Valuing the impact of food:

Towards practical and comparable monetary valuation of food system impacts

A report of the Food System Impact Valuation Initiative (FoodSIVI)

May 2020

GLOBAL ALLIANCE FOR THE FUTURE OF FOOD

FoodSIVI

wbcsd

FOOD SYSTEM IMPACT VALUATION IN PRACTICE SUMMARY

Based on the impact frameworks described in the previous section we phrase impact valuation in terms of footprint created by activities (quantities associated to impact such as tonnes CO_2-eq emitted or kg reactive nitrogen leached), the capital change attributable to the footprint, and the value change from the capital change. The activity might be the annual operations of a food company, the lifecycle of a food product, the production of a tonne of an agricultural commodity, or a change in farming practice. Footprints become the quantities associated to increase or decrease in economic value. In economic theory quantities should either be produced or reduced to maximise economic value overall.

A review of marginal social and abatement costs of carbon associated to the footprint of CO_2-eq emissions indicate the variation in estimates due to modelling and data choices, scenarios, parity, and discounting. Parity is the choice of how to compare economic value between economies, usually national economies. Discounting is the choice of how to compare economic value between an economy now and an economy in the future.

Marginal social and abatement costing are examined in detail with comment on adjustments for food system impact valuation. It is found that the variety of data, models, tools, scenarios, and valuation methods already used, and fundamental uncertainties in ethical choices as well as scientific estimates, will result in potential order of magnitude differences in food system impact valuations. It is unclear at present where the major sensitivities lie for practical estimation of error bars. Research is required on the sensitivity of valuation to intergenerational effects in other dimensions of food impact such as obesity and rural poverty, and international effects embedded in food's global value chains.

The foremost difference from carbon costing found is that impact from food system activities is associated to footprints in plural, most of which need to be broken down further due to spatial and contextual differences in impact due to those footprints.

A level of resolution in spatial and contextual divisions is recommended. If the resolution is too coarse the error bars in valuation estimates will be too large and not trusted. Also, users will not be able to highlight the differences in impact from distinct production practices. Too fine a resolution then energy and time are wasted on perturbations to valuation numbers that will not make much difference to global scale transformation.

An important argument for agreed monetary food impact costing is exposing and pricing longer-term value losses in the economy as a counter to short-term political dynamics. Enabling economic mechanisms to invest in offsetting or creating longer-term value. This was an important outcome of carbon costing. The same applies if a tandem food system and economic community were able to promote and calculate social and abatement costs for nitrogen, land-use, obesity and diabetes, rural welfare, and the other major external costs of the food system.

Social and abatement costing

Marginal social and abatement costs are two different marginal valuations. They lead to different impact valuations when applied to the same footprint.

A marginal social cost is the change in economic value from producing footprint. A marginal abatement cost is the cost incurred in reducing footprint. Reducing the footprint avoids incurring the social costs. Marginal abatement costs are derived from portfolios of abatement measures designed to achieve a footprint reduction target for the least cost.

Sustainable food and agricultural products, and companies incorporating sustainable practices or sustainable sourcing, are found to offer abatement of footprint compared to their unsustainable counterparts. The additional cost of the sustainable products and practices is their abatement cost. The reduction in footprint from substituting the unsustainable product or practice is the abatement. The social benefit associated to the abatement is the abatement value.

An impact valuation using marginal social costs and abatement as footprint calculates the abatement value of the sustainable product or practices.

An impact valuation using marginal abatement costs and abatement as footprint indicates the cost-effectiveness of the sustainable product or practice as an abatement measure contributing to a footprint reduction target.

It is found that the two are complementary views of the value of sustainable food and agricultural products. Both can be used to set incentives. It is presently unclear what will be the major viewpoint of those offering incentives – meeting footprint targets at least cost or achieving the most social benefit.

The 2019 EAT-Lancet Commission on healthy diets from sustainable food systems, the 2019 IPCC Special Report on Climate and Land, and the 2019 FABLE consortium report, have laid the foundation for 2050 global food system footprint reduction targets in CO2-eq emissions, biodiversity loss, freshwater use, reactive nitrogen and soluble phosphorus leakage, and land-use change. Also provided are global malnutrition footprint reduction target for food consumption categories. It is found that one of the major uncertainties in abatement costing is whether dietary changes will be realised. While international agreements can cap physical emissions and extractions, there is large uncertainty in the achievement of dietary targets. Dietary changes are necessary to reach global footprint targets.

There are no global targets as yet for social capital impacts. It is found that targets can be set with reference to the SDGs, but it is not clear that the food system can achieve them. While pushing down one target, another may rise. Assuming the global diet targets are achieved, the EAT-Lancet Commission report shows that environmental footprint reduction targets and preventable human death and disease targets can be achieved together. It is found in this section that maximising economic value is a rationale for disaggregating global footprint targets into spatial and contextual footprint targets. At least as a start point for political agreement. There is enough scientific work to inform food system impact or footprint targets. The gap is in the political and societal process.

Overall, because of the complexity in abatement costing, it is recommended to use social costs until abatement costings for food impacts are further developed. Abatement costing should be further developed for two reasons: one, to inform costs of tangible action and economic trajectories for food system transformation; two, to improve cost-effectiveness measures of the value provided by sustainable food products and practices. This section finds that the most useful measure for society and governments is the total abatement provided by products and practices. Calculating total abatement depends on projecting demand for the sustainable product and practice. More research on demand projections is recommended. Demand projections are discussed further next section.

Ethical choices and uncertainty

This section finds that the fundamental uncertainties in ethical choices as well as scientific estimates make it unlikely that agreement can occur on single values or single methods for marginal valuations. Food impact costing does not need to get the ‘correct’ answer. Agreement, credibility, and the opportunity to intervene in market failure in the direction of food system transformation, are the guiding principles for costings. A mechanism for retaining variation but pricing risk into impact valuations is suggested in this section. Costing is a mechanism designed to match quantity of production (for a quantity controlled by humans) with human and social well-being. It is recommended that practical and comparable valuation for users be based on shadow prices of footprint changes and not capital changes for this reason.

It is found that all impact valuations observed in practice use a linear approximation to estimate economic value change from footprint changes. Non-linear corrections to impact costing for scarcity and interactions created by food's multiple footprints are examined. Whether non-linear corrections make a significant difference for economic food policy designed to reduce food system impacts is unknown because they have not been quantified. It is recommended that research develop quantitative estimates of second order corrections due to the synergies and trade-offs described in the 2019 IPCC Special Report on Climate and Land.

Variation in valuations from different choices have real or perceived ethical implications. Businesses make implicit ethical choices in valuations themselves, or by using choosing calculations of shadow prices in literature that have. This section recommends that, given unavoidable ethical choices and order of magnitude uncertainties inherent in both social and abatement costing, a societal process building on private starts and national handbooks should compile, set and update marginal valuations with their uncertainty associated to food footprints.

A practical model for risk pricing is suggested in this section. It replaces terms in the linear model with random variable equivalents (uncertain shadow prices, uncertain footprints, etc) and calculates a risk premium that can be priced into the impact valuation. The following points are found:

- The risk premium describes how much society should "charge" to take on the uncertainty in external costs associated to the footprint produced by a product, practice, or company.
- Businesses have the same playing field if shadow prices and their uncertainty were agreed. The premium is a further chance for credibility and agreement in impact valuation – if set in collaboration with civil society and government who represent the bearers of risk. The food sector investing in a societal process for better information about impacts and valuation would reduce the risk premium on shadow prices, creating an incentive.
- Businesses can compete on footprint reduction and on disclosure. Calculating footprint is closer to the activity of the business itself. Methods for footprint calculation such as lifecycle analysis (LCA) are already well developed. Disclosure would reduce the risk premium, creating an incentive.
- Risk premiums are likely to be dominated by uncertainty and correlations between the greatest impacts, e.g. carbon and health. Major non-market costs that pose significant joint risk to global welfare. Research is required to understand and quantify correlations.

Nine case studies in the next section show the variation in practice in footprint, models and data, and valuation methodology, and a precedent for pricing uncertainty.

CONTENTS

FOOD SYSTEM IMPACT VALUATION IN PRACTICE

Impact valuation estimates external costs to inform internalisation. Impact valuation should also indicate who incurred the costs and what food system activities they originate from. The purpose of food system impact valuation is to align the market dynamics of food and agricultural toward the social and human well-being targets of food system transformation.

The process of impact valuation identified in impact frameworks (Table 2 in Alignment of Impact Frameworks). What society and individuals value is some function of produced, natural, social and human capital. Impact is value gained or lost due to capital change. Capital change is some function of activities in the food sector and additional drivers. A practical connection between activities in the food sector and capital change is footprint. Footprint is the quantities relevant to impact of a food system actor, see Figure 11. Footprint is some function of upstream inputs, an actor's own operations, and downstream outputs, depending on the extended responsibility implicit in the scope of the use case.

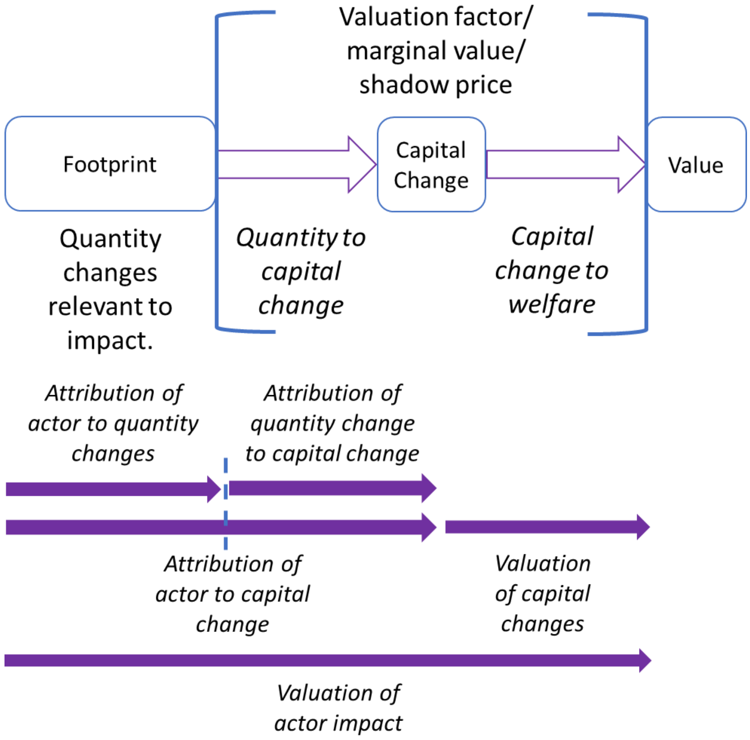

Figure 11: Impact valuation in terms of footprint change (quantities associated to impact such as tonnes CO2eq emitted or N leached), the capital change attributable to the footprint change, and the value change from the capital change.

Footprints should be identified by working backwards from impact. Where food systems are creating the most concern for social and human value change (Table 1 in Economic Theory of Change), traced through capital changes, identifies quantities relevant to impact such as tonnes CO2-eq emitted or kg reactive nitrogen leached[1]. Tracing from impact back to footprint identifies an impact pathway.

[1] Carbon footprint: B. P. Weidema et al., "Carbon Footprint," *Journal of Industrial Ecology* 12, no. 1 (2008), https://doi.org/10.1111/j.1530-9290.2008.00005.x.. T. Wiedmann and J. Minx, "A Definition of 'Carbon Footprint'," in *Ecological Economics Research Trends*, ed. C. C. Pertsova (Hauppauge NY: Nova Science Publishers, 2008). Water footprint: A. Y. Hoekstra et al., *The Water Footprint Assessment*

Examples of impact pathways:

Preventable respiratory diseases and death associated to air pollutants (NH3, So2, NOx, VOCs, PM10) which are increased in concentration or due to natural capital changes (soil erosion, ecosystem changes) resulting from agricultural activities including direct nitrogen fertiliser application. Loss of productivity from individuals and households of individuals affected by preventable respiratory disease is one monetary reflection of the loss of value.

Tonnes of air pollutant is the footprint. Loss of social and human well-being is the impact.

The agriculture and food production sectors are associated generally to low wages and high accident rates for small-holder farmers and production workers. Market concentration, power imbalances and contractual value chains coupled with bearing the direct burden of risk from extreme weather and plant and animal diseases further increase stress on households and communities of workers and farmers in the food sector (produced, social and human capital changes). The increased incidence of economic destitution of households and breakdown of community support leads to increased social costs from lost productivity, increased crime, and obesity (high intake of calorie-dense nutrient-poor cheap food)[2].

Incomes and accident rates in spatial, socio-economic and value chain context are the footprints. Loss of social and human well-being is the impact.

Preventable diseases and death related to obesity which have increased in prevalence and severity in part by diets high in sugar, fat and processed foods consumed by individuals and produced by the mostly private food sector. Increased social costs of healthcare are one monetary reflection of the loss of value associated to preventable diseases and death related to obesity.

Contribution to food products consumed in present diets with socio-economic and demographic context are the footprints. Distance of the present diets from reference diets for optimal health diets in context link the food products to preventable disease and death. Loss of social and human well-being is the impact.

Capital changes and the pathways leading to them are complex. The same activity can lead to changes in multiple footprint quantities. Change in the same footprint quantity can lead to changes in multiple capitals. The change in one capital, e.g. natural capital, can lead to changes in other capitals and multiple impacts (Figure 18 on p. 79). Scientific detail of impact pathways associated to food systems – environmental, social, health – can be found in the references for Table 1 in Economic Theory of Change. Impact pathways for food systems

---

Manual: Setting the Global Standard (London: Earthscan, 2011).. Nitrogen footprint: J. N. Galloway et al., "Nitrogen footprints: past, present and future," *Environmental Research Letters* 9, no. 11 (2014), https://doi.org/10.1088/1748-9326/9/11/115003.. A. M. Leach et al., "Environmental impact food labels combining carbon, nitrogen, and water footprints," *Food Policy* 61 (2016), https://doi.org/https://doi.org/10.1016/j.foodpol.2016.03.006.. L. Čuček, J. J. Klemeš, and Z. Kravanja, "A Review of Footprint analysis tools for monitoring impacts on sustainability," *Journal of Cleaner Production* 34 (2012), https://doi.org/https://doi.org/10.1016/j.jclepro.2012.02.036.

[2] National Research Council, *Framework for Assessing Effects of the Food System*, National Academies Press (Washington, 2015); H. J. Holzer et al., *The economic costs of poverty in the United States : subsequent effects of children growing up poor. Institute for Research on Poverty Discussion Paper no. 1327-07*, Center for American Progress (Washington DC, 2007), https://irp.wisc.edu/publications/dps/pdfs/dp132707.pdf; A. Drewnowski, "Obesity, diets, and social inequalities," *Nutrition Reviews* 67, no. suppl_1 (2009), https://doi.org/10.1111/j.1753-4887.2009.00157.x. C. B. Barrett et al., "Smallholder Participation in Contract Farming: Comparative Evidence from Five Countries," *World Development* 40, no. 4 (2012), https://doi.org/10.1016/j.worlddev.2011.09.006.

have yet to be collated. This was a potential function of an accounting standard mentioned last section. Collating impact pathways are steps toward the accounting standard.

More examples of impact pathways (involving natural capital changes) are described in the Natural Capital Protocol Food & Beverage Guide. From pages 38-50 the Guide provides a list of worked examples illustrating footprint, considering capital changes, and then a basic formula for multiplying total footprints by a marginal value (a monetary amount per unit of the footprint). This section, the longest in the report, is concerned with the details that go into marginal valuations: what causes variation and uncertainty in the amounts, what might reduce reliability in the figures produced and so limit the use of the valuation, and what are the considerations for enhancing the comparability of valuations while still retaining practicality.

Figure 11 is an abstraction of detail relevant to practice. Detail which makes comparison difficult and causes variation in valuations. The variation is illustrated in the nine case studies in the chapter Case Studies of Food System Impact Valuation. The case studies also provide additional examples of impact pathways. Ambiguity in monetary estimates resulting from the complexity of capital changes is discussed on p. 96.

Despite being conceptual, Figure 11 provides a basis from which to understand the process of valuation, to distinguish quantity (footprint) and marginal value (shadow price), and to break down what components and assumptions are involved in valuation. The components, overlayed onto Figure 11 in Figure 17 and discussed from p. 62, are actor footprint, societal footprint, assumptions about socio-economic drivers, models and data for attribution of capital change, choice of welfare measure, parity and discounting.

The breakdown into components and assumptions provides a template in which to examine the variation in each case study in Case Studies of Food System Impact Valuation and to distinguish available models and data in the chapter Inventory and Development of Methods. The conceptual view of Figure 11 is used to separate what parts of the valuation process are best developed through shared development (shadow prices) and which are competitive (footprint), which will feature again in the chapter Implications. The view of Figure 11 also provides a conditional sequence of random variables on which to build a simple approach to risk pricing from p. 112.

Carbon costing

Food systems are associated to 21-37% of global CO2-eq emissions[3]. Tonnes of CO2-eq emitted is a footprint associated to external impacts from the production and consumption of food products (Figure 12). Carbon costings, estimating both the social costs of the projected impact of capital changes due to a tonne of CO2-eq emission today and the abatement cost to avoid or sequester that tonne of emitted CO2-eq, are examples of marginal valuations. Reviewing carbon costing illustrates many features of valuations relevant to food system impact: social costs, abatement costs, discount rate, scenarios, actor footprint versus societal

[3] M. T. Niles et al., *Climate change and food systems: Assessing impacts and opportunities*, Meridian Institute (Washington DC, 2017); IPCC, *IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems*, Intergovernmental Panel on Climate Change (2019), https://www.ipcc.ch/report/srccl/. S. J. Vermeulen, B. M. Campbell, and J. S. I. Ingram, "Climate Change and Food Systems," *Annual Review of Environment and Resources* 37, no. 1 (2012), https://doi.org/10.1146/annurev-environ-020411-130608.; F. N. Tubiello et al., "The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990–2012," *Global Change Biology* 21, no. 7 (2015), https://doi.org/10.1111/gcb.12865.

footprint, the complications of a chain of capital changes, and risk pricing due to variation in the calculation due to choices and settings[4].

Figure 12 illustrates how the calculation of the social cost of carbon attributed to an actor factors through capital changes and the actor's carbon footprint. Sea level rise is indicated as an example; for explicit scientific detail of climate change impact pathways see the IPCC Special Report on Climate Change and Land[5]. In practice the actor's carbon footprint in tonnes is multiplied by a monetary value for the impact from one additional tonne of carbon emitted. The monetary value is the marginal social cost of carbon, marginal meaning the cost if one more tonne of CO2-eq was emitted in addition to existing CO2-eq levels in the atmosphere. The word marginal is routinely omitted.

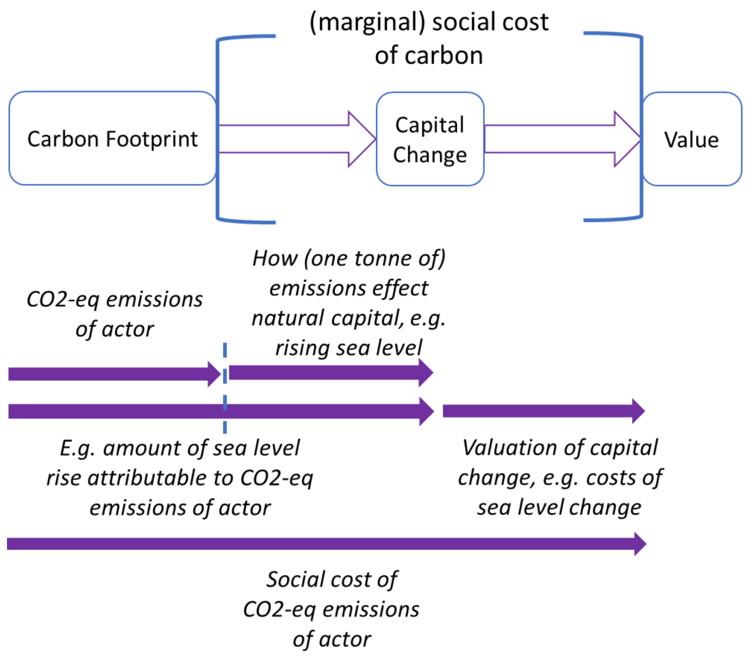

Figure 12: Example of Figure 11 for one capital change (sea level rise) included in the calculation of the social cost of carbon.

