZ agri-food sector, horticulture industries and products

The climate impacts of the NZ agri-food sector were estimated by combining datasets from different sources (Fitzgerald et al. 2011a, 2011b; MfE 2012; Stats NZ 2014). The direct and indirect impacts associated with NZ agricultural production activities were reported as 38.6 million tonnes CO₂ equivalent (MtCO₂eq) in 2013 (FAO 2018a). The upstream and downstream impacts occurring within the “cradle-to-NZ port” system boundary were calculated using data in the national input-output tables for the year 2013 (Allan 2016; Stats NZ 2014), and were 16.1 MtCO₂eq. These data included GHG emissions from a range of activities including fertiliser and pesticide production, electricity consumption, meat and meat products manufacturing, dairy product manufacturing, and local transportation (see Table S1.10 in supporting information S1 on the Web for a complete list). The data on GHGs emitted outside NZ during manufacture and onward transport of goods to NZ for use in agri-food systems, were derived from (Fitzgerald et al. 2011a; Fitzgerald et al. 2011b), which were based on the fossil fuel consumption and maritime trade during the year 2007 (calculations are in Table S1.9 in supporting information S1 on the Web). They included the GHG emissions from international transportation

activities associated with fertiliser and pesticide imports ($=0.22 \text{ MtCO}_2$), animal feed imports ($=0.16 \text{ MtCO}_2$) and NZ agri-food exports ($=1.2 \text{ MtCO}_2$). The total climate impacts from these different activities, representing NZ agri-food sector's life cycle-based climate impacts, were determined as $56.3 \text{ MtCO}_2\text{eq}$.

The climate impacts of the NZ horticulture industries and products were based on the data collected during the 2007-2009 plantation season, as these were the most recent LCA studies available. On a product-level, Mithraratne et al. (2010) calculated the climate impacts of NZ kiwifruit produced in 2008. The climate impacts of a kilogram of green kiwifruit for the “cradle-to-retail gate” was taken from this study, and the sea freight life cycle stage was adjusted to represent a weighted distance from NZ to all NZ kiwifruit export destinations (see Table S1.5 in supporting information S1 on the Web for calculation and for details of export destinations, distances and export volumes). Based on these adjustments, the average climate impacts of one kilogram NZ kiwifruit (hereinafter “NZ kiwifruit”) was calculated as $1143.2 \text{ gCO}_2\text{eq}$.

Since there was no dataset explicitly reporting the climate impacts associated with the entire NZ kiwifruit industry, the product-level impacts reported by Mithraratne et al. (2010) were scaled up to the total production of NZ kiwifruit (a total of 0.4 Mt in 2013, according to FAO (2018b)). Hence, the estimated climate impacts from the NZ kiwifruit industry were $457.2 \text{ ktCO}_2\text{eq}$ (see Table S1.5 in supporting information S1 on the Web).

The same procedure was used to calculate the “cradle-to-retail gate” climate impacts of apple and wine produced in NZ and consumed in any part of the world (hereinafter “NZ apple” and “NZ wine”); the climate impact analyses of McLaren et al. (2009) and Barry (2011) were used for apple and wine, respectively. The adjusted

climate impacts of one kg NZ apple and wine were 1062.2 gCO₂eq (in 2007) and 1640.4 gCO₂eq (in 2009), respectively. When scaled up to the industry-level, the climate impacts from the NZ apple and wine industries were 488.6 ktCO₂eq and 407.5 ktCO₂eq, respectively (see Tables S1.6 and S1.7 in supporting information S1 on the Web).

Carbon Budget Shares for NZ agri-food sector, horticulture industries and products

To calculate carbon budget shares at multiple economic levels, the available carbon budget share for the global agri-food sector ($CB_{Glo,AgFd}$, 7.1 GtCO₂eq) was downscaled using the four methods described above. According to the **grandfathering method**, given the NZ agri-food sector's share of the global agri-food sector's climate impacts in 2013 was 0.49%, the carbon budget share for the NZ agri-food sector was 34.9 MtCO₂eq. In the same year, of the NZ agri-food sector's climate impacts, the shares of the NZ kiwifruit, apple and wine industries were 0.81%, 0.87% and 0.72%, respectively. Therefore, the carbon budget shares for the NZ kiwifruit, apple and wine industries were 283.5 ktCO₂eq, 302.9 ktCO₂eq and 252.6 ktCO₂eq, individually. Subsequently, downscaling the industry-level carbon budget shares to product-level (based on the production volume) resulted in individual carbon budget shares of 708.8 gCO₂eq/kg kiwifruit, 658.6 gCO₂eq/kg apple and 1017.1 gCO₂eq/kg wine for the three horticulture products (for calculations, see SI1).