Social cost of carbon

The social cost of carbon (SCC) is a calculation of the difference in global economic value between a baseline economy with a specific quantity of CO2-eq emissions added to a continued trajectory of CO2-eq emissions and an alternative economy without that added quantity of CO2-eq emissions (for the SCC this quantity is usually one tonne). The difference in economic value between the economies is projected over time. The baseline economy gains

[4] Most reports on valuing food system impacts discuss the social cost of carbon, see e.g. p. 90 S. de Bruyn et al., *Environmental Prices Handbook EU28 Version*, CE Delft (Delft, The Netherlands, 2018), https://www.cedelft.eu/en/publications/2113/envionmental-prices-handbook-2017.; p. 10 TruCost, *Top-down methodology TEEB Animal Husbandry*, TruCost (London, 2016), http://www.teebweb.org/wp-content/uploads/2017/08/Top-down-methodology_TEEB-Animal-Husbandry_v2.pdf., p. 15 TruCost, *TruCost's Valuation Methodology*, TruCost (2015), https://www.gabi-software.com/fileadmin/GaBi_Databases/Thinkstep_Trucost_NCA_factors_methodology_report.pdf., p. 34 FAO, *Food wastage footprint: full-cost accounting*, Food and Agriculture Organization of the United Nations (Rome, 2014). p. 7-30 IPCC, *IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems*.

[5] IPCC, *IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems*.

the private and external benefits of the production and consumption of good and services that results in the additional CO2-eq emission but incurs the private and external costs of additional effects of climate change. The alternative economy avoids the private and external costs of additional climate change but loses the potential benefits of production and consumption from the CO2-eq emission. The difference is monetised by calculating PPP GDP changes. Welfare losses including greater morbidity and mortality, the extinction of species, and social disruptions are assumed to be reflected in GDP changes. Different weightings between national GDP for regions more, or less able, to absorb the effects of climate change have been used to calculate the SCC (parity choices)[6]. More general monetisation of social and human welfare than GDP has been used (welfare choices)[7]. The difference between the two trajectories is discounted to present value and then integrated over time to obtain an estimate for the total amount of social costs due to the quantity of CO2-eq emission (Figure 13).

The SCC depends how the difference in economic value between the economies is computed.

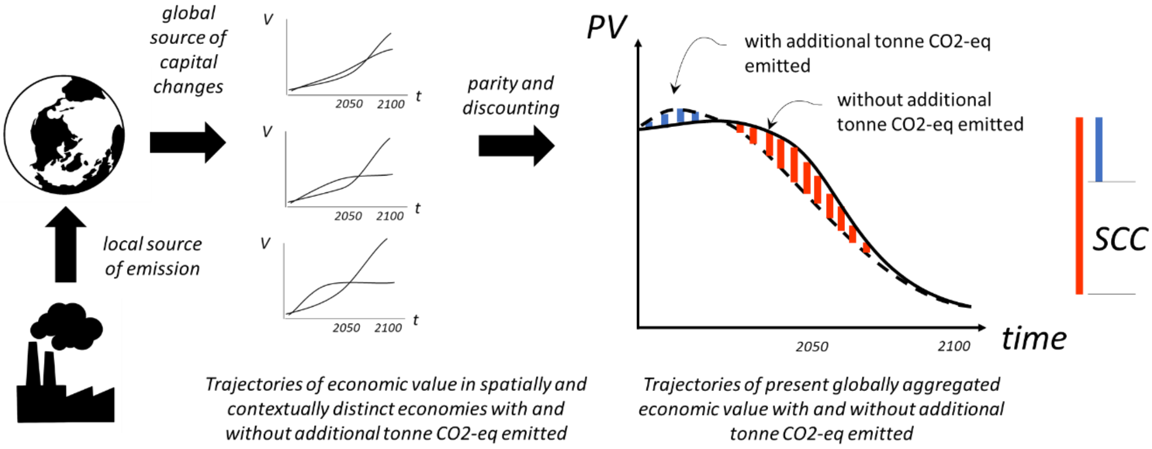

Figure 13: Calculating the social cost of carbon: one tonne of additional CO2-eq emission now changes global climate now and into the future, which is a source of capital changes; which causes change in economic value (V) globally over time (t); parity and discounting are used to equate and aggregate value in economies separated over time and space (present value PV). Integrating over the difference between the PV economic trajectories over time with and without the additional tonne of CO2-eq emitted (adding red comparative costs and subtracting blue comparative benefits of the additional tonne) leads to the estimate of the social cost of carbon (SCC).

We describe the modelling-based integrated modelling approach and the expert-based catastrophic risk approach[8]. Both methods are sensitive to assumptions about equivalence of

[6] M. Adler et al., "Priority for the worse-off and the social cost of carbon," *Nature Climate Change* 7, no. 6 (2017), https://doi.org/10.1038/nclimate3298; C. Kolstad et al., "Social, Economic and Ethical Concepts and Methods," in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. O. Edenhofer et al. (New York, NY: Cambridge University Press, 2014).
[7] M. Fleurbaey et al., "The Social Cost of Carbon: Valuing Inequality, Risk, and Population for Climate Policy," *The Monist* 102, no. 1 (2018), https://doi.org/10.1093/monist/ony023; Kolstad et al., "Social, Economic and Ethical Concepts and Methods."
[8] W. D. Nordhaus, "Revisiting the social cost of carbon," *Proceedings of the National Academy of Sciences of the United States of America* 114, no. 7 (2017), https://doi.org/10.1073/pnas.1609244114; R. S. J. Tol, "On the Uncertainty About the Total Economic Impact of Climate Change," *Environmental and Resource Economics* 53, no. 1 (2012), https://doi.org/10.1007/s10640-012-9549-3. R. S. Pindyck, "The social cost of carbon revisited," *Journal of Environmental Economics and Management* 94 (2019), https://doi.org/https://doi.org/10.1016/j.jeem.2019.02.003. M. Weitzman, "Fat-tailed uncertainty in the economics of catastrophic climate change," *Rev. Environ. Econ. Policy.* 5 (2011).

value between the economies affected by global climate change and its monetisation (parity)[9], what is included in terms of the scope of capital changes for both the damage estimates and the benefits of using carbon for production, and by the economic value of the long-term effects of carbon emitted now (discounting)[10]. The value of the SCC can also change depending whether the economies have non-optimal policy and structures in place, versus assuming the economies are optimising economic value. Discounting has been shown to be the most sensitive parameter resulting in ranges for the SCC in 2015 of 2010US$ 10 with a 5% discount rate and 2010US$ 200 for the discounting approach of the Stern review (effectively 1.4%)[11]. Discount rates greatly change the shape of the PV curves in Figure 13 and so the areas between them (the total amount of red and blue). The discount rate introduces decay in the difference of present value (even though the difference in non-discounted value may diverge) so that the signed area between the PV curves is finite. Otherwise the social cost of a certain amount of CO2-eq emitted becomes “infinite”. Catastrophic effects of climate change that create an increasing divergence in non-discounted value over time result in the possibility of greater area between the PV curves, resulting in higher estimates of the SCC. A non-finite area between the PV curves (that is the value loss diverges at a sufficiently fast rate compared to discounting) was discussed in Alignment of Impact Frameworks.

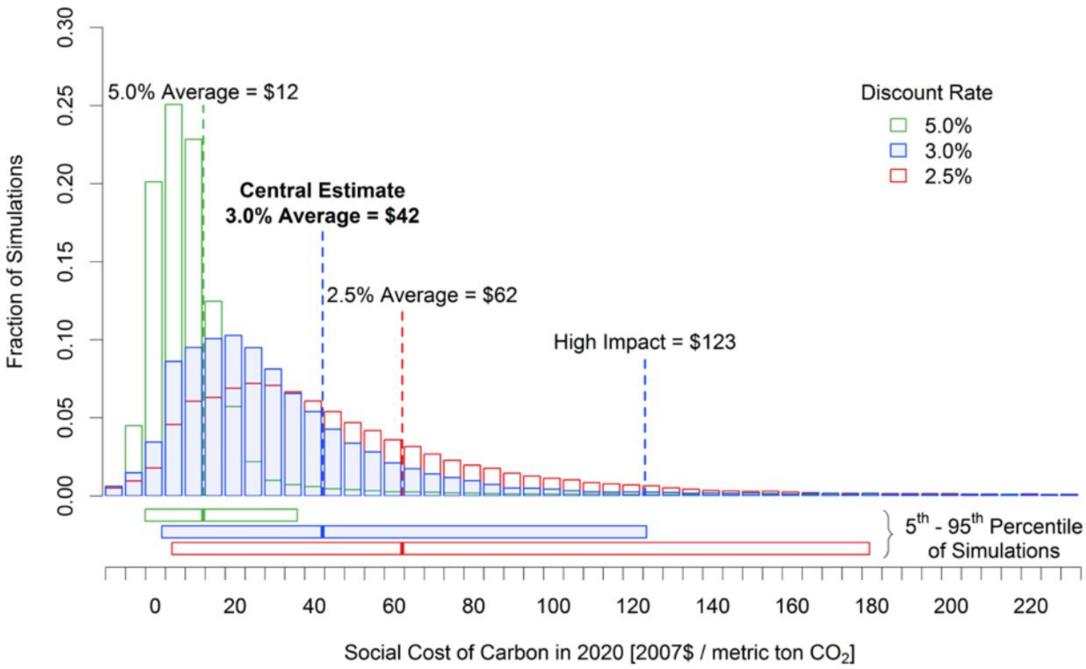

Figure 14: Distribution of SCC estimates using the DICE, FUND and PAGE models with variation in discount rate (Source: Figure 1 IWGSCGG, *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis*).

---

[9] Fleurbaey et al., "The Social Cost of Carbon: Valuing Inequality, Risk, and Population for Climate Policy."; Adler et al., "Priority for the worse-off and the social cost of carbon."; Kolstad et al., "Social, Economic and Ethical Concepts and Methods." There are country level as well as global estimates of SCC: K. Ricke et al., "Country-level social cost of carbon," *Nature Climate Change* 8, no. 10 (2018), https://doi.org/10.1038/s41558-018-0282-y. M. J. Kotchen, "Which Social Cost of Carbon? A Theoretical Perspective," *Journal of the Association of Environmental and Resource Economists* 5, no. 3 (2018), https://doi.org/10.1086/697241.

[10] P. Dasgupta, "The Stern Review's economics of climate change," *National Institute Economic Review* 199, no. 1 (2007), https://doi.org/10.1177/0027950107077111. Nordhaus, "Revisiting the social cost of carbon."

[11] Table 1. Nordhaus, "Revisiting the social cost of carbon." N. Stern, *The economics of climate change: the Stern review* (Cambridge, UK: Cambridge University Press, 2007).

The SCC is normally computed with an Integrated Assessment Model (IAM), which describes the coupling of the economy and the climate system. Three prominent IAMs which calculate the trajectories of GDP change: the PAGE model, the FUND model, and the DICE model, were used by the US Intergovernmental Working Group on the Social Cost of Carbon (IWGSCC) to examine variation in the models combined with variation in discount (Figure 14)[12].

The IAMs, in the terminology of food system impact frameworks, embody different representations of the impact pathway from the footprint of CO2-eq emissions to change in economic value. The literature cited on the social cost of carbon, noting a description relevant to food systems in an FAO study on food loss and waste in 2014[13], describe what is, and what is not, included in terms of benefits and costs in the IAM models. Generally included are damage effects on agriculture, forestry, sea-level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, diarrhoea, energy consumption, water resources, unmanaged ecosystems, and tropical and extra tropical storms. Three GHGs important to food production emissions[14], CO2, CH4 (methane) and N2O (nitrous oxide), are differentiated in their warming effects.

The spread of SCC estimates represent uncertainty in what the social cost of carbon will be (Figure 14). The nature of CO2-eq emissions as an externality of production and consumption means that uncertainty in the social cost amounts to risk transferred to society from those that benefited from the CO2-eq emissions.

The uncertainty and arguments for pricing the risk into the SCC is discussed in the social cost of carbon literature[15]. Risk pricing is basically taking a higher value in the distribution such as the 95-th percentile ("high impact" at 3% discount rate in Figure 14) instead of the mean ("central estimate" in Figure 14). Choosing in the tail (right-end) of the distribution has many precedents in precautionary approaches and industry standard practice in finance (VaR and CVaR)[16]. There are arguments that the SCC should be lower than the mean, that is, the SCC value should include the risk to economic growth and development from reducing CO2-eq emissions[17]. The IWGSCC SCC distribution (Figure 14) may be severely underestimating the tail uncertainty[18]. Despite social and human well-being beyond that derived from consumption

[12] IWGSCGG, *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis*, Interagency Working Group on Social Cost of Greenhouse Gases, United States Government (Washington DC, 2016), https://www.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf. G. E. Metcalf and J. H. Stock, "Integrated Assessment Models and the Social Cost of Carbon: A Review and Assessment of U.S. Experience," *Review of Environmental Economics and Policy* 11, no. 1 (2017), https://doi.org/10.1093/reep/rew014.

[13] Box 1, p. 37: FAO, *Food wastage footprint: full-cost accounting*.

[14] IPCC, *IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems*.

[15] S. Dietz, "The Treatment of Risk and Uncertainty in the US Social Cost of Carbon for Regulatory Impact Analysis," *Economics* 6, no. 18 (2012). J. C. J. M. van den Bergh and W. J. W. Botzen, "A lower bound to the social cost of CO2 emissions," Perspective, *Nature Climate Change* 4 (2014), https://doi.org/10.1038/nclimate2135. R. S. Pindyck, "The Use and Misuse of Models for Climate Policy," *Review of Environmental Economics and Policy* 11, no. 1 (2017), https://doi.org/10.1093/reep/rew012, https://doi.org/10.1093/reep/rew012.

[16] M. Choudhry, *An Introduction to Value-at-Risk* (Wiley, 2012).

[17] D. Pearce, "The Social Cost of Carbon and its Policy Implications," *Oxford Review of Economic Policy* 19, no. 3 (2003), https://doi.org/10.1093/oxrep/19.3.362.

[18] N. Stern, "The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models," *Journal of Economic Literature* 51, no. 3 (2013), https://doi.org/10.1257/jel.51.3.838. F. Ackerman and E. Stanton, "Climate Risks and Carbon Prices: Revising the Social Cost of Carbon," *Economics* 6, no. 10 (2012).

of goods having limited representation in PPP GDP changes[19], pricing risk into uncertain social costs would drive significant change with a SCC at over US$2010 100 if internalisation mechanisms based on the SCC were fully implemented. There are arguments that risk pricing could, or already does, include perturbation in welfare measurement.

For many economists, the social cost of carbon will never be resolved as a single number. The discounting rate for example is an ethical choice rather than a scientific fact, and so the uncertainty in the social cost is irreducible[20].

Following arguments of Weitzman (2009) and Pindyck (2019), probabilities of large changes in welfare (catastrophic changes, e.g. > 20% GDP reduction) from climate change constitute most of the SCC figure[21]. Because of the discount rate and long timeframes, the contribution of smaller or even medium economic changes becomes minimal when converted to present value. Asking experts to judge the chances of such large GDP reductions over a certain timeframe and what reduction in CO2-eq emissions are needed to reduce those chances constitutes a way to derive a SCC figure which does not involve IAMs. It is not clear that models and impact pathways are avoided by this method, only the appearance of precision: an explicit but epistemologically uncertain quantitative model of the mechanisms by which economic value is lost is replaced by the implicit subjective qualitative model in the mind of the expert.

To summarise the components to calculate the social cost of carbon and major sources of variance:

- Scenarios: assumption on socio-economic drivers and especially the societal carbon footprint now and into the future, i.e. emission scenarios. The SCC is routinely calculated by adding one additional tonne of carbon (from an actor) now onto an existing (societal) trajectory of emissions into the future. Change the trajectory of emissions into the future, or change population and GDP growth, and the SCC will change by an order of magnitude.
- Parity and discounting: choices in equating value in time and space will change the SCC by an order of magnitude as discussed. Prioritising poorer nations will not always increase the global social cost of carbon; poorer nations are likely to experience greater impact from climate change (though in PPP GDP this impact is deflated in monetary terms compared to a similar scale of capital change in a richer country) but also have more to lose in terms of not utilising carbon for development.
- Models and data: each IAM is structurally different and can use different data sources. Large changes (catastrophic events, tipping points[22], etc.) are fundamentally uncertain and struggle to be captured in modelling. One of the models analysed by the IWGSCC

[19] Fleurbaey et al., "The Social Cost of Carbon: Valuing Inequality, Risk, and Population for Climate Policy."
[20] J. C. V. Pezzey, "Why the social cost of carbon will always be disputed," *Wiley Interdisciplinary Reviews: Climate Change* 10, no. 1 (2019), https://doi.org/10.1002/wcc.558. Pindyck, "The social cost of carbon revisited." Pindyck, "The Use and Misuse of Models for Climate Policy." C. Hepburn, "Climate change economics: Make carbon pricing a priority," *Nature Climate Change* 7, no. 6 (2017), https://doi.org/10.1038/nclimate3302.
[21] Pindyck, "The social cost of carbon revisited." M. Weitzman, "On Modeling and Interpreting the Economics of Catastrophic Climate Change," *The Review of Economics and Statistics* 91, no. 1 (2009), https://doi.org/10.1162/rest.91.1.1.
[22] E. Kriegler et al., "Imprecise probability assessment of tipping points in the climate system," *Proceedings of the National Academy of Sciences* 106, no. 13 (2009). T. M. Lenton, "Arctic Climate Tipping Points," *Ambio* 41, no. 1 (2012), https://doi.org/10.1007/s13280-011-0221-x; S. E. Werners et al., "Thresholds, tipping and turning points for sustainability under climate change," *Current Opinion in Environmental Sutainability* 5 (2013).

computes small chances of a negative social cost for carbon (climate change is beneficial).

Applying the SCC to economic climate policy is as intricate and debated as calculating it[23]. The SCC literature is a good study for similar considerations needed for applying social costs from other footprints related to food system externalities to economic food policy[24].

The fundamental uncertainty in SCC estimates and perceived difficulties in applying it to national policies on emissions targets led to the abatement approach to costing carbon[25].

Abatement cost of carbon

The marginal abatement cost of carbon (MAC) is the cost to avoid or sequester the emission of an additional tonne of CO2eq over a specified emissions target. The social costs that would have been incurred from that additional tonne over the specified emissions target are abated. The abatement cost is not the mirror of Figure 13 (i.e. changing the labels of the present value trajectories so that they read “without and with one tonne removed” instead of “with and without additional tonne” respectively and with an emission trajectory starting at the emission target). The abatement cost is generally different than paying the social cost of an additional tonne of CO2eq over a specified emissions target. In the social cost, part of the benefit to the economy is the profit in the goods and service that the additional tonne of carbon enables. There are potentially lower costs utilising or associated to different goods and services to avoid or sequester a tonne of carbon; lower than the missed profit and different to the goods and service that the additional tonne would have enabled[26].

Calculating a marginal abatement cost requires substituting a baseline portfolio of activities in the economy with an abatement portfolio of actual or potential activities, that meets the specific emission target by avoiding or sequestering carbon, without change in economic value[27]. The

[23] For example, Fleurbaey et al., "The Social Cost of Carbon: Valuing Inequality, Risk, and Population for Climate Policy." p. 86 “Another concern with the standard approach is that it suggests that a unique tax, corresponding to the magnitude of the SCC, should be imposed on all private agents in order to maximize overall welfare. But this recommendation is not always correct. A unique tax equal to the SCC is optimal if the distribution of resources among individuals is socially optimal. If inequalities are excessive and will not be corrected by inequality-reducing transfers implemented in addition to climate policy, then a single carbon tax is actually socially worse than differentiated taxes that favor disadvantaged populations…It is often objected that differentiated taxes would generate an inefficient distribution of abatement, because the marginal cost of abatement would be greater where the tax is greater, thereby failing to minimize the total abatement cost. But this objection assumes that minimizing the total abatement cost is a good objective, which is not the case if the cost is distributed among individuals with unequal social priority (because some are poorer).”

[24] Chapter 7: IPCC, *IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems*.

[25] Hepburn, "Climate change economics: Make carbon pricing a priority." CCE, *Carbon valuation in UK policy appraisal: a revised approach*, UK Department of Energy and Climate Change. (London, 2009), https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/245334/1_20090715105804_e____carbonvaluationinukpolicyappraisal.pdf. CPLC, *Report of the High-Level Commission on Carbon Prices*, Carbon Pricing Leadership Coalition (Washington DC, 2017), https://www.carbonpricingleadership.org/report-of-the-highlevel-commission-on-carbon-prices.

[26] K. Gillingham and J. H. Stock, "The Cost of Reducing Greenhouse Gas Emissions," *Journal of Economic Perspectives* 32, no. 4 (2018), https://doi.org/10.1257/jep.32.4.53. McKinsey & Company, *Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve*, McKinsey & Company,, (New York NY, 2019), https://www.mckinsey.com/~/media/McKinsey/Business%20Functions/Sustainability/Our%20Insights/Pathways%20to%20a%20low%20carbon%20economy/Pathways%20to%20a%20low%20carbon%20economy.ashx.