Using the **economic method**, the share of the $CB_{Glo,AgFd}$ for the NZ agri-food sector was calculated based on its relative contribution (US\$21.8 billion, FAO 2018d) to the global agri-food sector's GDP (US\$1.34 trillion, FAO 2018d). Therefore, the

carbon budget share of the NZ agri-food sector was 115.1 MtCO₂eq. This share was further downscaled to industry- and product-levels based on the same principle. Given the relative contribution of the NZ kiwifruit, apple and wine industries to the NZ agri-food sector's GDP were 1.4%, 0.63% and 2.8%, respectively, the corresponding carbon budget shares were 1633.4 ktCO₂eq, 722.7 ktCO₂eq and 3193.9 ktCO₂eq. The product-level carbon budget shares were then calculated based on the production volumes of each industry as 4083.9 gCO₂eq/kg kiwifruit, 1571.2 gCO₂eq/kg apple, and 12858.0 gCO₂eq/kg wine.

In the **agri-land method**, carbon budget shares for the different agri-food systems were calculated based on the agricultural land used by these systems. According to FAO (2018c), of the globally available agricultural land (=48.8 billion hectares¹²), 11.1 million hectares are located in NZ. Therefore, the share of the carbon budget assigned to the NZ agri-food sector was 1.6 MtCO₂eq. A share of this NZ budget was then assigned to each of the three horticulture industries based on their agricultural land use; the carbon budget shares were 1.8 ktCO₂eq, 1.3 ktCO₂eq, and 5.2 ktCO₂eq for the NZ kiwifruit, apple and wine industries, respectively. Based on the production volumes of these industries (FAO 2018b), the product-level carbon budget shares were calculated as 4.5 gCO₂eq/kg kiwifruit, 2.7 gCO₂eq/kg apple, and 21.0 gCO₂eq/kg wine.

Finally, using the **calorific content method**, carbon budget shares were calculated according to the calorific contribution of different agri-food systems to the total calories produced by the global agri-food sector for human consumption. Of the

¹² One billion is equal to 1,000,000,000, whereas one million is equal to 1,000,000.

total calories produced globally in 2013 (7.3 quadrillion calories¹³), 8.2 trillion calories were produced in NZ (see Table S2.5 in supporting information S2 available on the Journal's website). The carbon budget share of the NZ agri-food sector was therefore 7.9 MtCO₂eq. This was further downscaled to the industry- and product-levels based on their associated calorific contributions. According to that, the carbon budget shares for the NZ kiwifruit, apple and wine industries were 17.3 ktCO₂eq, 123.2 ktCO₂eq and 48.7 ktCO₂eq, respectively. According to the production volumes (available for human consumption) of these industries, the product-level carbon budget shares were calculated as 47.6 gCO₂eq/kg kiwifruit, 421.0 gCO₂eq/kg apple, and 646.2 gCO₂eq/kg wine. See SI for detailed calculations (SI1 for Method 2 and 3; SI2 for Method 4).

The ASLCA results

Figure 1 graphically represents how different agri-food systems in NZ operate in terms of their 2°C carbon budget shares calculated using the four alternative methods (for the year 2013). Given the calculated climate impacts of the NZ agri-food sector were 56.3 MtCO₂eq, the sector operated within its carbon budget share in the given year only for the **economic method**.

The results in Figure 1(a) show that the carbon budget shares of the NZ agri-food sector calculated using the four methods varied significantly; the highest (115.1 MtCO₂eq) and the lowest (1.6 MtCO₂eq) shares were obtained using the **economic** and **agri-land methods**, respectively. Similar results were obtained for the studied NZ horticultural industries and their products (see Figures 1(b) and 1(c)).

¹³ One quadrillion is equal to 1,000,000,000,000,000, whereas one trillion is equal to 1,000,000,000,000.