[27] The original McKinsey & Co. report p. 9 states that substitution of the abatement portfolio for the baseline is “not having a material effect on the lifestyle of consumers and our results are therefore

marginal abatement cost of the portfolio meeting the emissions target is the maximum cost of an abatement measure in the portfolio. Smaller abatement and baseline portfolios, starting with those that have the lowest marginal abatement costs, can be aggregated into larger portfolios if their provision of goods, services, and CO2-eq avoidance or sequestration do not intersect.

The McKinsey & Co. global marginal abatement cost curve (MACC) is an aggregate of individual measures such that the global abatement portfolio meets 2030 emission targets (as assessed in 2009) to stay within 2 deg C of global warming (Figure 15). The baseline portfolio is associated to business-as-usual. In Figure 15 the vertical axis is the marginal abatement cost for that measure, the area of each box is the total cost (or benefit if the marginal

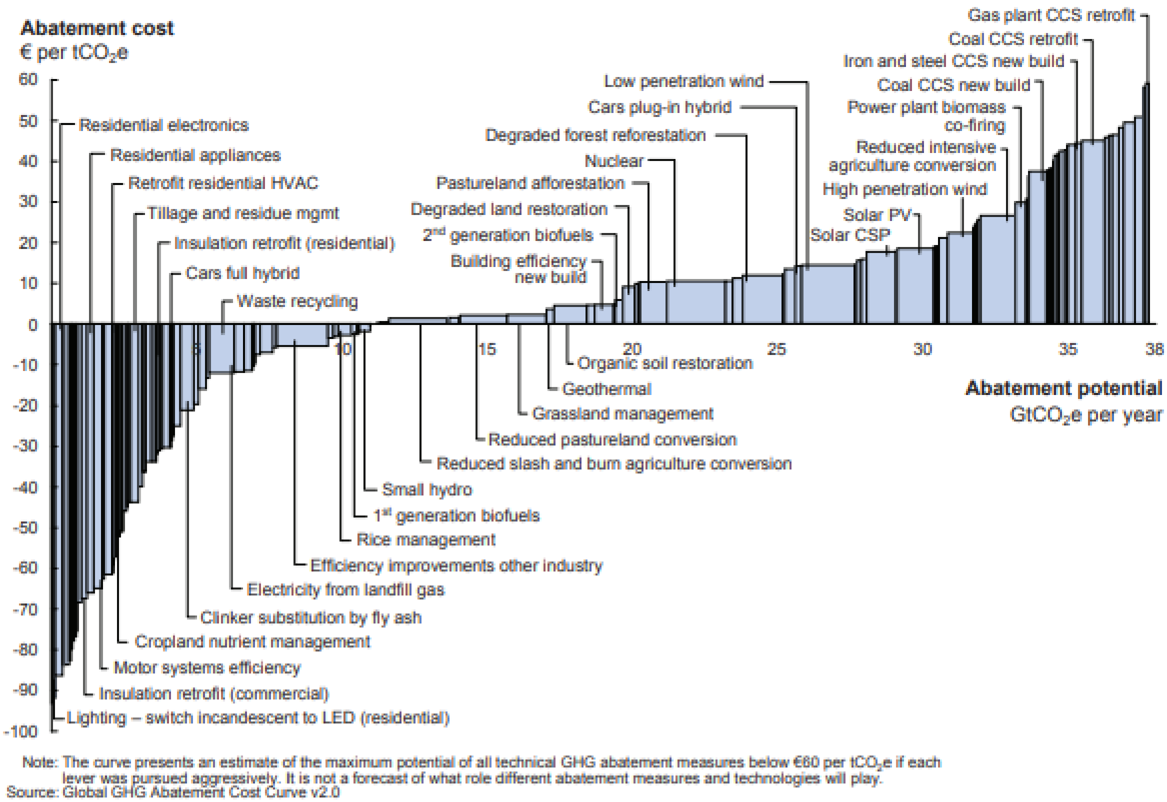

Figure 15: Global GHG abatement cost curve with CO2-eq emissions reduction target of 38Gt by 2030 to stay within 2 deg C of global warming. The portfolio of carbon abatement measures is listed from lowest abatement cost to highest, with the width of the box on the horizontal axis the total reduction in CO2-eq emissions the abatement measure offers. The total abatement cost of the portfolio of measures is the area between the curve above the horizontal axis minus the area of the curve below the horizontal axis. The MAC or global marginal abatement cost of carbon is 2009€ 60 /tCO2eq, the cost of the highest abatement cost in the abatement portfolio (Source: McKinsey & Co. *Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve*)

abatement cost is negative) for that measure above the baseline equivalent, and the horizontal axis is the change in footprint compared to the baseline (CO2-eq emissions). The target for

consistent with continuing increases in global prosperity”. We take this to mean equivalent welfare. The total abatement cost is how much more it would cost to substitute the baseline portfolio for a portfolio of abatement measures that achieve the same welfare. It is implicit that the effect of the additional cost of abatement portfolios on welfare is greater than or equal to the welfare gains in meeting the abatement target. Optimising to find the lowest cost abatement portfolio results in theoretically matching the lowest cost abatement portfolio with the welfare gain from meeting the abatement target. This is the rational for the abatement cost as a valuation: it assigns a monetary value (the lowest cost amongst abatement portfolios) to the welfare gain of meeting the abatement target.

2030 emission targets to stay within 2 deg C of global warming is to reduce CO2-eq emissions by 38Gt. The total abatement cost of the entire portfolio is the area between the curve above the horizontal axis minus the area of the curve below the horizontal axis. The marginal abatement cost for carbon with a certain emission target is the cost of the most expensive abatement measure in the abatement portfolio with the lowest total cost. This is what it would cost to avoid or sequester an additional tonne of carbon above the emissions target assuming all other lower cost options have been utilised to meet the emissions target already. In the case of Figure 15, the 2009 estimate of the marginal abatement cost of carbon for the 38Gt emission reduction target by 2030 is €60 /tCO2-eq.

The calculation of the MAC in practice depends on existing baselines, designing abatement portfolios of substitutions which, essentially, provide the same utility to consumers except for the abatement and additional cost, and estimating the costs of CO2-eq avoidance or sequestration to achieve that same level of utility.

MAC, like the SCC, has supporters and detractors. MACs are viewed as lower estimates of carbon costing to achieve international obligations on emissions (and therefore more advantageous from the viewpoint of minimal intervention to many governments). They are argued to be less uncertain than the SCC as they involved tangible portfolios of measures costed now versus manifest uncertainty in modelling or forecast economic trajectories over one hundred years[28]. The UK shifted from a social cost of carbon approach to an abatement cost approach for policy appraisals in 2011[29]. MACCs enable concrete discussions of transition and transformation grounded in the economic activities of the private and public sectors[30].

That marginal abatement costs are more certain than social costs is contestable[31]. Marginal abatement cost curves are static. They cannot reflect changes in costs, including fossil fuel prices, and actions and technology over time[32]. Interdependencies between the measures in in the portfolio are often not considered and can be consequential[33]. Abatement costing has clear variation and is highly specific to the assumptions about the abatement portfolios, substitution of the baseline, the emissions target, and policy support for implementation including carbon prices and other policy measures[34].

---

[28] S. Dietz and S. Fankhauser, "Environmental prices, uncertainty, and learning," *Oxford Review of Economic Policy* 26, no. 2 (2010), https://doi.org/10.1093/oxrep/grq005; Dietz, "The Treatment of Risk and Uncertainty in the US Social Cost of Carbon for Regulatory Impact Analysis."

[29] CCE, *Carbon valuation in UK policy appraisal: a revised approach*.

[30] S. K. Huang, L. Kuo, and K.-L. Chou, "The applicability of marginal abatement cost approach: A comprehensive review," *Journal of Cleaner Production* 127 (2016), https://doi.org/10.1016/j.jclepro.2016.04.013.

[31] D. Helm, *Carbon valuation in UK policy appraisal: a revised approach and peer reviews. Peer review Dieter Helm.*, Natural Capital Comittee. UK Department of Energy & Climate Change. (London, 2009), https://www.gov.uk/government/publications/carbon-valuation-in-uk-policy-appraisal-a-revised-approach; F. Kesicki and P. Ekins, "Marginal abatement cost curves: a call for caution," *Climate Policy* 12, no. 2 (2012), https://doi.org/10.1080/14693062.2011.582347. Ackerman and Stanton, "Climate Risks and Carbon Prices: Revising the Social Cost of Carbon."

[32] A. Vogt-Schilb and S. Hallegatte, "Marginal abatement cost curves and the optimal timing of mitigation measures," *Energy Policy* 66, no. C (2014), https://doi.org/10.1016/j.enpol.2013.11.045; Kesicki and Ekins, "Marginal abatement cost curves: a call for caution." Gillingham and Stock, "The Cost of Reducing Greenhouse Gas Emissions."

[33] F. Levihn, "On the problem of optimizing through least cost per unit, when costs are negative: Implications for cost curves and the definition of economic efficiency," *Energy* 114 (2016), https://doi.org/https://doi.org/10.1016/j.energy.2016.08.089.

[34] L. Bernard and W. Semmler, *The Oxford handbook of the macroeconomics of global warming*, Handbook of the macroeconomics of global warming, (New York: Oxford University Press, 2015).

One disadvantage of the MAC is that the presentation of uncertainty is relatively unexplored and not as developed as the SCC. High and low abatement cost figures based on emissions targets and Dutch WLO socio-economic scenarios are used in the EU-28 CE-Delft pricing handbook[35]. An upper and lower range of marginal abatement costs is also expressed in the 2017 report of the High-Level Commission on Carbon Prices[36].

Technically, from footnote 27, the marginal abatement cost as a valuation comes from the lowest cost abatement portfolio with no other change in economic value except for abatement of the social cost of carbon above a certain level of emissions. Amongst valuation methods it might be described as potential-to-pay (it assumes exact trade-off between the abatement cost and the abatement). With this assumption on abatement portfolios the minimal abatement cost provides the maximal increase in economic value for that cost.

Inclusions or omissions in the consideration of economic value can change which is the lowest cost abatement portfolio[37]. Another abatement portfolio might provide an increase or decrease in economic value in other areas besides abatement which more than offsets a higher or lower cost, respectively, than the minimal abatement cost. This is relevant for the consideration of abatement costing of food system impacts and discussed from p. 103.

Abatement costs generally feature economic costs, so costs of investment and costs of implementation. Changing to LED bulbs is a market efficiency for those making the LED bulb and the consumer of LED bulbs (the higher purchase price is paid back by lower electricity costs over the lifetime of the bulb), but a manufacturer of lighting that is unable to shift to LEDs is likely to lose out. It is not necessarily a Pareto gain in financial value for the entire market. The secondary consequences for the economy with such changes are not generally accounted for.

The cost to make plant protein as attractive as animal protein for a certain number of consumers has potential health benefits above the carbon abatement[38]. Based on a comparison with an abatement measure with the same cost in a MACC, the replacement plant protein product appears an inefficient way to abate carbon, but it may be a greater economic efficiency gain (costs less overall when external health benefits are subtracted from the development cost).

Note that marginal abatement cost curves list all potential market efficiency gains with negative marginal abatement cost first. According to the MACC in Figure 15, nearly 30%, or 11 Gt, of emissions reduction are achievable by financial efficiency where the private savings outweighs the private costs and abatement of carbon is available for free. The representation of negative costs and inefficiencies has been criticized on the account of whether all economic costs have been accounted for and whether an imperfect but still competitive economy has neglected such large potential efficiencies[39].

[35] Described on p. 94 de Bruyn et al., *Environmental Prices Handbook EU28 Version*.: Using the EU ETS to reflect abatement potential is described in: R. Aalbers, G. Renes, and G. Romijn, *WLO-klimaatscenario's en de waardering van CO2-uitstoot in MKBA's*, Centraal Planbureau (CPB), Planbureau voor de Leefomgeving (PBL) (Den Haag, 2016).
[36] CPLC, *Report of the High-Level Commission on Carbon Prices*.
[37] Kesicki and Ekins, "Marginal abatement cost curves: a call for caution."
[38] M. A. Clark et al., "Multiple health and environmental impacts of foods," *Proceedings of the National Academy of Sciences* (2019), https://doi.org/10.1073/pnas.1906908116.
[39] Gillingham and Stock, "The Cost of Reducing Greenhouse Gas Emissions." Levihn, "On the problem of optimizing through least cost per unit, when costs are negative: Implications for cost curves and the definition of economic efficiency."

The MAC should be less than the SCC adjusted for the emissions target. If no abatement portfolio costs less than the damage costs from doing nothing, then paying the damage cost is optimal for welfare (Figure 16). In this sense the social benefit (the social cost abated by an abatement portfolio) is the abatement value that can be obtained by the abatement cost of that portfolio. Owners of measures that have greater costs to avoid or sequester a tonne of carbon than un-utilised measures with lower costs would theoretically gain in exchanging carbon emission rights, as the lowest cost available measure is more efficient at abating carbon. This is the theory by which an emission rights trading scheme, with caps designed to limit emissions to the emissions target, will realise the potential in the abatement curve, filling up the low cost opportunities until the point where the emission target is reached and the market price for emissions rights approaches the marginal abatement cost of the realised abatement portfolio[40].

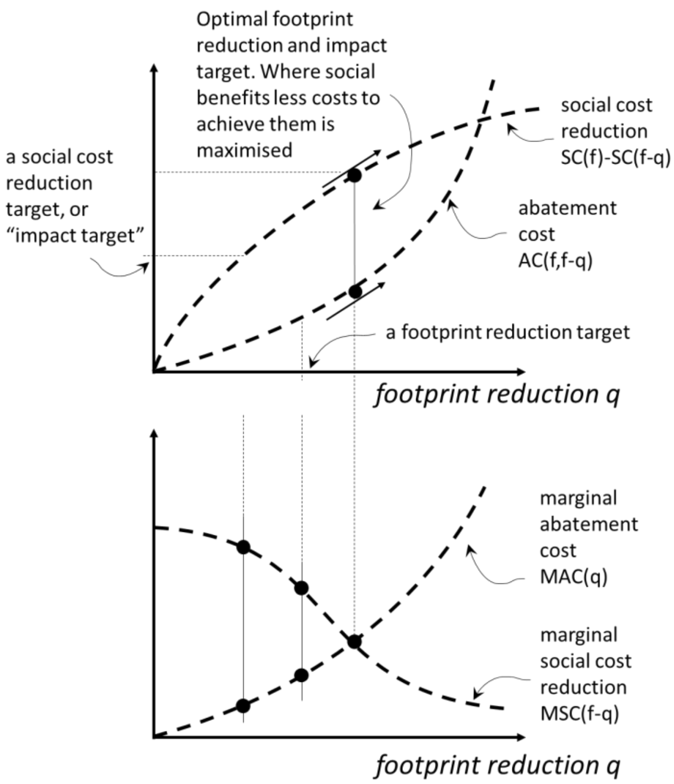

Figure 16: Conceptual relationship between marginal abatement cost and marginal social cost as the marginal value of abatement. Marginal social cost depends upon an emission trajectory with current carbon emissions f and the emissions reduction target q as an adjustment to that trajectory. As the emissions reduction q increases, the marginal social cost of an additional unit of emission in the reduced emission trajectory should decrease. The marginal abatement cost increases. An optimal economy able to exchange social costs with the cost of increased abatement will tend to the equilibrium point and the amount of emissions reduction where MSC(f-q) and MAC(q) are equal.

The MAC theoretically equals the SCC adjusted for the emissions target only under assumptions of optimal economic policy (Figure 16). That policy is assumed to resolve future economic trajectories into the abated trajectory. Optimising the social cost involves paying abatement costs where the cost is lower than damages. Those forecasted economies where the capital changes occur and cause damage costs more expensive than the economy with abatement are not realised. The uncertainties mentioned in calculating damage costs and calculating abatement costs, and the ability of an economic policy to perfectly realise the

[40] E. Narassimhan et al., "Carbon pricing in practice: a review of existing emissions trading systems," *Climate Policy* 18, no. 8 (2018), https://doi.org/10.1080/14693062.2018.1467827.

exchange value between the profit loss and external costs of certain goods and services and the abatement cost for other goods and services, means that equating the marginal abatement cost to a marginal social cost adjusted for the emissions target involves strong assumptions and is likely incorrect for non-optimal economies.

The components to calculate, and major sources of variance in, the marginal abatement cost of carbon are categorically like the social cost of carbon:

- Scenarios: assumptions about socio-economic drivers are embedded in the costs, availability, and realisation of abatement measures over time, and what is an acceptable substitution of baselines for present and future welfare. Emission scenarios are still relevant because they determine emission targets.
- Parity and discounting: PPP is used to aggregate costs of abatement measures across multiple nations into a global cost. Parity becomes more directly relevant than in SCC in terms of the different costs, availability, and realisation of abatement measures across countries. Discounting as a balance between present and future generations is relevant in terms of future societal wealth or increased resources available now to influence costs and availability of abatement measures. Setting different national targets to achieve a global total involves parity considerations.
- Models and data: models and data are still required to calculate costs and the reduction of CO2-eq emissions. Uncertainty about the long future in the SCC is traded against lack of knowledge of the present in the MAC. Realisation of abatement though political and economic processes may be more uncertain than damage costs that depend on mechanistic physical processes like sea level rise. The McKinsey & Co. 2009 report identified a 10-year window of action. Many of the efficiency measures, and abatement potentials, were not realised in 2019[41]. The uncertainty in whether the potential in an abatement portfolio is realised would suggest a similar risk pricing approach to the SCC in terms of using estimates above the central values to incorporate a risk premium. Uncertainty in the realisation of abatement measures is discussed again under the heading of abatement demand of products and practices in the food system in Case Studies of Food System Impact Valuation.

Food impact costing

Carbon costing illustrated features of valuations relevant to food system impact: social costs, abatement costs, discount rate, scenarios, actor footprint versus societal footprint, the complications of calculating monetary amounts from models of complex chains of capital changes across space and time, parity and discounting, and risk pricing due to variation in the calculation.

These features are relevant for calculating other social and abatement costs for the food system. We discuss them generally and comment on adjustments for food system impact valuation[42]. Case studies in Case Studies of Food System Impact Valuation use a template that illustrates the social and abatement costs, discount rate and parity chosen, how footprints were calculated and models applied.

The foremost difference for the food system from carbon costing is that impact from food system activities is associated to footprints in plural, some of which need to be broken down further due to spatial and contextual differences in impact due to those footprints.

[41] https://www.nytimes.com/interactive/2018/12/07/climate/world-emissions-paris-goals-not-on-track.html

[42] Commonly listed valuation methods such as willingness-to-pay, damage costs, market values, averting expenditure, are used as appropriate within the models of social or abatement costs. Examples of their use can be found in the case studies in Case Studies of Food System Impact Valuation.

Valuation as a function of footprint

Issues where food systems are creating the most concern for social and human value change (Table 1 in Economic Theory of Change), traced through capital changes, identifies quantities relevant to impact such as tonnes CO2-eq emitted (CO2, CH4, N2O), tonnes reactive nitrogen (N) and soluble phosphorous (P) leached, water consumption m^3, ha land-use change, number of injuries in a workforce, etc. Amongst all quantities that could be associated to activities in the food system, impact valuation requires a balance between a tractable list of quantities and those capturing most of the impact.

Footprint is a vector of individual footprint quantities. The nine case studies in Case Studies of Food System Impact Valuation indicate a range of footprint quantities considered for food system impacts. Footprint for an impact valuation should be delineated to account for spatial and contextual variation. These details will be considered subsequently on p. 77 and p. 96. In the case of valuing social and human capital change the footprint quantity also needs to be considered alongside the models (of marginal valuation) that will be used to perform the valuation. Quantities associated to environmental marginal valuations are well established.

We denote a vector, or list, of footprint quantities

$$f = [f_1, \cdots, f_n].$$

For instance, the first quantity in the footprint f_1 could be t CO2-eq emitted into the atmosphere by society after a certain date.

Denote by V a function that takes a list of present footprint quantities f as input and assigns to them a monetary amount relating to economic value $V(f)$ as output (Figure 11). If a food system actor is responsible for a change in societal footprint from f to $\hat{f}$ (the amount of generated CO2-eq emissions, leached nitrogen, improvement of community access to drinking water, food products sold that caused preventable death and disease compared to reference diets, etc.) then the change in economic value, or impact, is

$$V(\hat{f}) - V(f).$$

The change in economic value due to the change in footprint depends on the societal footprint. This dependency is what is reflected in the variation in the social cost of carbon due to emissions trajectories and other socio-economic factors. Similarly, the health costs of food products depend not just on health and lifestyle factors but economic and environmental factors, etc. To include these other factors s, and if these other determinants of value are kept constant from the actor's contribution to footprint increase,

$$V(s, \hat{f}) - V(s, f)$$

is the change in economic value. This notation simply means that the calculation is dependent on the other factors denoted by s. That economic value is changing significantly due to variation in the footprint quantities is not included in conventional economic measurement. Ignoring the total value loss and gain through non-financial capital changes is equivalent to setting the difference to be zero and saying that economic value is independent of the variation in footprint.

The scientific evidence, and evidence from initial valuations such as the social cost case studies in Case Studies of Food System Impact Valuation, is that economic value is not invariant to changes in footprint quantities. The implication is that footprints are economic quantities, hence are factors to welfare like other quantities measured and tracked by the economic system.

For large changes in footprint, other socio-economic quantities embodied in s are unlikely to remain constant. Footprint quantities are the result of production and consumption. Inverting that relationship, reducing footprint results in changes in production and consumption with flow-on effects through the economy. For large changes in footprint the flow-on effects are extremely important to understand to estimate the change in economic value:

$$V\left(s(\hat{f}),\hat{f}\right) - V(s(f),f)$$

where $s(f) \mapsto s(\hat{f})$ is the simultaneous change in other socio-economic quantities associated to the change in footprint $f \mapsto \hat{f}$. For example, large scale changes in food loss and waste will either result in a drop in agricultural production (if the same amount of food is consumed less production required) with flow on effects for agriculture and input industries, or flow on effects for human health and society (if the same amount of food is produced with no loss then much more food is consumed)[43]. As another example, large scale dietary changes for plant-based meat and dairy results in large structural changes in all industries attached to animal meat and dairy production, and frees enormous land resources with flow-on effects for biofuels, bioplastics, and/or ecosystem benefits. If the dietary changes are not voluntary but are achieved through fiscal pressure which raises large amounts of revenue, then what is done with the revenue is also a factor. In 2018, Canada legislated a carbon tax where revenue raised from CO2-eq emission is transferred to households[44]. What consumers might do with the extra revenue in terms of increased consumption of emissions embedded in goods from outside Canada is uncertain. The redistribution of revenue is not likely to cancel out the benefit from reducing production from the most intensive sources of emission and increasing production of likely less intensive sources, but it is a second order correction to the size of the benefit.

Estimating $V\left(s(\hat{f}),\hat{f}\right) - V(s(f),f)$ for changes in footprint f to $\hat{f}$ associated to food system actor(s) is an impact valuation.

We do not have the models, data, or knowledge to be definitive about the estimates. There are presently no global or national general equilibrium models that include footprint quantities as variables and measure economic value in terms of wider aspects of social and human well-being. For CO2-eq emissions the closest are the IAMs used in the calculation of the social cost of carbon. They are not general equilibrium models; they describe basic feedback between the climate and the economy and use a variety of proxy valuations to estimate monetary damage to PPP GDP. Theoretically, with general equilibrium models that could include footprints associated to major external costs, the natural dynamics moving the economic system to equilibrium and economic efficiency are depicted in Figure 16. The model would depict optimal shadow prices (also called efficient prices) and the sustainable level of footprint[45].

---

[43] M. M. Rutten, "What economic theory tells us about the impacts of reducing food losses and/or waste: implications for research, policy and practice," *Agriculture & Food Security* 2, no. 1 (2013), https://doi.org/10.1186/2048-7010-2-13.

[44] https://www.theguardian.com/environment/climate-consensus-97-per-cent/2018/oct/26/canada-passed-a-carbon-tax-that-will-give-most-canadians-more-money

[45] Understanding valuation as an approximation to the welfare difference using an equilibrium model that can incorporate externalities is the fundamental link between welfare economics and impact valuation, noted in: T. M. Bachmann, "Optimal pollution: the welfare economic approach to correct market failures," in *Encyclopedia on Environmental Health.*, ed. J. Nriagu (Burlington: Elsevier, 2011); K. J. Arrow et al., "Sustainability and the measurement of wealth," *Environment and Development Economics* 17, no. 3 (2012), https://doi.org/10.1017/S1355770X12000137; P. Dasgupta and A. Duraiappah, "Well-being and wealth," in *Inclusive Wealth Report 2012: measuring progress toward sustainability*, ed. IHDP-UNU and UNEP (Cambridge: Cambridge University Press, 2012); FAO, *Food*

In the absence of such models impact valuation involves: a) an approximation of the difference $V(s(\hat{f}),\hat{f}) - V(s(f),f)$, and b) arguments why aspects of the calculation can be simplified and what the degree of error might be.

Filling in the steps

The general components that feature in present approximations of economic value change from a footprint change are actor footprint, societal footprint, assumptions about socio-economic drivers, models and data for attribution of capital changes across space and time, choice of welfare measure, parity and discounting. The overlay of the components on Figure 11 (Figure 17) demonstrate what is required to fill in the "Measure and Value" steps (Steps 05-07) of the Natural Capital, and Human and Social Capital, Protocols (Figure 6 in Alignment of Impact Frameworks) for monetary valuation. The Natural Capital Protocol Food & Beverage Guide from pages 38-50 provides a list of worked examples on the basic steps in Figure 17 of determining footprint, considering capital changes, and then multiplying total footprints by a marginal value. This section concerns the detail behind the numbers.

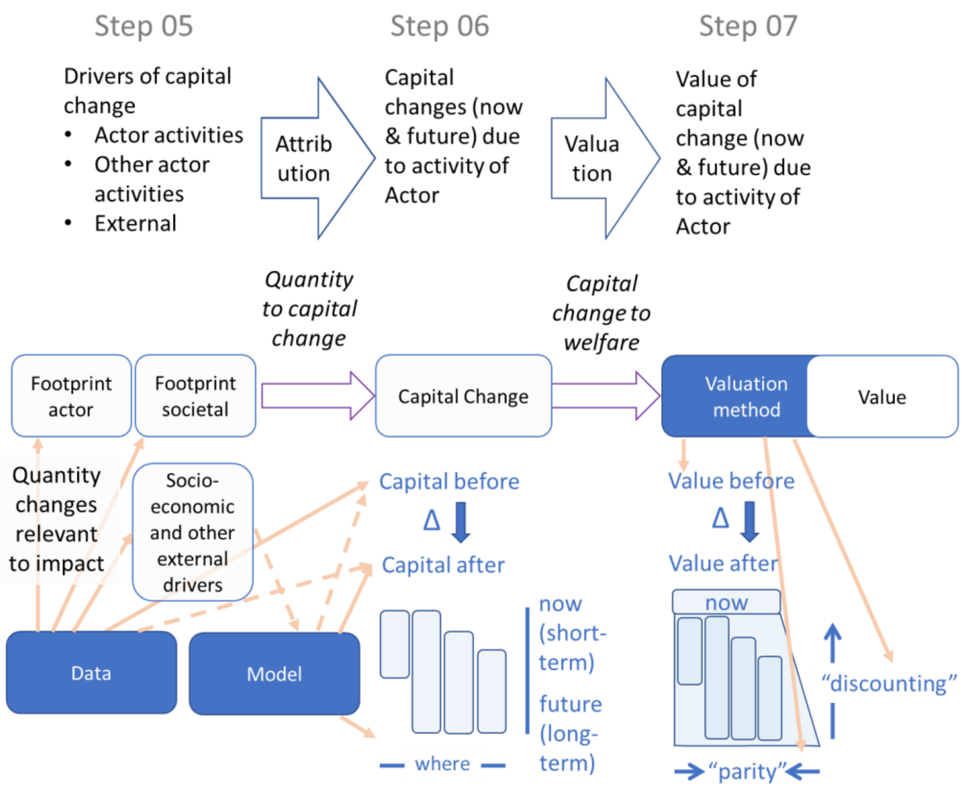

Figure 17: Measure and value steps in impact frameworks as the process of attribution and valuation of capital changes. Data and models are needed to estimate footprints of actor, footprints of society and other socioeconomic drivers. Further data and models are needed to attribute the footprint of the actor to capital changes. Valuation methods estimate the value change from the capital change. They involve a new set of data and models, as well as ethical choices on how to compare value changes between economies (parity) and across time (discounting to present value).

We break down the steps into the simplest logic. We have a food system actor. This might be a government, a sector, a company, a farmer. The final task is to estimate the eventual difference in a monetary representation of economic value, be it positive or negative, from

wastage footprint: full-cost accounting; de Bruyn et al., *Environmental Prices Handbook EU28 Version*. E. P. Fenichel and Y. Hashida, "Choices and the value of natural capital," *Oxford Review of Economic Policy* 35, no. 1 (2019), https://doi.org/10.1093/oxrep/gry021.

changes to natural, social and human capital due to the actor. Thought needs to be given in the measure of economic value and which economies are affected by the capital changes. Those details are discussed further on.

Impact of activities factor through capital changes. In impact frameworks like the TEEB AgriFood Evaluation Framework, without capital changes there are no impacts. To estimate the difference in a monetary representation of economic value requires determining the capital changes due to the actor. To do that requires determining the drivers of change in quantity and quality of produced, natural, social and human capital. Going from Step 06 to 07 is valuation of a capital changes. Going from Step 05 to 06 is attribution of a capital change, i.e. how much of the capital changes valued are due to actor activities. Capital changes due to the actor factors through footprint. The same footprint can be associated to different capital changes, and the same capital change can be associated to different impacts.

Actor footprint, societal footprint, and socio-economic drivers

The drivers of capital change are the present activity of that actor and other actors who are using or changing that capital which might be from other sectors. For example, the actor in question might not be the only one drawing water from a non-renewable water source. If other users are extracting more water, and on a trajectory to accelerate the extraction in the future, a unit of additional extraction by the actor has potentially worse impacts. Another example from the social costs of carbon are the impacts of one emitter depends on total societal emissions. Most impact pathways associated to the food system have the same consideration. What food the rest of the food system is producing, and what people are eating beside the produce or products of the actor, is a central determinant of the health impacts. The determination of the impact from a can of soft drink without context is impossible. The nutrient profile of the product itself is insufficient.

Therefore, given the footprint of a food system actor, the footprint of other actors and other external factors are required to calculate, from the actor's footprint, the capital changes attributable to the actor.

In climate science, emission scenarios are used to indicate different possible trajectories of total emissions. However, the same emissions trajectory can have worse impacts depending on a range of socio-economic factors from population, attitudes to natural renewable and non-renewable resources, and general ability to absorb economic and social shocks reflected in GDP and community resilience. Nutrient pollution into an already degraded ecosystem will generally accelerate degradation and loss of services more than the same pollution into a healthy ecosystem. Public health outcomes depend on levels of physical exercise in the population and general metabolic factors not only on dietary intake. External factors to the actor footprint and the total footprint may have a major effect on the total capital change such as ecosystem dynamics and social trends. The capital changes occur in the general context of socio-economic trends such as demographics, social dynamics, technology, ecosystem dynamics, etc. that effect the exiting quantities and qualities of capital stocks.

Factoring impact of food system actors' activities through footprint has implications. There are other activities, e.g. advertising, lobbying, of food system actors that influence socio-economic trends and estimation of future footprints and impacts. They are not captured by the kind of footprints currently suggested by scientific studies for food system impact (Table 1 in Economic Theory of Change). If not captured in footprint, they are not observable as economic quantities whose variation is explicit in change of economic value except through the specification of external factors. They can be captured in a static way in scenarios and in models for the calculation of capital change. Changes in the static picture can be reflected by an update mechanism of scenarios and shadow prices suggested further in Implications.

The exogenous information required to determine capital changes not calculated endogenously, within the models for capital change described next section, is either provided by data or by scenarios. Scenarios do not relate only to long-term events. Scenarios are alternative specifications when there is uncertainty. For example, specifying alternatives for consumers spending of revenue from carbon taxation, or how consumers and producers respond to food price increases from Pigouvian taxation, are scenarios. Scenarios are implicit in a valuation calculation where there are assumption about what happens when footprints change in the short-term, e.g. economic flow-on effects, or what may be happening now but we do not have the monitoring ability to obtain data, e.g. community damage, health effects in subpopulations.

Models and data to determine capital changes

Given the footprint of a food system actor and the context of the footprint of other actors and external factors the next step of the process is to calculate the capital changes attributable to the actor's footprint.

For capital change we need to calculate the capital quantity and quality before and the capital quantity and quality after. The capital quantity and quality after is not at some fixed time after. It needs to be the total change due to the footprint change (emission, pollution, nutrition embedded in product, etc.). It is the total change which relates to damage to present and future economies from activities today. An example is that carbon emitted today will be contributing to temperature change and so damages from those temperature changes until climate equilibrium is reached. Another example is health where nutrition or injuries today contributes to long-term health and social effects, some for generations[46]. Nitrogen leakage (NO3) to groundwater from nitrogen fertiliser applied to soils is highly variable but can continue for decades[47]. It is both the level and change of quantity and quality that are relevant to damages. Species lost in an abundant and diverse ecosystem are different from the last few species lost in an endangered ecosystem.

Monitoring of the present level and quantity of capital stocks would provide direct data on capital change. It might also be able to observe direct attribution to actors by correlating footprints with capital changes. Most likely the capital changes must be modelled and this is the norm. IAMs were discussed in the last section on costing carbon. Well-developed models exist for air and water pollution for developed countries – the NEEDS model that underpins the CE-Delft EU28 Environmental Prices Handbook is discussed in case study 7 in . A model of life stages impacted by stunting, to calculate income difference is adulthood is discussed in case study 6. A linear regression model associating income changes to social repercussions of climate change, soil degradation, pesticide use from growing food that was lost and wasted is in case study 1. Large amounts of data are, or would be, required to populate the models, train them, and estimate their error.

[46] C. G. Victora et al., "Maternal and child undernutrition: consequences for adult health and human capital," *The Lancet* 371, no. 9609 (2008), https://doi.org/https://doi.org/10.1016/S0140-6736(07)61692-4; K. L. Whitaker et al., "Comparing maternal and paternal intergenerational transmission of obesity risk in a large population-based sample," *The American Journal of Clinical Nutrition* 91, no. 6 (2010), https://doi.org/10.3945/ajcn.2009.28838. D. Hulme, K. Moore, and A. Shepherd, "Chronic Poverty: Meanings and Analytical Frameworks," *SSRN Electronic Journal* (2001), https://doi.org/10.2139/ssrn.1754546; D. Conley and J. Thompson, *Health Shocks, Insurance Status and Net Worth: Intra- and Inter-Generational Effects*, National Bureau of Economic Research (Cambridge, MA, 2011).

[47] S. Mathieu et al., "Long-term fate of nitrate fertilizer in agricultural soils," *Proceedings of the National Academy of Sciences* 110, no. 45 (2013), https://doi.org/10.1073/pnas.1305372110.

In many cases not only the change, but the existing level of capital needs estimating through a model[48]. Even for natural capital there is an increasing but limited monitoring capability. Many of the present stocks are likely not directly observed but are extrapolated or calculated.

For footprints incurred today, that have the potential to lock-in impact over longer time periods including generations, complicated models that require exogeneous projections of socio-economic drivers and trajectories for societal footprint introduce significant uncertainty, e.g. IAMs in carbon costing. Modelling is associated to a catch-22 situation; using a model introduces uncertainty but not costing the impact introduces potentially greater error.

Parsimony was observed in climate costing. Resolution of modelling impacts over time can become coarser. Large generational impacts are potentially the only ones that survive not being reduced to very small differences in present value by discounting. However, uncertainty can introduce caveats to this principle. Uncertainty in compounding or cascading effects from locked-in capital changes allow a potential inflation in impact that outstrips the deflation represented by discounting[49]. Especially when continued trajectories of use create scarcity. Few of the social costs from the case studies consider lock-in impacts outside of carbon costing.

The prices in the CE-Delft EU28 Handbook of Environmental Prices are an exception due to the development embodied in the NEEDS model of impact and environmental pollution. The EU funded a progression of research projects that provided continuity of development leading to the NEEDS model[50]. Environmental pricing handbooks are concentrated on environmental pollution and similar well-developed studies on noise pollution. There are few other prices in the handbooks suitable for non-environmental aspects of food system impact valuation.

The division of the impact attributable to an actor into the three-step conditional sequence of change in economic value given capital changes, capital changes given societal footprint, other drivers, and actor footprint, and the calculation of footprints (Figure 17) is useful conceptually.

The case studies, and examples such as carbon costing, evidence that models and data are used at each step of the process. It is more helpful in discussions to categorise the models and data whether they are for calculation of footprints, or used in valuation and attribution for either calculation of capital changes, or estimation of welfare changes from those capital changes. Often the terms data and model are discussed without reference to the steps, which is discussed further in Inventory and Development of Methods.

Models and data for footprints: models to calculate footprints are the most developed, particularly for environmental footprints. Models are used to calculate the footprint of actors (usually by companies, e.g. life-cycle inventories (LCI) calculated from lifecycle models and databases), Models estimate total footprints (usually in scientific literature, e.g. a combination of monitoring data and models are used to determine non-renewable water use by region or globally, soil degradation regionally or globally, etc.[51]). LCI was developed to calculate environmental footprints. The data used for LCI is mostly a compilation of open source databases generated initially by European government funded initiatives. The data is rarely specific to a product or a production process, but instead uses averages for that type of product

[48] UNEP, *Inclusive wealth report 2018 : measuring progress towards sustainability* (Cambridge: Cambridge University Press, 2018).
[49] C. Gollier, "Valuation of natural capital under uncertain substitutability," *Journal of Environmental Economics and Management* 94 (2019), https://doi.org/10.1016/j.jeem.2019.01.003.
[50] p. 139: de Bruyn et al., *Environmental Prices Handbook EU28 Version*.
[51] For example: D. Carole et al., "Groundwater depletion embedded in international food trade," *Nature* 543, no. 7647 (2017), https://doi.org/10.1038/nature21403.

with varying levels of spatial and contextual specification (e.g. organic apple grown in Spain)[52]. Life cycle analysis (LCA) is a widely used and standardised tool, which is increasing coverage applicable to food systems including better treatment of complicated environmental aspects such as land-use, pesticide exposure, and footprints relating to other capital changes such as social capital[53]. LCA also uses societal footprints as part of normalisation[54]. LCA footprint calculation for activities associated to a food product is used in case study 7 and 8 and some part in most of the other case studies.

The list of estimates from scientific literature of CO2-eq emissions, water use in agriculture, pesticide use, etc., social and nutritional footprints related to food systems using a range of different models, modelling methods, and data sources, is tremendous. The challenge is processing them so that they can be made available for footprint and capital change calculations. Tools have emerged to consolidate scientific knowledge about agricultural footprints specifically such as the CoolFarmTool[55] as part of a shift by the food sector towards metrics of improvement rather than compliance with standards[56].

An input-output model used by the consulting company TruCost offers a different way to associate environmental footprints[57]. It associates revenue of sectors of the economy to environmental footprint. It then uses the input-output structure of the economy to determine the dependence of a company or one sector on other sectors to calculate their "upstream" environmental impacts. This method is justifiably described as a top-down approach. The bottom-up approach would be to use LCA to calculate the production of all products of the company and ancillary footprints associated to that production.

At a global level global agricultural and trade production models such as GLOBIOM, IMPACT and MAGPIE[58] can be used to back-calculate some footprints. This is the perspective of case studies 1-3 on impact of activities of the global food system. Given exogenous settings of

[52] L. Peano et al., "The World Food LCA Database project: towards more accurate food datasets" (paper presented at the Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector (LCA Food 2014), San Francisco, CA, 8-10 October, 2014. 2014).

[53] Land use: B. Vidal Legaz et al., "Soil quality, properties, and functions in life cycle assessment: an evaluation of models," *Journal of Cleaner Production* 140, no. P2 (2017), https://doi.org/10.1016/j.jclepro.2016.05.077.. Pesticide: P. Fantke and O. Jolliet, "Life cycle human health impacts of 875 pesticides," *The International Journal of Life Cycle Assessment* 21, no. 5 (2016), https://doi.org/10.1007/s11367-015-0910-y.. Social: A. Jørgensen et al., "Methodologies for social life cycle assessment," *The international journal of life cycle assessment* 13, no. 2 (2008). UNEP, *Guidelines for social life cycle assessment of products: social and socio-economic LCA guidelines complementing environmental LCA and Life Cycle Costing, contributing to the full assessment of goods and services within the context of sustainable development*, UNEP DTIE Sustainable Consumption and Production Branch (Paris, 2009), http://hdl.handle.net/20.500.11822/7912.