The carbon budget results obtained for the sector can be explained by the specific characteristics of that sector. A high proportion of agricultural land in NZ is used for extensive grazing of livestock (Parliamentary Commissioner for the Environment 2016); as a result, NZ significantly contributes to the total global production of dairy and meat products (by mass, see Tables S2.2 and S2.4 in supporting information S2 on the Web). These are all products with relatively high carbon footprints (see, for example, Chobtang et al. 2016, 2017), economic values, and calories compared with many other agri-food products on a mass basis (e.g. many cereals, fruits and vegetables); however, the yield per hectare is low compared with many other major agri-food products (e.g. maize, potatoes, sugar cane). Therefore the carbon budget for the NZ agri-food sector is relatively high when using the **grandfathering, economic and calorific content methods**, and low when using the **agri-land method**. The particularly high carbon budget using the **economic method** is explained by the fact that many NZ agri-food sector products achieve price premiums in international markets (Plant & Food Research 2016).

According to Figure 1(b), the NZ kiwifruit, apple and wine industries generally have a greater difference in carbon budget shares between the **economic** and the **other methods**, compared with the NZ agri-food sector results. This is due to the premium prices achieved for these products, their relatively higher yields per hectare (at least for kiwifruit and apples), and lower calorific content per kg, compared with other major agri-food products produced in NZ (such as dairy and meat products). As seen in Figure 1(b), the carbon budget share calculated using the **economic method** for the NZ wine industry (3193.9 ktCO₂eq) is between two and four times larger than the carbon budget shares of the NZ kiwifruit (1633.4 ktCO₂eq) and apple (722.7 ktCO₂eq) industries; this is despite the fact that the wine industry produces

roughly 40% less product (by mass) than the other two industries. These results provide an example of how an agri-food industry (i.e. the wine industry in this case) receives a relatively higher carbon budget share (using the **economic method**) as it adds more value to its agri-food supply chain.

The carbon budget shares calculated for the NZ agri-food products present similar patterns of variation between results for the different methods as for the NZ agri-food industries. However, it is worth noting that, using the **grandfathering method**, the carbon budget share assigned to the NZ wine is the highest (1017.1 gCO₂eq/kg wine) while the NZ apple is the lowest (658.6 gCO₂eq/kg apple), and this is opposite to the ranking at industry level where the carbon budget share assigned to the NZ apple industry (302.9 ktCO₂eq) is higher than the share assigned to the wine industry (252.6 ktCO₂eq). This is explained by the higher climate impacts of NZ wine (per kg) but lower production volume of the wine industry, compared with the apple industry. Moreover, according to the **calorific content method**, at product level, the carbon budget of the NZ wine is the highest (646.2 gCO₂eq/kg wine); however, at industry level, the carbon budget of the NZ apple industry is the highest (123.2 ktCO₂eq). These differences are explained by the different production volumes and calorie contents of these agri-food products.

Discussion

This study demonstrates that the ASLCA method can provide a basis for setting GHG emissions reduction targets to operate agri-food systems within carbon budget shares. Setting a sector-level target for the NZ agri-food sector may influence its supply chain stakeholders (e.g. industries, companies, farmers) to align their business activities by indicating the level of GHG emissions reductions (in absolute

terms) at industry-, company- and farm-levels. This target-setting process will provide information about inefficient producers and their poor practices, which may incentivise the development of a range of technical and managerial initiatives. Examples include adaptation of land management practices, improved pest and disease management practices, development of more sustainable supply chains, and uptake of innovative technologies (e.g. Garnett 2011; Smith et al. 2013; Vermeulen et al. 2012). At the same time, ASLCA can be used to inform consumers about the climate impacts of a range of agri-food products and services.

However, the case study results illustrate the significance of the choice of method for downscaling the global carbon budget to sub-global levels. As each of the four alternative methods (i.e. **grandfathering**, **economic**, **agri-land**, and **calorific content**) effectively rewards (via higher carbon budget shares) some countries, industries and/or producers over others, it is, therefore, important to reflect on the implications of choice of any one method. The **grandfathering method** effectively rewards the larger emitters with larger carbon budget shares, leaving small emitters (who may have lower emission intensities) with smaller, or potentially even zero, carbon budget shares. This method, therefore, provides little incentive to countries (and/or industries and/or producers) that are operating agricultural systems inefficiently to become more efficient, and fails to recognize producers who are already operating agricultural systems efficiently. In a similar way, the **agri-land method** effectively rewards emitters (via higher carbon budgets) who have more agricultural land available, and fails to reward (via higher carbon budgets) those countries, industries and/or producers with high production efficiencies. Also, this method is based on an intrinsic assumption that agricultural land will inevitably be used for agri-food production (Smith et al. 2013). The **economic method** assigns