[54] S. Sala et al., *Global normalisation factors for the Environmental Footprint and Life Cycle Assessment*, Publications Office of the European Union (Luxembourg, 2017). E. Crenna et al., "Global environmental impacts: data sources and methodological choices for calculating normalization factors for LCA," *The International Journal of Life Cycle Assessment* 24, no. 10 (2019), https://doi.org/10.1007/s11367-019-01604-y.

[55] B. Kayatz et al., "Cool Farm Tool Water: A global on-line tool to assess water use in crop production," *Journal of Cleaner Production* 207 (2019), https://doi.org/https://doi.org/10.1016/j.jclepro.2018.09.160; J. Hillier et al., "A farm-focused calculator for emissions from crop and livestock production," *Environmental Modelling & Software* 26, no. 9 (2011), https://doi.org/http://dx.doi.org/10.1016/j.envsoft.2011.03.014.

[56] S. Freidberg, "Big Food and Little Data: The Slow Harvest of Corporate Food Supply Chain Sustainability Initiatives," *Annals of the American Association of Geographers* 107, no. 6 (2017), https://doi.org/10.1080/24694452.2017.1309967.

[57] TruCost, *Top-down methodology TEEB Animal Husbandry*.

[58] K. Wiebe et al., "Comparing impacts of climate change and mitigation on global agriculture by 2050," *Environmental Research Letters* 13 (2018).

GDP, population, technological advance and consumption demand (which is translated back to commodities from exogenously set global diets), the models can determine agricultural land use associated to crops and livestock, water use, estimates of fertiliser use, commodity prices and yields. The resolution is at sub-regional level, accounting for spatial distinction of suitable or existing primary growing regions for commodities. For example, the IMPACT model divides the land surface of the globe into 320 units of food production which overlap a similar division of associated water basins with 36 crop and 6 livestock production categories[59].

Valuation method

Following the approach of impact frameworks, we use economic value synonymously with welfare and human well-being in a broad sense. A valuation method specifies whose values for which loss or gain is being considered, and the representation of economic value in monetary terms. We discuss the measure of welfare and parity and discounting below.

Economic valuation theory has a list of valuation methods applicable to valuation of capital changes including willingness-to-pay using revealed preferences or contingent valuation, damage costs, market values, averting expenditure, etc. Summaries of these methods and their application to valuing non-financial capital changes can be found in Chapter 5 of the Inclusive Wealth Report, Chapter 7 of the TEEB AgriFood Evaluation Foundations report, and the 2014 FAO report on valuing food loss and waste[60]. Applications of different methods can be found in the case studies, and meta-studies of monetary values have aggregated monetary amounts across different valuation methods[61]. Our concern is less on the distinction between valuation methods, though they are important, than on the distinction between social and abatement costs. From the rationale in Figure 16 social costs represent the economic value loss from food systems and abatement is the economic means, the mechanisms, the least cost pathways and merit orders of action, to avert or recover that value loss.

<u>Models and data for valuation</u>: In case study 3 data and models within the Global Burden of Disease Study perform the attribution of preventable global disease and death in DALYs to the dietary intake of individuals that differ from a defined diet for ideal health[62]. Footprint is canonical in the case study because the global food system is the focus and it provides all global dietary intake. Therefore, with DALYs as a measure of human health change, the Global Burden of Disease Study has in this case performed the step of attribution.

Turning DALYs into a monetary amount reflecting welfare loss is an example of a valuation of a capital change. Models and data, with assumptions resulting in significant variation, are used to determine the value of a DALY[63].

---

[59] S. Robinson et al., *The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model description for version 3*, International Food Policy Research Institute (IFPRI) (Washington, DC, 2015), http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/129825.
[60] UNEP, *Inclusive wealth report 2018 : measuring progress towards sustainability*. TEEB, *TEEB for Agriculture & Food: Scientific and Economic Foundations*, UN Environment (Geneva, 2018). FAO, *Food wastage footprint: full-cost accounting*.
[61] R. de Groot et al., "Global estimates of the value of ecosystems and their services in monetary units," *Ecosystem Services* 1, no. 1 (2012), https://doi.org/10.1016/j.ecoser.2012.07.005.
[62] A. Afshin et al., "Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017," *The Lancet* 393, no. 10184 (2019), https://doi.org/https://doi.org/10.1016/S0140-6736(19)30041-8.
[63] P. J. Neumann et al., "A Systematic Review of Cost-Effectiveness Studies Reporting Cost-per-DALY Averted," *PLOS ONE* 11, no. 12 (2016), https://doi.org/10.1371/journal.pone.0168512. T. Arnesen and E. Nord, "The value of DALY life: problems with ethics and validity of disability adjusted life years," *BMJ (Clinical research ed.)* 319, no. 7222 (1999), https://doi.org/10.1136/bmj.319.7222.1423.

Other examples of modelling used in valuation relate to established valuation methods such as revealed preference valuation studies and benefit transfer[64]. Parametrised benefit transfer tries to associate, often through linear regression, the variation in monetary amounts from valuations at study sites to broad parameters such as population, population density, average income per capita, etc. By linking the monetary value to these parameters, the valuation can be transferred to new sites by substituting the appropriate parameters, e.g. population, income per capita, of the new site. For example, damage costs from studies across multiple EU countries might reveal relationships between the monetary amount and other variables which enable the damage cost estimate to be transferred to another country. The regression usually has very few study sites to inform it and missing variables can lead to large errors[65].

Consolidations of valuations in the scientific literature into databases relevant to food system impact costing exist, for example the Global Health Cost-Effectiveness Analysis (GHCEA) Registry, a repository of Cost-per-DALY-averted Studies (http://healtheconomics.tuftsmedicalcenter.org/ghcearegistry/), and the Ecosystem Services Valuation Database (ESVD) (https://www.es-partnership.org/services/data-knowledge-sharing/ecosystem-service-valuation-database/) [66].

Data and models are needed to calculate footprint (e.g. lifecycle inventory), other models and data calculate attribution (e.g. biophysical models that calculate dispersion of air pollution sources and their concentration in human habitats to determine dose, coupled with dose response models to determine disease) and then data and models for valuation are required (e.g. data on healthcare costs of respiratory diseases and estimates of reduced productivity). Different data and models are used at each step. Placing them together into an integrated model is an estimate of one or many impact pathways and represents the valuation of the food system actor's activities represented by the footprint change $\hat{f} - f$. That is, the integrated model is an estimate of the function $\hat{f} - f \mapsto V(\hat{f}) - V(f)$ from p. 60. All the case studies in Case Studies of Food System Impact Valuation represent integrated models that have assembled existing modelled estimates of footprints, capital changes and valuations. The assembling is mostly multiplying a footprint quantity by a valuation factor or shadow price, see p. 89 below on linear approximation.

Using different models and data can result in variation in valuations even though the valuation is conceptually of the same actor, with the same socio-economic drivers, the same activities, and the same impact pathway(s)[67]. The variation is observed in the case studies.

---

[64] I. Crawford and B. De Rock, "Empirical Revealed Preference," *Annual Review of Economics* 6, no. 1 (2014), https://doi.org/10.1146/annurev-economics-080213-041238; M. L. Plummer, "Assessing benefit transfer for the valuation of ecosystem services," *Frontiers in Ecology and the Environment* 7, no. 1 (2009), https://doi.org/10.1890/080091. K. J. Boyle et al., "The Benefit-Transfer Challenges," *Annual Review of Resource Economics* 2, no. 1 (2010), https://doi.org/10.1146/annurev.resource.012809.103933.

[65] S. Kaul et al., "What can we learn from benefit transfer errors? Evidence from 20 years of research on convergent validity," *Journal of Environmental Economics and Management* 66, no. 1 (2013), https://doi.org/10.1016/j.jeem.2013.03.001. R. Ready et al., "Benefit Transfer in Europe: How Reliable Are Transfers between Countries?," *The Official Journal of the European Association of Environmental and Resource Economists* 29, no. 1 (2004), https://doi.org/10.1023/B:EARE.0000035441.37039.8a. Kaul et al. (2013) indicates that parameterisation in terms of environmental quantity variables reduces errors compared to quality variables and that similarity of sites reduces errors.

[66] Neumann et al., "A Systematic Review of Cost-Effectiveness Studies Reporting Cost-per-DALY Averted." de Groot et al., "Global estimates of the value of ecosystems and their services in monetary units."

[67] M. Tremmel et al., "Economic Burden of Obesity: A Systematic Literature Review," *International journal of environmental research and public health* 14, no. 4 (2017), https://doi.org/10.3390/ijerph14040435. H. J. M. van Grinsven et al., "Costs and Benefits of Nitrogen

A first step toward consistency and comparability in valuations does not involve making all the models and data the same. The first step is structural consistency. That the, in practice, integrated models assembled by practitioners doing valuations for the same uses are:

i) working with the same footprints
ii) including the same components in the impact pathway (what aspects of capital changes should be considered, and what economic costs, so that one study does not include scarcity effects while another does, or one study does not include the cost of securing investment capital while another does not, or one study does not include health changes from increased consumption while another does not)
iii) specifying the welfare measure and recording the discount rate and parity used (next section).

Structural consistency promotes the ability to compare valuations and to perform comparative testing by substitution of different parity and discount settings.

In the environmental dimensions, LCI and LCIA represent a host of standardised footprint and impact pathway structures. The structural consistency enables handbooks of environmental prices such as the CE Delft EU28 Environmental Prices to be attached to the LCIA. This enables valuation to be added efficiently into LCA software such as SimaPro and GaBI (case studies 7 and 8). Uncertainty from using different data and models for footprint, capital changes and valuation of capital changes decreases if data and models have the same structural basis. As mentioned, the SEEA-EEA offers a blueprint for standardising the structure of food system footprints and impact pathways.

There are databases and registers that are promoting ontological integration of attribution and valuation. They act to increases structural consistency. SROI is an impact framework (Table 2 in Alignment of Impact Frameworks) based on indicators of outcomes (measures of capital changes) and impacts (valuations of value loss or gain). The Global Value Exchange (GVE) online database supported by Social Value UK is an example of an integrated repository where indicators of outcomes and valuations are ontologically connected and can be assembled for the purposes of impact valuation attributable to actors[68].

Welfare measure

In welfare economics the purpose of an economy is to maximise economic value from the utilisation of capital. Economic value has a long philosophical history[69] which identifies distinctions between

---

for Europe and Implications for Mitigation," *Environmental Science & Technology* 47, no. 8 (2013), https://doi.org/10.1021/es303804g.

[68] http://www.globalvaluexchange.org/news/b07bcb501c. A search in GVE on food lists 6 outcomes, 27 indicators of those outcomes and 127 valuations that have been ingested from literature or reports. As such the valuations are very specific to the study sites and participants. Links to the sources of the valuations enable a user to examine the structural considerations and assumptions behind a valuation, say of the cost of food loss and waste per kg. The consistency between food loss and waste valuations in the GVE can only be checked by reverting to the sources.

[69] p. 6: B. Sandelin, H.-M. Trautwein, and R. Wundrak, *A short history of economic thought*, 3rd ed. (London: Routledge, 2014); J. A. McGregor and N. Pouw, "Towards an economics of well-being," *Cambridge Journal of Economics* 41, no. 4 (2016), https://doi.org/10.1093/cje/bew044; R. K. Turner, I. Bateman, and D. W. Pearce, *Environmental economics : an elementary introduction* (New York-London: Harvester Wheatsheaf, 1994). S. Parks and J. Gowdy, "What have economists learned about valuing nature? A review essay," *Ecosystem Services* 3 (2013), https://doi.org/https://doi.org/10.1016/j.ecoser.2012.12.002. P. Dasgupta, *Human Well-Being and the Natural Environment* (Oxford: Oxford University Press, 2002).

Exchange value: the price of a good or service which can be sold and bought in markets

Use Value: the satisfaction or utility which obtained from the using goods or receiving services

Non-use value: value independent of use value.

Following the approach of the TEEBAgriFood Framework and the Natural and Human Capital Protocols we treat economic value as synonymous with social and human well-being and synonymous with welfare in a broad sense. Activities in the food system are mostly intended to produce goods and services for exchange, e.g. private food products for consumption. The activities also create natural, social or human capital changes in addition to produced capital changes. It is exchange, use and non-use value in the associated capital changes that aggregate to the additional and mostly external economic value loss or gain from the activities outside of market (exchange) values of the produced goods and services.

Despite its flaws as a measure of well-being[70], GDP as a measure of the conventional sense of welfare (the satisfaction of aggregated individual utilities by produced goods) can be sufficient to understand that market failures created by the food system can lead to a lower economic value than might otherwise be possible. That is, that internalisation can lead to higher economic value from reducing impacts of food systems[71]. Monetary estimates are never “exactly” economic value. The purpose of valuations is to inform and enable choices believed to increase economic value[72]. The social cost of carbon projects loss of GDP. The social cost of carbon could be higher if a greater range of use and non-use values were incorporated into IAMs. However, pricing risk in the current social cost of carbon (Figure 14) could lead to an implemented carbon price at over 2010$US 100, driving significant change.

A similar argument applies for health costs. Based on existing productivity monetary estimates or direct costs of public healthcare or health insurance without incorporating non-use values[73], an appropriate risk adjusted price would likely drive significant change. The changes driven by internalised costings of the overt material issues of the food system are likely to constitute the majority, or, at the lowest expectation provide a kickstart to, food system transformation. The more overt the magnitude of the externality due to food systems, the more likely they reflect in changes in conventional economic measures once factored.

Exercises that measure the utility of the outcomes of an economy (quality of life, life expectancy, equality, as well as consumption) as a measure of economic value show that GDP is only one factor. GDP is a primary factor; it is strongly correlated with outcomes-based measures of economic value[74]. However, among nations there are outliers. In practice this would mean that economic value loss or gain is being incurred and GDP is not sensitive enough to this gain or loss to inform optimal policy responses. One way to introduce a monetary indicator of economic value which is more sensitive to added factors of well-being

---

[70] P. Dasgupta, "Nature's role in sustaining economic development," *Philosophical Transactions of the Royal Society B* 365, no. 1537 (2010), https://doi.org/10.1098/rstb.2009.0231. J. E. Stiglitz, A. Sen, and J. P. Fitoussi, *The measurement of economic performance and social progress revisited. Reflections overview.*, Commission on the measurement of Economic Performance and Social Progress (Paris, 2009),
https://wedocs.unep.org/bitstream/handle/20.500.11822/19041/Report_by_the_Commission_on_the_Measurement_of.pdf?sequence=1.

[71] R. Tinch, "Debating Nature’s Value: The Role of Monetary Valuation," in *Debating Nature's Value: The Concept of 'Natural Capital'*, ed. V. Anderson (Cham: Springer International Publishing, 2018).

[72] Fenichel and Hashida, "Choices and the value of natural capital."

[73] Tremmel et al., "Economic Burden of Obesity: A Systematic Literature Review."

[74] C. Jones and P. Klenow, *Beyond GDP? Welfare across Countries and Time*, National Bureau of Economic Research (Cambridge, MA, 2010).

is to derive shadow prices of capital quantities based on production of income or GDP, then multiply those shadow prices directly by capital stocks. This is the approach to human capital used in the 2012, 2014 and 2018 UN Inclusive Wealth Report. Another way to inflate the sensitivity of GDP is to determine how much substitution of consumption is required to match the increased utility of leisure, life expectancy, and equality[75]. Using GDP increased by the equivalent consumption amount for non-financial production factors creates a more sensitive measure of economic value.

It is not entirely clear that the valuation methods commonly used, and the valuations of social costs from the case studies in Case Studies of Food System Impact Valuation are measures of change in societal economic value. Healthcare costs are monetary losses for society and individuals but in paying healthcare professionals there are benefits to society and other individuals. Some of the costs imposed by the food system are benefits to the health sector. The net change in economic value from reducing food system impacts is the social benefits of better health minus the social costs of less healthcare spending. This is less than just the benefits of better health alone. While well-being approaches should emphasise the greater value in having health over spending in the healthcare sector, it will still generally be an overestimate of the social cost to omit benefits of healthcare employment altogether. Over- and under-estimates from not accounting for subsequent economic changes are part of the additional uncertainty (error) in valuations. If subsequent economic changes are not included the social or abatement costs statement should have a clear statement on the inclusions or omissions, or the indication that other economic changes are assumed to balance out *ceteris paribus*.

Projecting potential GDP losses for large capital changes and scaling those monetary estimates back to smaller capital changes is another way to obtain monetary estimates more reflective of well-being. By projecting forward either in time, or hypothetically, to a situation here the well-being loss is creating manifest distortion in the economy the well-being factors are overt. Using this situation as the basis for a valuation, and then scaling back to a smaller amount of change likely results in different answers than basing the valuation on the current or historical situation where well-being factors are absent from exchange values due to relative abundance or being public goods. As an example, it is likely revealed individual preferences will give a low value to the planetary life-support services provided by local ecosystems when, presently and historically within the observed bubble of activity of those individuals, enough eco-system services exist to provide those services. If all individuals value the services independently as low, and concurrently destroy local ecosystems with the loss of the life-support services, the total loss of ecosystem services and consequential effects invalidate the original assumption of abundance and stationarity (the future being like the past). This “tragedy of the commons” argument reveals the initial undervaluation that comes from an individual considered only their own local actions and assuming all else being constant or equal. It is an unrealistic ask on individual preferences to project forward the value loss of capital changes with covariant global changes, or to know with certainty the market price in a market that does not yet exist but may in a future economy due to scarcity resultant from their actions[76].

More on values is relevant. Alignment of economic systems with value systems is outside the scope of this report though. To summarise, there are conceptual welfare measures beyond GDP, including projecting GDP under large capital changes, that have an extensive background of development and discussion in economics. The main practical criteria for

---

[75] Jones and Klenow, *Beyond GDP? Welfare across Countries and Time*.
[76] T. Prugh et al., *Natural capital and human economic survival* (Boca Raton: Lewis Publishers, 1999). See also, for example, 3.10.1.5 in Kolstad et al., "Social, Economic and Ethical Concepts and Methods." J. Loomis, "What's to know about hypothetical bias in stated preference valuation studies?," Article, *Journal of Economic Surveys* 25, no. 2 (2011), https://doi.org/10.1111/j.1467-6419.2010.00675.x.

monetary estimates are that they are indicative of changes to social and human well-being, and that they are sufficient to realise the positive change or abate the negative change if those estimates were embodied in internalisation mechanisms. In practice, for nearly all the valuations in the food system (and all case studies in Case Studies of Food System Impact Valuation) the welfare measure itself is unspecified and unclear. The use of first order approximation, described from p. 89 below, means all that is seen of the welfare measure is its part specification in partial derivatives with respect to various footprint quantities. Those partial derivatives are specified in shadow price estimates or valuation factors.

The ambiguity in what is welfare is pushed into the uncertainty in the marginal social costs or marginal abatement costs. As are the values represented by a welfare measure. This may appear to be passing the buck and trading one uncertainty for another. However, structural uncertainty in social or abatement cost, and measuring it, has precedents in the social cost and marginal abatement cost of carbon. Incorporating a risk price can conceptually also reflect the risk that monetary measures are underestimating social and human well-being losses.

Parity and discounting

Value and supply chains of the food sector are global[77]. Agricultural inputs such as phosphorous can be mined in first countries, fertiliser can be used in agricultural production in second countries, agricultural commodities can be processed into food products in third countries, to be sold and consumed in fourth countries, with financial, managerial and marketing services and financial flows accumulating in a fifth set of countries[78]. Footprints are created in this chain of production and consumption at each spatial location at each stage and with contextual distinction. The same volume of water extracted from a renewing catchment for phosphorus mining in North Carolina has different impacts than extraction from a non-renewing aquifer for wheat farming in Pakistan[79]. It would be an error to treat the total water footprint for the activity of food system actors aggregated across different countries and contexts as an economic quantity. The economic effects occur in what should be viewed as different economies. For example, the health effects of consumption and the economic consequences of improved human capital and shifting health expenditure occur in the consumption country. The health effects of production and the economic consequences of pesticide application or fertiliser leakage occur in the production country or other countries down-wind or downstream[80]. There are economies within national economies[81]. While cognisant of the importance in recognising subnational economic distinctions, our interest in this report is a practical disaggregation of footprint and impact that features major variances.

Parity is a method for comparing economic value across economies at the same point in time. Parity is used when aggregating the changes in economic value across the various economies

[77] P. Montalbano, S. Nenci, and L. Salvatici, *Trade, value chains and food security. Background paper prepared for The State of Agricultural Commodity Markets 2015–16*, Food and Agriculture Organization of the United Nations (Rome, 2015), http://www.fao.org/3/a-i5220e.pdf.