higher carbon budget shares to those countries (and/or industries and/or producers) producing high-value agri-food products per unit of GHG emission (such as some alcoholic beverages, vegetable oils, nuts, sweet treats) but there is no recognition of the role of agri-food systems in meeting the nutritional requirements of the world's human population. The **calorific-content method** overcomes the shortcoming of the economic method by assigning carbon budget shares for different agri-food systems based on the calorie contribution of those systems; however, it fails to account for the range of nutrients provided by different agri-food products. Hence, future research should focus on developing a greater understanding of the role of different carbon accounting methods in incentivising desired changes in agri-food systems.

Regarding other modelling aspects, the selection of global climate boundary and method to calculate the carbon budget has different implications for decision-making. In this study, the 2°C target was used as the global boundary and an associated annual carbon budget was calculated ($=29.9 \text{ GtCO}_2\text{eq}$) using the method of Doka (2015, 2016). Although the 2°C target has been ratified globally and strategized within different business activities (e.g. Clift et al. 2017; SBT 2017), it is recognised that the target is partly political as it does not address all types of climate impacts (Bjørn and Hauschild 2015). Future benchmarking studies should, therefore, consider adopting the global boundaries defined in the planetary boundaries, which are solely based on scientific analysis (Steffen et al. 2015).

There are alternative methods for calculating an annual carbon budget that provide different values; these values are either constant (e.g. Alcorn 2010; Bjørn and Hauschild 2015; Dao et al. 2018) or shrink over time (e.g. SBT 2017). For example, applying the Absolute Global Temperature change Potential (AGTP)

metrics for GHG emissions, Bjørn and Hauschild (2015) estimated an annual carbon budget of 6.8 GtCO₂eq for the 2°C target, which remains constant over time. This is approximately one-fifth of the carbon budget applied in this work. If this carbon budget is used instead, all the agri-food systems considered in this study would have transgressed their carbon budget shares in all methods (see Table S1.12 in supporting information S1 on the Web).

Moreover, the metric of Global Warming Potential for a 100-year time horizon (GWP₁₀₀) was used to calculate the climate impacts of agri-food systems. This metric has been criticized for assigning equal weights to GHG emissions regardless of emission time; relying on the integrative radiative forcing; and failing to address the importance of short-lived GHG emissions (e.g. methane, hydrofluorocarbons, sulphates) (Jørgensen et al. 2014; Reisinger et al. 2013, 2017). Researchers have started developing alternative metrics, approaches and time horizons, such as the Global Temperature change Potential (GTP) and Climate Tipping Potential (CTP) (e.g. Jørgensen et al. 2014; Reisinger et al. 2017; Owsianiak et al. 2018). Although these alternative metrics and time horizons are relevant to this study, and particularly in relation to the assessment of short-lived GHG emissions from agri-food systems, this aspect is not addressed in this study and is recommended for future research.

Conclusions

This article contributes to the emerging field of absolute environmental sustainability by introducing an AESA method (called ASLCA), which informs climate impacts of different agri-food systems in absolute terms. The study used a novel approach to benchmark the climate impacts of agri-food systems, and in

particular the NZ agri-food sector, NZ horticulture industries and their products. The proposed method provides a basis for calculating GHG emissions reduction targets for agri-food systems at multiple economic levels. Moreover, it has the potential to provide information about inefficient producers and their poor practices, which could incentivise the development of a range of technical and managerial initiatives. At the same time, it can provide information to consumers about the climate impacts (in absolute terms) of a range of agri-food products and services. However, as described in the previous section, a number of aspects of the proposed method require further consideration and development in order to utilise the ASLCA as a comprehensive AESA framework as envisaged by Chandrakumar and McLaren (2018b).

Overall, then, the study provides some insights into the complex topic of how to achieve food security within the 2°C global carbon budget. Of course, other environmental, social and economic aspects associated with agri-food systems must be considered, alongside climate impacts, in the quest for sustainable agri-food systems (Biermann et al. 2016; McLaren 2017; Sala et al., 2017). In addition, an important methodological aspect concerns how to account for environmental impacts whose boundaries are only meaningful when defined at a regional or local level (e.g. eutrophication, acidification). However, use of absolute environmental sustainability-based budgets at multiple economic levels provides a mechanism for supporting global governance capable of delivering a sustainable future for humanity.

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Figure 1

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