[78] A reconstruction of the Nutella® value chain is an example p. 17: K. De Backer and S. Miroudot, *Mapping Global Value Chains, OECD Trade Policy Papers, No. 159*, OECD Publishing (Paris, 2013)..J. Greenville, K. Kawasaki, and M.-A. Jouanjean, *Dynamic Changes and Effects of Agro-Food GVCS, OECD Food, Agriculture and Fisheries Papers, No. 119*, OECD Publishing (Paris, 2019).

[79] A. Rehman et al., "Economic perspectives of major field crops of Pakistan: An empirical study," *Pacific Science Review B: Humanities and Social Sciences* 1, no. 3 (2015), https://doi.org/https://doi.org/10.1016/j.psrb.2016.09.002.

[80] Fantke and Jolliet, "Life cycle human health impacts of 875 pesticides." J. Liu et al., "Reducing human nitrogen use for food production," *Scientific Reports* 6, no. 1 (2016), https://doi.org/10.1038/srep30104.

[81] D. Acemoglu and M. Dell, "Productivity Differences between and within Countries," *American Economic Journal: Macroeconomics* 2, no. 1 (2010), https://doi.org/10.1257/mac.2.1.169.

so that the net impact of the activities associated to a food product, or a food company, or a food industry, can be valued.

There are exchanges of economic value attached to the market transactions and physical exchanges in the global value chains of the food sector. When accounting for non-financial capital changes the term “value-add” gains a wider meaning. There are implicit substitutions of economic value from capital changes associated to the chain of exchanges, some of which will be inequitable under standard measures such as exchange rates.

For financial capital flows along these chains currency exchange rates are used. If a monetary amount is used for a straight exchange of financial capital in one county for another (e.g. one stock holding for another), then currency exchange rates are appropriate. Arguments for using currency exchange rates rely on the “the law of one price”. The law of one price is an economic maxim that arbitrage results in very small deviation of most produced capital goods because of low transaction and transportation costs. It is debated whether the law of one price applies to food and agricultural products[82].

Most valuations in case studies 1-9 use purchasing power parity (PPP), which is the rate at which the currency of one country would have to be converted into that of another country to buy the goods and services in each country offering the same amount of satisfaction of basic needs. PPP acknowledges the value in use represented in value of exchange produced goods. It is based on bundles of good and services set and tracked by the World Bank International Comparison Program[83]. PPP is used to rescale GDP as a welfare measure based on consumption of produced goods.

The consumptive indices that underpin PPP are based on market price. The value of these exchanges of produced capital are centralised to market prices through frequent transactions. Imperfect information and the production of externalities create the situation where market prices do not reflect the economic value in non-financial capital changes being implicitly exchanged in produced and financial capital exchanges. Whether the economic value of natural and produced capital changes are substitutable has been an ongoing debate between ‘weak’ and ‘strong’ sustainability in sustainable development and ecological economics[84].

Exchange of value in human health is one impact for which it is contentious to use PPP. Declarations such as the Sustainable Development Goals (SDGs) indicate universal values for certain aspects of human and social capital irrespective of the economy in which the individuals are based[85]. Global parity for human capital impacts converts monetary values of economic loss to individuals to global PPP GDP per capita; that is, utilitarianism[86]. Global parity is used in Stern’s valuation of the social cost of carbon[87] and in case study 3 below.

Prioritarianism, meaning benefits to individuals are higher in value the worse off in human development individuals are, is another philosophy of equality than can be applied to parity

[82] D. Miljkovic, "The Law of One Price in International Trade: A Critical Review," *Review of Agricultural Economics* 21, no. 1 (1999), https://doi.org/10.2307/1349976.
[83] https://www.worldbank.org/en/programs/icp M. Silver, *IMF Applications of Purchasing Power Parity Estimates*, International Monetary Fund (Washington DC, 2010).
[84] S. Dietz and E. Neumayer, "Weak and strong sustainability in the SEEA: Concepts and measurement," *Ecological Economics* 61, no. 4 (2007), https://doi.org/https://doi.org/10.1016/j.ecolecon.2006.09.007; J. Pelenc and J. Ballet, "Strong sustainability, critical natural capital and the capability approach," *Ecological Economics* 112 (2015), https://doi.org/10.1016/j.ecolecon.2015.02.006.
[85] https://unstats.un.org/sdgs/report/2018/overview/
[86] https://plato.stanford.edu/entries/equality/#Uti
[87] C. Kenny, "A Note on the Ethical Implications of the Stern Review on the Economics of Climate Change," *The Journal of Environment & Development* 16, no. 4 (2007), https://doi.org/10.1177/1070496507308576.

and discounting of economic value[88]. The IPCC indicates using alternative scaling factors for different countries to consider disproportionate economic costs from climate change, as have other studies on the social cost of carbon[89].

The method of benefit transfer is a parity calculation; it estimates the economic value change in a different economy based upon economic value change in another.

The case studies in Case Studies of Food System Impact Valuation demonstrate a range of parity choices used within first- and third-party valuation factors.

Parity choice is a mixture of technical and ethical considerations. Technical, in terms of tracking the implicit exchange of capital changes occurring in exchanges of produced capital (financial capital to financial capital, natural capital to financial capital) and calculation, e.g. the consumptive indices needed for PPP. Ethical choices concern equality and ambiguity on substitution of economic value in exchange value, e.g. weak and strong sustainability.

Discounting is a means to compare economies separated in time. Economic values from the past and present are usually converted into present value for comparison with economic value now[90]. Discounting has two components. The first reflects that economies in the future are richer in the sense that one dollar of money spent on consumption at a future time provides more satisfaction. This first factor combines several aspects: efficiency, consumption as a measure of welfare, and an assumption of what society and individuals in the future value[91]. Forward projections of how much can be consumed at a future time for the same cost are based on GDP. GDP has an observed real growth rate (projecting forward historical trends that allocative and production efficiencies such as technical advances, etc. result in the same amount of goods and services in real terms costs less in the future) between 1-2%. This is generally uncontested in estimates of social carbon[92]. The assumption about what future generations value is generally phrased as marginal utility, which relates to the fact that, say a 2% decrease in the cost of the same goods and services results in more than a 2% increase in satisfaction. The increase in marginal utility usually multiplies the GDP growth projection by a factor of 1-3, resulting in an estimate that economies of the future have an overall increase in welfare (based on utility of consumption) of 1-6% per year – a mean of 3.5%. In the United Kingdom, HM Treasury fixes the social discount rate for the public sector at 3.5% with recommended adjustments for intergenerational effects[93]. Interest rate returns on private investments average 7-10% per year (so the present person would be more than 1-6% per year richer by investing without considering tax); the higher figure has been ascribed to risk bearing[94].

---

88 D. Parfit, *Equality or priority?*, Lindley lecture, (Lawrence, Kan.: Dept. of Philosophy, University of Kansas, 1995).

89 Adler et al., "Priority for the worse-off and the social cost of carbon." Kolstad et al., "Social, Economic and Ethical Concepts and Methods."

90 J. Roche, "Intergenerational equity and social discount rates: what have we learned over recent decades?," *International Journal of Social Economics* 43, no. 12 (2016), https://doi.org/10.1108/IJSE-07-2015-0193. K. J. Arrow et al., "Should Governments Use a Declining Discount Rate in Project Analysis?," *Review of Environmental Economics and Policy* 8, no. 2 (2014), https://doi.org/10.1093/reep/reu008.

91 Dasgupta, "The Stern Review's economics of climate change."

92 Table 3.2: Kolstad et al., "Social, Economic and Ethical Concepts and Methods."

93 M. A. Moore et al., ""Just Give Me a Number!" Practical Values for the Social Discount Rate," *Journal of Policy Analysis and Management* 23, no. 4 (2004), https://doi.org/10.1002/pam.20047; J. Lowe, *Intergenerational wealth transfers and social discounting: Supplementary Green Book guidance*, HM Treasury (London, 2008).

94 Moore et al., ""Just Give Me a Number!" Practical Values for the Social Discount Rate."; P. A. Grout, "Public and private sector discount rates in public–private partnerships," *Economic Journal* 113, no. 486

The second component of discounting is called time preference. This is not an assumed increase of value in the future. It reflects that there is a utility loss to present economies compared to future ones from not utilising a present resource. The time preference rate has various interpretations and ethical interpretations[95]. They range from setting time preference to zero so that no generation is given preference to the others to using mortality rates and consumer preference studies to quantify impatience for satisfaction. Assumptions about intergenerational welfare create variability in the application of the two components[96]. Stern's valuation of the social cost of carbon assumes a very small time preference compared to earlier studies, resulting in a higher amount for the SCC[97].

As noted in Alignment of Impact Frameworks, discounting can provide finite value of changes in economic value for comparison of full impact from footprints incurred now. Discount rates kills more certain, time limited and smaller scale economic impacts in the future[98]. Relating to intergenerational wealth, discount rates are a key aspect of sustainable development[99].

Like the effects of carbon, the scale and nature of impacts from food systems have the potential to dampen the growth of economic value. While produced capital may grow and be reflected in GDP growth as a welfare measure in forward projections, this does not imply an optimal path for economic value[100]. Social costs of obesity and poverty attributable to the food system have not yet been calculated to the same degree as the social cost of carbon to examine these dampening and non-optimal effects over time (footnote 46). Like the last section, economic value needs to be measured over time with benefits and costs flowing between sectors. An economy with the social costs incurred, and the economy with potential costs from shifting production to reduce footprint but with social costs averted.

There are methods for converging full impacts not based on discounting or variants. Priority parity over time converged the comparative difference in full impact between economies in a social cost of carbon study[101]. Lifecycle impact assessment (LCIA) is used as a basis for the CE Delft EU28 environmental prices handbook. Based on the ReCiPe model, it applies one of three perspectives to environmental damage to determine certain inclusions for damage costs and the time span to account for undiscounted impacts[102]. The individualist perspective uses only established cause-effect relationships for damage calculations and a time span for impacts of 20 years. The hierarchist perspective uses facts backed up by scientific and political bodies and a time span of 100 years. The egalitarian perspective is based on the precautionary principle and a very long-term perspective. In the CE Delft EU28 environmental prices handbook the individualistic perspective is mostly used. For some prices lower values are based on the individualistic perspective and higher values on the hierarchist perspective. The perspectives from the ReCiPe model relate not only to time factors, but to variation in social costs according to inclusion of damages in impact pathways.

(2003), https://doi.org/10.1111/1468-0297.00109. Part IV: C. Gollier, *Pricing the planet's future : the economics of discounting in an uncertain world*, University Press Scholarship Online, (Princeton: Princeton University Press, 2017).

95 Roche, "Intergenerational equity and social discount rates: what have we learned over recent decades?."

96 Dasgupta, "The Stern Review's economics of climate change." Kolstad et al., "Social, Economic and Ethical Concepts and Methods."

97 Stern, *The economics of climate change: the Stern review*.

98 Pindyck, "The social cost of carbon revisited."

99 Arrow et al., "Sustainability and the measurement of wealth."

100 Dasgupta, "Nature's role in sustaining economic development."

101 Adler et al., "Priority for the worse-off and the social cost of carbon."

102 p. 136: de Bruyn et al., *Environmental Prices Handbook EU28 Version*.

For social discount rates, mostly the specification is exogeneous in assumptions about GDP growth. It has been noted that integrated models of climate change should update GDP growth endogenously in an evolving economic model with climate effects[103].

Part of the ambiguity in discount rates relates to ethical choices[104]. An ambiguity which is not easy to resolve. However, there are key implications for uncertainty in the discount rate coming just from uncertainty in the GDP growth rate due to probabilities of catastrophic damage to GDP. Weitzman argues that a low overall discount rate in the order of 1-2%, such as that taken by Stern in the Stern review, can be justified by risk aversion in stochastic GDP growth rates[105]. Weitzman and Gollier also showed that discount rates should decline in the presence of uncertainty for longer time frames of lock-in impact[106].

Parity and discounting are not generally separable. Simple forms are, e.g. a global discount rate to convert to present value combined with an application of PPP GDP to convert to international dollars. The implication of this simple treatment is that the PPP GDP structure of the present is projected forward statically into the future. Applying different discount rates to countries with the assumption of static parity is difficult to distinguish from applying a global discount rate with dynamic changes in parity. They are not equivalent in practice[107]. Substitution of capital is not a static consideration either. Weak sustainability has temporal aspects. It assumes that the substitution of natural for produced capital is temporary and development leads to efficient economies decoupled from resources. Uncertainty in actions over time and which natural capital changes are irreversible or recover are part of the uncertainty associated to a substitution[108].

Discounting is one of the most sensitive parameters for the social cost of carbon. Discounting introduces order of magnitude changes. Parity also introduces order of magnitude changes[109]. Parity choices make a significant difference to climate costing. How sensitive food impact costing is to assumptions of parity and discounting, and uncertainty, depends on further studies. Obesity has potential generational effects and spatially heterogenous contextual factors for impact, though the potential for catastrophic tipping points like that of the climate system is less clear. Like the RCP and SSP specifications in climate science, suitable reference scenarios with explicit reference to parity and discounting could guide quantification for food impact costing.

---

103 S. Dietz and N. Stern, "Endogenous Growth, Convexity of Damage and Climate Risk: How Nordhaus' Framework Supports Deep Cuts in Carbon Emissions," *The Economic Journal* 125, no. 583 (2015), https://doi.org/10.1111/ecoj.12188.

104 Dasgupta, "The Stern Review's economics of climate change."

105 M. Weitzman, "Risk-adjusted gamma discounting," *Journal of Environmental Economics and Management* 60, no. 1 (2010), https://doi.org/10.1016/j.jeem.2010.03.002. p. 192 Gollier, *Pricing the planet's future : the economics of discounting in an uncertain world*. C. Gollier, "On the Underestimation of the Precautionary Effect in Discounting," *The Geneva Risk and Insurance Review* 36, no. 2 (2011), https://doi.org/10.1057/grir.2011.6.

106 C. Gollier and M. L. Weitzman, "How should the distant future be discounted when discount rates are uncertain?," *Economics Letters* 107, no. 3 (2010), https://doi.org/10.1016/j.econlet.2010.03.001.. A recommendation also in Moore et al., ""Just Give Me a Number!" Practical Values for the Social Discount Rate."

107 Figure 4: Adler et al., "Priority for the worse-off and the social cost of carbon."

108 F. Figge, "Capital Substitutability and Weak Sustainability Revisited: The Conditions for Capital Substitution in the Presence of Risk," *Environmental Values* 14, no. 2 (2005), https://doi.org/10.3197/0963271054084966. Gollier, "Valuation of natural capital under uncertain substitutability."

109 Figure 3: Adler et al., "Priority for the worse-off and the social cost of carbon."

Footprint and impact

A short survey of existing calculation methods including those described last section is tabulated from in Inventory and Development of Methods. The components in Figure 17 in practice are illustrated in nine case studies in Case Studies of Food System Impact Valuation.

In the next few sections, we reinforce some of the distinctions and choices in valuation.

At the risk of being obvious, footprints and impact are not direct proxies to each other. The stark difference is highlighted in the steps and examples of calculations required to relate footprint and impact discussed last section.

Carbon creates a ruse where footprint and impact seem to be interchangeable by multiplying by the marginal valuation - a single number. Marginal valuation, or shadow price, is the estimate of the full lifetime economic value loss or gain attributable to an additional unit of footprint. The social cost and marginal abatement costs of carbon are marginal valuations. By multiplying or dividing by this number it appears that footprint (t CO2-eq emitted) and impact (cost to society) become interchangeable. It should be remembered though that footprint is a quantity and impact is a value. The same quantity can change in value over time and due to context. Currently more carbon is bad because we have too much in the context of current and projected CO2-eq levels in the atmosphere. In terms of net value to society carbon used to be good because of the production and material improvements it enabled. The balance between the value carbon emissions enable (the cost in shifting production and material improvements – abatement costs) and the present and future value loss in context (social cost) is what economics attempts to determine (Figure 16).

Because of the global effect of carbon, one tonne emitted anywhere in the world contributes to radiative forcing everywhere. Local differences in the consequence of increased radiative forcing are not attributed to local emissions. Where a tonne CO2-eq was emitted makes no difference to its impact. The context of a carbon footprint is also treated globally. The conditions (the atmosphere and its present carbon content) are global and an actor's contribution goes into a pool of 52 Gt CO2-eq emitted annually[110] which is traced to impact. There is no contextual distinction except for scaling through global warming potential of different GHG gases to convert them to CO2-eq. That is, there is no distinction in impact in current carbon costing whether the t CO2-eq emitted it is from burnt coal for electricity, burnt fuel for transport, calcium carbonate decomposition in manufacturing cement, or methane belching ruminants.

The situation for carbon that makes footprint and impact readily interchangeable is not repeated for the quantities associated to other major food system impacts[111]. There are large variations in impacts according to where emissions, pollutants, water extraction, ha of land-

[110] p. 9 IPCC, *IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems*.

[111] H. Neufeldt et al., "Beyond climate-smart agriculture: toward safe operating spaces for global food systems," *Agric Food Secur* 2 (2013), https://doi.org/10.1186/2048-7010-2-12. R. Neff, *Introduction to the US Food System: Public Health, Environment, and Equity* (Wiley, 2014). C. Abhishek, G. David, and M. Alexander, "Multi-indicator sustainability assessment of global food systems," *Nature Communications* 9, no. 1 (2018), https://doi.org/10.1038/s41467-018-03308-7. P. Prosperi et al., "Towards metrics of sustainable food systems: a review of the resilience and vulnerability literature," *Environment Systems and Decisions* 36, no. 1 (2016), https://doi.org/10.1007/s10669-016-9584-7; IPES-Food, Unravelling the food-health nexus: addressing practices, political economy, and power relations to build healthier food systems, 2017, Global Alliance For The Future of Food and IPES-Food. O. de Schutter et al., *Advancing Health and Well-Being in Food Systems*, Global Alliance for the Future of Food (Toronto, 2015). M. Zurek et al., "Assessing Sustainable Food and Nutrition Security of the EU Food System—An Integrated Approach," *Sustainability* 10, no. 11 (2018), https://doi.org/10.3390/su10114271.

use change, etc. occur. This has been highlighted for natural capital and agricultural supply chains generally[112], for valuation of changes in ecosystem services[113], reactive nitrogen[114]; water use[115], land use[116], and regularly mentioned in studies of environmental valuation[117].

The last section mentioned the difference in impact from extracting the same volume of water from a renewing catchment for phosphorus mining in North Carolina compared to a non-renewing aquifer for wheat farming in Pakistan. Changes to renewable and non-renewable capital stocks provide one clear contextual difference for valuations of capital changes.

To highlight water, the Water Footprint Manual views it as inappropriate to assign a single marginal value to the total water footprint of a company or product[118]. Water footprint and impacts are not readily interchangeable. Water extraction in one location is not going to have a global effect. Economies downstream from extraction or pollution will be affected. Water extraction by the food system globally - 70% of all freshwater extraction is for agriculture - has a global effect which is highly varied[119].

For food impact, a substitute for the simple formula between carbon footprint and impact of multiplying by the marginal valuation - a single number – is multiplication of a matrix of marginal valuations against a vector of spatial and contextual footprints (this is described from p. 99).

[112] E. T. Addicott and E. P. Fenichel, "Spatial aggregation and the value of natural capital," *Journal of Environmental Economics and Management* 95 (2019), https://doi.org/https://doi.org/10.1016/j.jeem.2019.03.001. Section 3: B. Notarnicola et al., "The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges," *Journal of Cleaner Production* 140 (2017), https://doi.org/10.1016/j.jclepro.2016.06.071.

[113] Section 5.5: de Groot et al., "Global estimates of the value of ecosystems and their services in monetary units." C.-K. Rebecca et al., "Life cycle assessment needs predictive spatial modelling for biodiversity and ecosystem services," *Nature Communications* 8 (2017), https://doi.org/10.1038/ncomms15065. S. Schmidt, A. M. Manceur, and R. Seppelt, "Uncertainty of Monetary Valued Ecosystem Services – Value Transfer Functions for Global Mapping," *PLOS ONE* 11, no. 3 (2016), https://doi.org/10.1371/journal.pone.0148524.

[114] D. J. Sobota et al., "Cost of reactive nitrogen release from human activities to the environment in the United States," *Environmental Research Letters* 10, no. 2 (2015), https://doi.org/10.1088/1748-9326/10/2/025006. A. Leip et al., "Nitrogen-neutrality: a step towards sustainability," *Environmental Research Letters* 9, no. 11 (2014), https://doi.org/10.1088/1748-9326/9/11/115001.

[115] D. Pimentel et al., "Water Resources: Agricultural and Environmental Issues," *BioScience* 54, no. 10 (2004), https://doi.org/10.1641/0006-3568(2004)054[0909:WRAAEI]2.0.CO;2. B. L. Keeler et al., "Linking water quality and well-being for improved assessment and valuation of ecosystem services," *Proceedings of the National Academy of Sciences* 109, no. 45 (2012), https://doi.org/10.1073/pnas.1215991109.

[116] Vidal Legaz et al., "Soil quality, properties, and functions in life cycle assessment: an evaluation of models."

[117] p. 31: COWI, *Assessment of potentials and limitations in valuation of externalities*, The Danish Environmental Protection Agency (Copenhagen, 2014). FAO, *Food wastage footprint: full-cost accounting*.

[118] Appendix VI: Hoekstra et al., *The Water Footprint Assessment Manual: Setting the Global Standard*.. P. Reig et al., *Volumetric Water Benefit Accounting (VWBA): A Method for Implementing and Valuing Water Stewardship Activities. Working paper*, World Resources Institute (Washington DC, 2019), https://wriorg.s3.amazonaws.com/s3fs-public/volumetric-water-benefit-accounting.pdf.

[119] Pimentel et al., "Water Resources: Agricultural and Environmental Issues."

A spatial and contextual footprint means the units of emissions, pollutants, water extraction, ha etc. within a specific geographic boundary incurred by a specific method of extraction, production, delivery, consumption, etc. The spatial and contextual distinctions which make a significant difference in accounting for the major external costs of food systems are what matter[120]. What a complete list of these divisions we leave for the development of food footprint protocols and food system non-financial accounting standards. This section is concerned with the evidence that the distinctions do matter and what level of resolution in spatial and

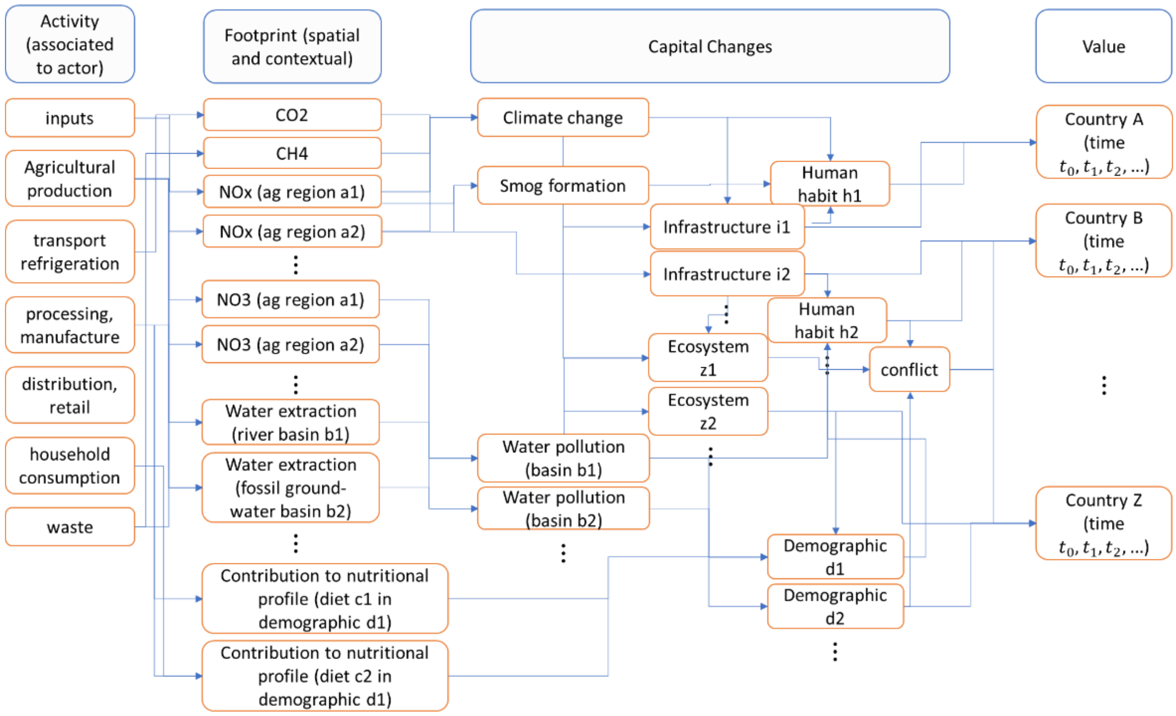

Figure 18: Outside of carbon costing, food impact costing will depend on where and in what context the footprints occur, where when and in what context the capital changes occur, where and when economic value changes occur. We are interested in impact calculation of the activities of food system actors, which means we trace their activity (from the left-hand side) to a footprint and then to impact to society. Valuation of the dependencies of the food actors would start with the actor on the right-hand side (at their value gain and loss) and the costs they occur from capital changes, and then trace that back to whose activities. Conceptually the scope on the left- and right-hand side can be targeted: the impact of actor A on actor B (equivalently the dependencies of actor B on actor A). (Source: adapted from Figure 9 de Bruyn et al., *Environmental Prices Handbook EU28 Version*)

contextual divisions is possible and practical for comparable valuations to inform food system transformation. If the resolution is too coarse the error bars in estimates will be too large and not trusted. Also, users will not be able to highlight the differences in impact from their distinct production practices. Too fine a resolution then energy and time are wasted on perturbations to valuation numbers that will not make much different to global scale transformation.

When considering the difference between impact and footprint the report advocates distinguishing footprints spatially and contextually into “sources of impact now” and impact

[120] p. 31: COWI, *Assessment of potentials and limitations in valuation of externalities*., S. J. Vermeulen et al., "Addressing uncertainty in adaptation planning for agriculture," *Proceedings of the National Academy of Sciences* 110, no. 21 (2013), https://doi.org/10.1073/pnas.1219441110.

occurring in economies distinguished in space and time "receivers of impact now and in the future". This is a standard view at least in environmental valuation (Figure 18)[121].

For distinguishing impact in space and time the economic effects occur in what should be viewed as different economies. For example, the health effects of consumption and economic consequences of improved human capital and shifting health expenditure occur in the consumption country. The health effects of production and the economic consequences of pesticide application or fertiliser leakage occur in the production country or other countries down-wind or downstream.

As the social costs vary in terms of the origin and context of the footprint, and the economy and time period in which the impacts occur, food impact costing involves many shadow prices (described from p. 99). The social cost of carbon avoids this because of the indistinguishable effects of the origin of emission and its global impact. Other shadow prices, for example for water, nutrient pollution, and malnutrition, are very dependent on context. The social cost(s) of obesity, like carbon, have intergenerational components. Unlike carbon which has a clear footprint unit (t CO2-eq emitted) additional research will be required to determine appropriate footprint and impact pathways with spatial and contextual distinctions for health impacts. A food system non-financial capital accounting standard would guide what to measure and disclose in terms of other footprints, guide transacting the contributions to value and impact along the food and agriculture sector's complex value chains and provide a standard set of quantities on which to base shadow prices.

So far, the picture has been where footprint occurs and where damage occurs, i.e. social costing. What about abatement costing?

There are no standardised food system footprints equivalent to carbon footprints yet and few disclosure and offset opportunities equivalent to carbon disclosure or carbon offset. Offset allows equalisation of price – converting carbon emission rights into a global commodity, whoever can abate emissions at the lowest price – and the realisation of a global abatement curve. Carbon is estimated to produce less than one-third of global food system social costs[122]. Abatement of food system impacts is not mostly of carbon with the other footprints requiring negligible consideration. Offset needs to occur in the same catchment for water extraction and water pollution[123]. This requires local abatement measures or local offset markets. So spatial and temporal distinction in impacts have consequences for both social and abatement costing.

What geographic scope exists already that may be suitable and practical for shadow prices to inform food system transformation?

The System of Extended Economic Accounting – Agriculture, Forestry and Fisheries (SEEA-AFF) includes national accounting of carbon footprint, water footprint, pollutants, and food loss. This footprint accounting is too coarse for impact valuation or impact offset. The data going into calculation of the national accounts is of more interest. The footprints accounted for in the SEEA-AFF include a common list of environmental physical accounting (see case studies): flow account for water extraction; flow account for water distribution and use; flow account for energy use and GHG emissions; flow account for nitrogen and phosphorous, and pesticide use. In terms of contextual scope for land use, SEEA-AFF considers land areas used

---

[121] de Bruyn et al., *Environmental Prices Handbook EU28 Version*. M. Pizzol et al., "Monetary valuation in Life Cycle Assessment: a review," *Journal of Cleaner Production* 86 (2015), https://doi.org/10.1016/j.jclepro.2014.08.007.

[122] FOLU, *Growing Better: Ten Critical Transitions to Transform Food and Land Use, The Global Consultation Report of the Food and Land Use Coalition.*, Food and Land Use Coalition (New York, 2019), https://www.foodandlandusecoalition.org/global-report/.

[123] Appendix VI: Hoekstra et al., *The Water Footprint Assessment Manual: Setting the Global Standard*..

for agriculture, forestry, aquaculture, and maintenance and restoration of environmental functions.

The System of Extended Economic Accounting – Experimental Ecosystem Accounting (SEEA-EEA) recognises that capital changes do not accord with national boundaries. The SEEA-EEA is spatially specific to ecosystem[124]. The physical accounting and consideration of valuations in the SEEA-EEA are more akin to considerations for a food system non-financial accounting standard.

Though not formalised into an accounting standard, a tremendous amount of consideration and modelling exists for capital changes associated to food system activities. Spatial and contextual boundaries for footprints do not need to be considered from scratch. Nor the understanding how the footprints align to capital changes, and capital changes to subsequent capital changes, along the chain of outputs and outcomes. The integrated assessments models (IAMs) used to determine the social cost of carbon are attached to existing climate models. The IAMs connect economic modelling, in some cases just direct economic valuations from previous literature, to the climate modelling. The same approach – a process of attaching economic modelling or collating agreed economic valuations from literature to food system modelling - is a feasible start for food impact costing.

We provide an example of the type of resolution in food system models.

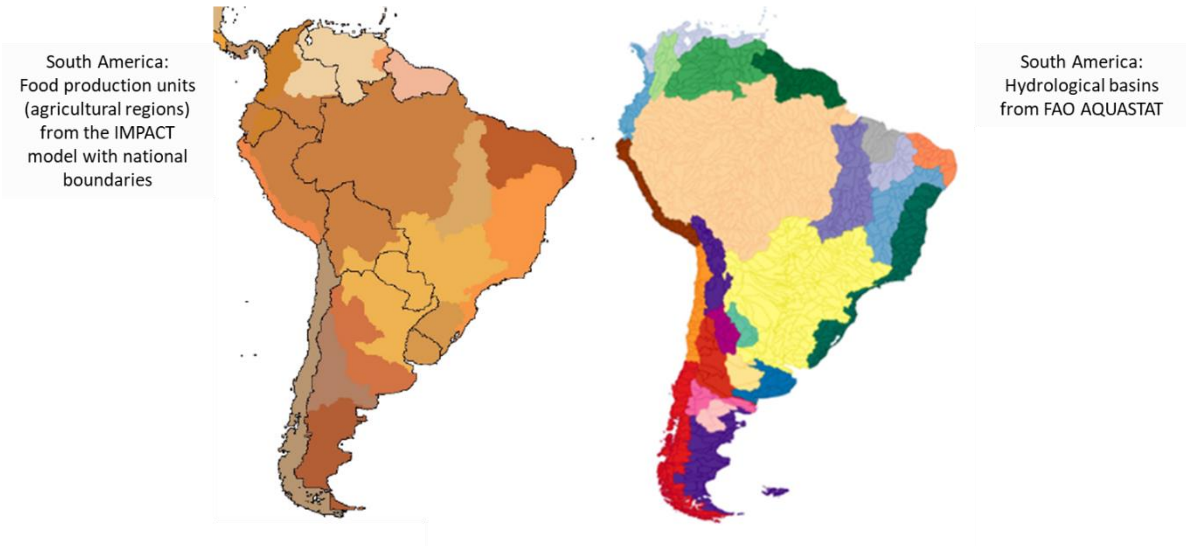

Figure 19: IMPACT food production units in South America compared with national boundaries and hydrological basins (Sources: Robinson et al., *The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model description for version 3* and FAO Geonetwork http://www.fao.org/geonetwork/srv/en/metadata.show?id=37174)

We mentioned previously that the IMPACT model divides the land surface of the globe into 320 units of food production with 36 crop and 6 livestock production categories which overlap a similar division of associated water basins[125]. The food production units and water basins have some coincidence, but not entirely (Figure 19). Neither coincide with national boundaries.

The 36 crop and 6 livestock production categories are likely not enough contextual resolution. Production context such wholly grass-fed livestock meat versus intensively finished livestock meat may be relevant to impact valuation although the distinction between these contexts is

[124] UN et al., *System of environmental-economic accounting 2012 : experimental ecosystem accounting*, United Nations Organization (New York, 2014).
[125] Robinson et al., *The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model description for version 3*.

highly debated for CO2-eq emissions[126]. Polarisation in what distinctions matter, and how much they matter in the end in terms of impact costings, is one of the contributing reasons for a societal process for a footprint protocol and shadow prices as recommended in this report.

As mentioned in the section on parity, spatial and temporal disaggregation of changes in economic value at the national level are crude approximations of the effects caused by capital changes. The existence of economic data at national levels make it a pragmatic choice of resolution. Shadow prices disintegrated into national and temporal value changes with respect to spatial and contextual footprint quantities overall provide a sufficient resolution for initial measures of equity and substitution as discussed in Implications.

Measurement of the differences in capital changes of spatial and contextual footprints at a finer resolution than broad commodities and agricultural regions, water catchments, populations distinguished by diet, age, sex, exercise level, etc. exist in a vast collection of site or context specific literature studies, models and some lifecycle analysis databases. Costing at this resolution is currently infeasible. This literature is the basis for informing costing at a broader resolution. Similarly, a patchwork of very specific valuations exists in a vast collection of site or context specific literature across many disciplines. The most cited studies for valuations are those that attempt to collate the studies. Matching the two ends, footprints working forward from the left side in Figure 18 and valuations working back from the right side in Figure 18, is a large task for comparable impact valuation of food products and companies that have footprints across the globe. It requires an ongoing process appropriate to the scale of use of social or abatement costing.

A spectrum of models and data to inform shadow pricing is discussed in Inventory and Development of Methods. The argument is made there that the resolution described in the paragraphs above is currently optimal between a practical ability to assign credible shadow prices and simplifications like global valuation factors. The optimum will shift over time. Heterogeneity of capital changes in food products – exactly who has eaten them, which factory in which social conditions has produced them, and on which farm were the commodities grown, is outside the scope of this report. It is an aspiration for technology to track and account the footprints and capital changes at this level of resolution. The resolution suggested is broader to make possible and practical comparable valuations. The present priority is to obtain impact costings that measure useful gross differences in value change due to companies, practices, and products. For use in initial policy or market corrections that make major steps to food system transformation.

Scenarios

Last section discussed the variation that the same quantity of footprint, incurred in a different spatial location or context, can have on a shadow price.

As discussed under models and data to determine capital changes, and under carbon costing, the complex models used to determine capital changes do not depend only on the footprint of the actor. It is a function of the present and future levels of societal footprint and other socio-economic drivers and determinants of value. The degree of dependency of the shadow price on these factors will depend on the footprint; short-lived impacts are less dependent on future paths. However, the atmosphere and many terrestrial systems, including soil, can take long

[126] P. L. Stanley et al., "Impacts of soil carbon sequestration on life cycle greenhouse gas emissions in Midwestern USA beef finishing systems," *Agricultural Systems* 162 (2018), https://doi.org/10.1016/j.agsy.2018.02.003; T. Garnett et al., *Grazed and confused? : Ruminating on cattle, grazing systems, methane, nitrous oxide, the soil carbon sequestration question - and what it all means for greenhouse gas emissions*, Food Climate Research Network (London, 2017), https://www.fcrn.org.uk/sites/default/files/project-files/fcrn_gnc_report.pdf.

periods of time to equilibrate with introduced pollution changes. The same applies of human systems and health damage. We have referenced several potential intergenerational features of food system impact. More research is required to determine the potential contribution of lock-in effects to food impact costing outside of carbon.

The ideal integrated models of capital changes would endogenously include temporal effects in the calculation of full impacts. Meaning that the model would include the feedbacks from climate damage on the economy as well as production factors such as technology. That damage would adjust the level of emissions, which in turn calculates the climate damage in a dynamic progression. The integrated assessments models (IAMs) used to determine the social cost of carbon connect economic modelling to the climate modelling, but they do not include feedback changes in emissions trajectories. Emissions trajectories, and what is happening to economic growth outside climate damage, is specified exogenously. It is set in each time step externally to the IAM.

Whatever complex of models are used, to assess capital changes from spatial and contextual footprints incurred by food systems will require exogenously set variables. The relevant questions are which variables? What is the degree of lock-in effect from incurred spatial and contextual footprints? What other assumptions are relevant to estimating gross differences in value change due to companies, practices and products for fiscal policy or market corrections that make major steps to food system transformation?

Climate science standardised scenarios to be used in the estimation of climate impacts. Societal emissions now and into the future (RCPs) and the socio-economic drivers into the future which might coincide with those RCPs (called SSPs). Food systems science has developed scenario methods and scenario sets. They are designed to examine different combinations of the variables that will make major differences to food system outputs in the future[127]. The scenarios are not standardised to the degree of RCPs and SSPs. Food system outputs are not all the major societal sources of CO2-eq, air pollutants, water pollutants, factors in human health risks from food consumption, and changes in socio-economic states (in some spatial locations and contexts they will be dominant however). However, it is likely that aspects of scenarios that are used to determine changes in the food system will overlap with the aspects that would cause large difference to future impacts caused by the food system now.

Scenarios are not only relevant for social costs. Abatement costings represent potential abatement provided by products and practices if they were taken up at a specified scale. How much abatement the products and practice provide, what is their price in the market, and whether the scale assumed is realised through either demand or government intervention is highly uncertain. Specification of these possibilities all depend on the kind of exogenous parameters found in food system future scenario sets. Uncertainty in demand, in relation to

[127] M. Reilly and D. Willenbockel, "Managing uncertainty: a review of food system scenario analysis and modelling," *Philosophical transactions of the Royal Society of London. Series B, Biological sciences* 365, no. 1554 (2010), https://doi.org/10.1098/rstb.2010.0141; J. R. Beddington, *The future of food and farming : challenges and choices for global sustainability ; [final project report of the UK Government Foresight Global Food and Farming Futures]* (London, UK: The Government Office for Science, 2011). WRAP, *Food futures: from business as usual to business unusual*, The Waste and Resources Action Programme (Banbury, 2016). H. C. J. Godfray et al., "The future of the global food system," *Philosophical Transactions of the Royal Society of London B: Biological Sciences* 365, no. 1554 (2010), https://doi.org/10.1098/rstb.2010.0180. WEF and Deloitte Consulting, *Shaping the Future of Global Food Systems: A Scenarios Analysis*, World Economic Forum (Geneva, 2017). R. O. Valdivia et al., "Representative Agricultural Pathways and Scenarios for Regional Integrated Assessment of Climate Change Impacts, Vulnerability, and Adaptation," in *Handbook of Climate Change and Agroecosystems*, ed. C. Rosenzweig and D. Hillel, Series on Climate Change Impacts, Adaptation, and Mitigation (London UK: Imperial College Press, 2014).

the abatement value of food products and practices, is discussed on p. 103 and in Case Studies of Food System Impact Valuation.

Scenarios are essential to footprint reduction targets for food system impacts.

There is evidence that scenarios cause large changes in valuation estimates: UN population forecasts to 2100 can cause ±50% change to the social cost of carbon[128]; the abatement cost of carbon used by the Dutch Environmental Prices Handbook has a lower value of 57 2015€/t and a higher value of value of 94 2015€/t based on revising emission targets in the Dutch High and Low WLO scenarios[129]; an estimate of damage to global ecosystems service to 2050 differed by up to $81 trillion/yr by 2050 in four alternative global land-use and management scenarios[130]; and a FOLU valuation of the global food system projects a difference of $10.5 trillion/yr by 2050 in two global scenarios[131].

The studies mentioned illustrate the potential ranges of valuation estimates. Some of the ranges involve comparisons of business-as-usual against aspirations for the future (normative scenarios). Normative scenarios have distinct value for policy and target setting[132]. However, for risk pricing and valuation estimation scenarios need to be assessed against the chance they manifest the future at that date[133]. The distribution over these valuation ranges is essential information. Critics of assigning probability to scenarios often ignore that the other essential choice in risk pricing is the measure of risk. Risk pricing includes the option of a full precautionary approach as much as use of the expected value.

Ethical choices in valuation

We summarise the ethical choices in the process of Figure 17 that have been discussed.

- What to include and not to include in the scope of the impact pathways leading to total value loss or gain. Actors that selectively omit some impact pathways of loss and include other impact pathways of gain can distort impact valuation.
- Failure to disclose a credible footprint through lack of, or selective, data distorts impact valuation.
- Choice of welfare measure. Impact valuation, implicitly, is a measure of change in welfare that is being approximated by shadow prices. Choice of shadow prices includes choice of welfare as an implicit measure of social and human well-being. Included here is the ethical concern of monetary estimates.
- Choice in parity. Using PPP, designed to compare countries on the provision of individual utility from consumption of produced goods, to compare DALYs and more inclusive well-being measures with produced capital is contentious. Parity choices make a significant difference to climate costing. Most of the other food impacts are regional with 80% of global total calories produced, processed, and consumed (or wasted) in the same country. Currently 20% of calories in agricultural and food commodities are traded, which is projected by the FAO to increase and may also

128 E. K. Robert and K. M. Bryan, "The U.S. Government's Social Cost of Carbon Estimates after their First Year: Pathways for Improvement," *Economics : the Open-Access, Open-Assessment e-Journal* (2011).
129 p. 95: de Bruyn et al., *Environmental Prices Handbook EU28 Version*.
130 I. Kubiszewski et al., "The future value of ecosystem services: Global scenarios and national implications," *Ecosystem Services* 26 (2017), https://doi.org/10.1016/j.ecoser.2017.05.004.
131 FOLU, *Growing Better: Ten Critical Transitions to Transform Food and Land Use, The Global Consultation Report of the Food and Land Use Coalition.*
132 K. Wiebe et al., "Scenario development and foresight analysis: exploring options to inform choices," *Annual Review of Environment and Resources* 43 (2018), https://doi.org/10.1146/annurev-environ-102017-030109.
133 S. Kaplan and B. J. Garrick, "On the quantitative definition of risk," *Risk Analysis* 1, no. 1 (1981).

decrease in heterogeneity[134]. Parity choices will be required to calculate the impact for products and companies involved in global value chains, or for governments or investors to compare actors operating within different countries. In the analysis cited in footnote 134, financial capital flows are expected to increasingly concentrate in developed or BRIC countries. In terms of market value, traded food products constitute much more than 20%. Traded products are higher-value products which accumulate in higher PPP countries[135]. The percentage of global impact attributable to traded products has not been identified even using PPP (which is likely to be higher again than 20% due to the proportion of animal products traded internationally). The implication is that choice of parity matters in food impact costing. Substitution along food value chains is likely a major sensitivity for parity choices outside of carbon. Environmental and health costs are incurred in producing or consuming countries while social benefits accrue from financial capital flows in potential third countries.

- Ethical choice in discounting. Discounting is a major factor for carbon costing. Intergenerational costs are present for food impacts outside of carbon, but whether it is as sensitive is unclear. Some part of the discounting rate is linked to scenario projections of growth and future marginal utility. Another part is a purely ethical choice of consumption for enjoyment of the present generation. It is likely that projection of societal footprints is a larger uncertainty for food impact costing outside of carbon than time preference.

Variation in valuations from different choices have real or perceived ethical implications. Businesses that make these implicit choices in valuations themselves, or by using calculations of shadow prices in literature that have (using the linear model of next section), are increasing their contestability with government and civil society.

Our view is that variation due to ethical choices as well as variation in numbers from other choices and sources should be treated together. Agreed and comparable marginal valuation inclusive of ethical choices should be taken out of individual choices by actors and placed into a societal process. Ethical choices conform with societal norms or expectations of what is right. By allowing uncertainty and risk pricing in the marginal valuation, the societal process has even greater flexibility to not make singular ethical choices. It can include ranges to accord with the plural views. The building of a distribution of valuation estimates and the measure of risk is a societal process, as society globally is the bearer of social costs. What to include (footprint and the impact pathway structure informing shadow pricing) should similarly be defined by a common food system non-financial accounting standard. What form the marginal valuation numbers should take for food impact costing is discussed next section.

There is no simple way to avoid concerns about the monetisation of intrinsic value. Money is an instrument of exchange value. Monetary value is centralised and discovered through frequent transactions. Inclusive monetary estimates that inflate the sensitivity of exchange value to social and human well-being factors still need to be careful about substitution. The

---

[134] L. L. Porfirio et al., "Economic shifts in agricultural production and trade due to climate change," *Palgrave Communications* 4, no. 1 (2018), https://doi.org/10.1057/s41599-018-0164-y. FAO, *The State of Agricultural Commodity Markets 2018. Agricultural trade, climate change and food security*, The Food and Agriculture Organization of the United Nations (Rome, 2018), http://www.fao.org/3/I9542EN/i9542en.pdf. https://resourcetrade.earth/stories/food-security-trade-and-its-impacts#top

[135] G. K. MacDonald et al., "Rethinking Agricultural Trade Relationships in an Era of Globalization," *BioScience* 65, no. 3 (2015), https://doi.org/10.1093/biosci/biu225. M. Porkka et al., "From food insufficiency towards trade dependency: a historical analysis of global food availability," *PloS one* 8, no. 12 (2013), https://doi.org/10.1371/journal.pone.0082714.

disintegration of shadow prices proposed in the next section has the potential to extract additional statistics about substitution in the impact valuation of companies and products.

There are ethical arguments for monetary estimates. Exactly because of the connection to exchange value and market dynamics. The evolution to the present food system has prioritised short-term value – food provides calories and nutrition, it is tasty, it provides immediate physiological and psychological satisfaction and comfort. Providing this short-term value has been the triumph of the present food system. Once a resource is seen as abundant and not scarce, monetary value decreases according to the subjective theory of value. Though food is essential to life agricultural production now sits at 4% of global PPP GDP. Low costs of food, allowing incomes to be spent on other goods of greater marginal utility, and short-term satisfaction fits well with short-term political cycles. Which presently elected national government wants to tell their constituents what to eat through regulation or through taxation[136]? The answer is Mexico with a sugar tax on clear impacts on national well-being and productivity that began to demonstrably offset short-term value gain[137].

The presence of lock-in and secondary effects does not always make the value offset immediate or visible. Secondary effects from food impacts include mass migration and political destabilisation. Food policy is complex, raising political barriers[138]. An important argument for agreed monetary food impact costing is exposing and pricing longer-term value losses into the political-economy as a counter to short-term political dynamics. Enabling economic mechanisms to invest in offsetting or creating that longer-term value. This was an important outcome of carbon costing, though it is not completely safe from short-term political challenge[139]. The same applies if a tandem food system and economic community were able to promote and calculate, for example, the social cost(s) of obesity and malnutrition to perform the same function. Though the costs are plural and not global (there is some argument for a transferable component of common harm in emerging global diets[140]) an intergovernmental body, or alliance of institutional actors, may succeed in promoting impact costing and business opportunities in avoiding those costs.

Food impact costing does not need to get the 'correct' answer. An attempt to determine the social costs and benefits of food products to an unending degree of precision according to the myriad of processes constituting and connecting to and from the food system is a rabbit hole. What should be in and out of scope for impact pathways is unsolvable and is a choice that is agreed; it is scientifically guided rather than scientifically established. The opportunity to

136 L. Wellesley, C. Happer, and A. Froggatt, *Changing climate, changing diets : pathways to lower meat consumption*, Chatham House report, (London: The Royal Institute of International Affairs, Chatham House, 2015).

137 S. W. Ng et al., "Did high sugar-sweetened beverage purchasers respond differently to the excise tax on sugar-sweetened beverages in Mexico?," *Public Health Nutrition* 22, no. 4 (2019), https://doi.org/10.1017/S136898001800321X.

138 D. Mozaffarian et al., "Role of government policy in nutrition—barriers to and opportunities for healthier eating," *BMJ* 361 (2018), https://doi.org/10.1136/bmj.k2426. R. Carey et al., "Opportunities and challenges in developing a whole-of-government national food and nutrition policy: lessons from Australia's National Food Plan," *Public Health Nutr* 19, no. 1 (2016), https://doi.org/10.1017/s1368980015001834. E. M. Ridgway, M. A. Lawrence, and J. Woods, "Integrating Environmental Sustainability Considerations into Food and Nutrition Policies: Insights from Australia's National Food Plan," *Front Nutr* 2 (2015), https://doi.org/10.3389/fnut.2015.00029. K. Parsons and C. Hawkes, *Brief 5: Policy Coherence in Food Systems. In: Rethinking Food Policy: A Fresh Approach to Policy and Practice*, Centre for Food Policy (London UK, 2019).

139 A. Revkin, "Trump's attack on social cost of carbon could end up hurting his fossil fuel push," *Science* (2017), https://doi.org/10.1126/science.aap7709.

140 B. A. Swinburn et al., "The Global Syndemic of Obesity, Undernutrition, and Climate Change: The Lancet Commission report," *The Lancet* 393, no. 10173 (2019), https://doi.org/10.1016/S0140-6736(18)32822-8.

intervene in market failure in the direction of food system transformation is the guiding principle for costings[141]. In economics the market does the costing of the minute details, the fine scale tuning discovered by value in exchange rather than calculated. The purpose of shadow prices are not to predict the price of footprint as a commodity nor to provide an exhaustive catalogue of damage costs, but to enable the wedge of a benchmark, and to enable the experiments (introduction of internalisation) through which refinement of value around the benchmark can be discovered and centralised. The risk of not including or missing a major damage cost or impact pathway is lessened both by the emphasis on a societal process and the introduction of risk pricing to incorporate error bars into the benchmark.

Footprint is a quantity from production under human control the same as the production and consumption of the product incurring the footprint. The price of wheat is not the value of the land, the price of carbon is not the value of the earth. Pricing is a mechanism designed to match quantity of production (for a quantity controlled by humans) with human and social well-being. Conceptually food impact costing involves shadow prices of footprint. In impact frameworks footprint changes conceptually factor through capital changes. This introduces the implicit valuation of capital (natural, social, and human) as part of the marginal valuation of footprint quantities. There is a long debate on the ethical implications of implicitly valuing nature and humans[142]. However, it is not clear there is a pretence that costing of footprints (in the absence of exchange mechanisms presently for pricing) is philosophically different than valuing market goods. Both include implicit and flawed partial representation of the value of the underlying capital to achieve similar ends. When wheat becomes scarce the price rises to stimulate production and capital in all its forms is very much part of the implicit function between the amount desired for social and human well-being and the capacity for production. When footprints become abundant the price rises to reduce production[143]. The hope is we should never reach the total impoverishment required to know the true value of the fundamental capitals. The pricing of footprints should accelerate with the quantity of footprints to a degree which excludes any feasible economic position of environmental and social collapse.

As mentioned, many of the ethical choices are pushed into valuation factors, which perform most of the process of a valuation in Figure 17. Choices become implicit in which valuation factors are chosen.

Valuation factors

The last section illustrated features of valuations of food system impact and the calculations required (Figure 17): calculating actor footprint; calculating capital changes across space and time from footprint using complex models in the context of the present and future levels of societal footprint and other socio-economic drivers and determinants of value; and a monetary representation of present and future economic value changes associated to the capital changes. Parity and discounting together are used to compare impact (the economic value changes) across space and time. The last section also discussed the potential errors in the calculation.

Lining up the data and modelling for impact valuations and justifying ethical choices is a considerable task.

---

[141] Vermeulen et al., "Addressing uncertainty in adaptation planning for agriculture."
[142] V. Anderson, ed., *Debating Nature's Value: The Concept of 'Natural Capital'* (Cham: Springer International Publishing, 2018). G. Folloni and G. Vittadini, "Human capital measurement: a survey," *Journal of Economic Surveys* 24, no. 2 (2010), https://doi.org/10.1111/j.1467-6419.2009.00614.x.
[143] van Grinsven et al., "Costs and Benefits of Nitrogen for Europe and Implications for Mitigation."

There are some standardised modelling suites for ecosystem costing by large university modelling groups, e.g. Stanford Natural Capital project or King College London[144].

There are some large population level studies with complex determinations of attribution of dietary intake to health outcomes[145]. There are limited equilibrium food economic models geared to either welfare costing of understanding follow-on effects from footprint abatement, e.g. IMPACT at IFPRI or GLOBIOM at IIASA[146]. There are some published national abatement curves for carbon emissions in agriculture in the literature (footnote 159).

Data would have to be specifically compiled. Local models and monitoring exist for specific water catchments or agricultural regions. Piecing them together to determine the impacts of large corporations requires significant resources and expertise found presently only in national or international organisations like UN Environment. There are some intergovernmental efforts to align footprint calculations for environmental footprints, e.g. the product environmental footprint (PEF) scheme of the EU[147].

It is beyond the ability and resources of most food system actors and users to explicitly acquire each component and integrate them into a valuation. Many large food companies have limited data presently on their own footprints[148]. Explicit valuations require many choices and extrapolations of missing components to develop an integrated model. Making them difficult to compare and validate as discussed last section and evidenced further by the case studies in Case Studies of Food System Impact Valuation. Without incentives for using the valuations there would seem to be little to justify the effort in compiling them.

The social and marginal abatement costs of carbon are valuation factors. Valuation factors are an extremely practical means to value externalities. They are easy for government and business to use, even small and medium enterprises, supposing that the material footprint of any activity has already been calculated. The valuation factor is multiplied by the appropriate footprint. For example, tonnes of carbon equivalent emissions get multiplied by the social cost of carbon. The valuation factors are the marginal costs associated to individual footprint quantities. As explained below, it is a linearization of the process in Figure 17.

Carbon costings demonstrated the complexity of determining valuation factors. Valuation factors are doing a lot of heavy lifting (Figure 20). Behind the numerical value of a valuation factor is a tremendous calculation. A calculation fraught with uncertainties of modelling cumulative impacts into the future, trade-offs, scientific disagreement, choices in valuation approach, the ethics of implicit exchanges of welfare value across nations and generations. Volumes of scientific literature on food systems and their environmental and social impacts, and volumes of economics, are dedicated to the territory covered by these single numbers. The permutations of choices that could be substituted into the same calculation of a shadow price produces enormous variation (Figure 14 illustrates the partial variation for the social cost

---

144 https://naturalcapitalproject.stanford.edu/; https://blogs.kcl.ac.uk/eoes/2016/06/07/costing-nature-tool-to-support-sustainable-decisions/

145 Afshin et al., "Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017."

146 C. Rosenzweig et al., "Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison," *Proc Natl Acad Sci U S A* 111 (2014), https://doi.org/10.1073/pnas.1222463110.

147 B. Vanessa et al., "Product Environmental Footprint (PEF) Pilot Phase—Comparability over Flexibility?," *Sustainability* 10, no. 8 (2018), https://doi.org/10.3390/su10082898; S. Manfredi et al., "Comparing the European Commission product environmental footprint method with other environmental accounting methods," *The International Journal of Life Cycle Assessment* 20, no. 3 (2015), https://doi.org/10.1007/s11367-014-0839-6. https://ec.europa.eu/environment/eussd/smgp/ef_transition.htm

148 https://agfundernews.com/big-agrifood-companies-supply-chains.html

of carbon). It is not clear the variation can be reduced due to the irreducible factors describe in the last section involving ambiguity, epistemological uncertainty, and ethical choices.

Like carbon costing, the difficulties, choice, and variations in food impact costings would be best served by a societal process rather than selective use of shadow prices from literature.

Besides making it simpler for the food sector, and providing a comparative basis for food economic policy, it enables the difficult task of determining the correct risk premiums to be included in the process. The transfer of risk to society of the uncertainty in the value loss from food impacts is likely to be omitted in a diversity of explicit first- and third-party estimates.

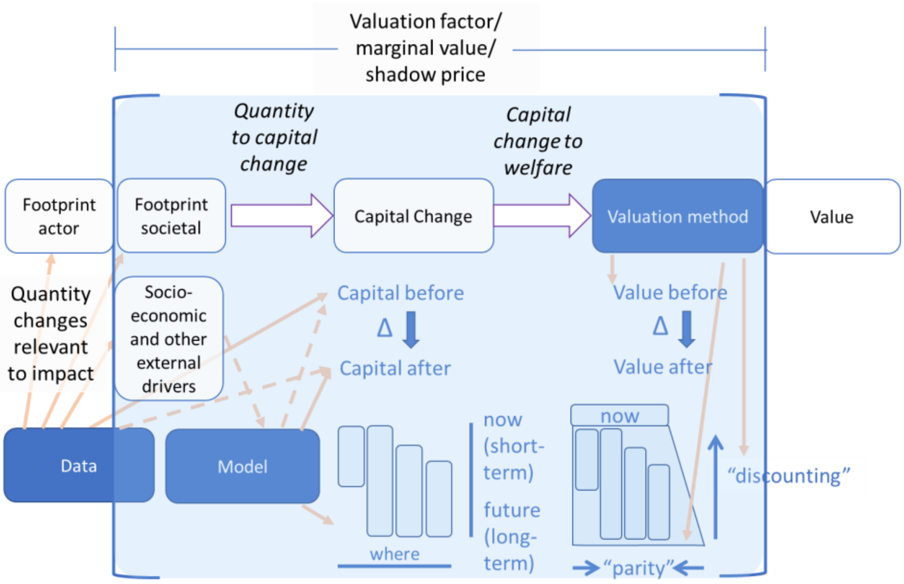

Figure 20: Valuation factors, as shadow prices associated to footprint quantities, that reduce valuation to multiplication of the actor's footprint times the valuation factor. Implicit within valuation factors are most of the measure and value steps in impact frameworks, and calculation and choices of models, data, impact pathways, measurement of welfare and ethics of implicit exchanges of welfare across nations and generations.

Businesses being aware of the components in valuations that they create, or use, can lead to disclosure of them. It sponsors comparability of the methods.

Businesses have the same playing field if valuation factors for food impact and their uncertainty were agreed. This incentivises the sector to co-invest in the societal process for better information about impacts and valuation to reduce the uncertainty and so reduce the risk price. Businesses can compete on footprint reduction and on disclosure.

Food system impact valuation involves determining social and abatement costs for the material environmental, social, and human health impacts of food systems. While carbon costing is a sound basis from which to begin food impact costing, there are unique challenges not found in the process of costing carbon. The next section is technical. Readers looking to applications should briefly understand equation (1) below and move to the section on social or abatement costs from p. 103.

Linear model

The approach being used in practice is addition of terms involving valuation factors multiplied by the footprint of the actor. This corresponds to a linear model of the valuation function V in footprint quantities f introduced on p. 60.

Shadow prices of footprint quantities

As before denote a vector of footprint quantities

$$f = [f_1, \cdots, f_n].$$

For instance, the first term in the footprint f_1 might be t CO2-eq emitted into the atmosphere by society after a certain date.

Denote by V the function in Figure 11 that takes a list of present footprint quantities f and assigns to them a monetary amount relating to economic value $V(s(f), f)$. If a food system actor is responsible for a change in footprint from f to $\hat{f}$ (the amount of generated CO2-eq emissions, leached nitrogen, improvement of community access to drinking water, food products sold that caused preventable death and disease compared to reference diets, etc.) then Taylor's theorem approximates the change in economic value, or impact, by

$$V\big(s(\hat{f}), \hat{f}\big) - V(s(f), f) = J_V(s(f), f) \cdot \big(\hat{f} - f\big) + error \qquad (1)$$

The difference in footprint, $\hat{f} - f$, is the footprint of the actor. For example, $\hat{f}_1 - f_1$ would represent the t CO2-eq emitted by the actor per annum. Here s is a list of other determinants of value of the kind mentioned above, such as socio-economic drivers, that may depend on the footprint.

The dot product notation represents multiplying component-wise then adding the terms

$$J_V(s(f), f) \cdot \big(\hat{f} - f\big) = \frac{\partial V}{\partial f_1}(s(f), f) \times (\hat{f}_1 - f_1) + \cdots + \frac{\partial V}{\partial f_n}(s(f), f) \times (\hat{f}_n - f_n).$$

The vector of shadow prices of footprint quantities, or marginal valuations, or valuation factors, is denoted by[149]

$$J_V(s(f), f) = \left[\frac{\partial V}{\partial f_1}(s(f), f), \cdots, \frac{\partial V}{\partial f_n}(s(f), f)\right], \qquad f = [f_1, \cdots, f_n].$$

In this case the first term in the footprint $\frac{\partial V}{\partial f_1}(s(f), f)$ would be the social cost of carbon given the societal footprint f and other factors such as socio-economic drivers specified exogenously by s. Even in this linear approximation to the change in economic value due to the change in footprint due to the actor, the shadow prices still depend on the societal footprint and additional factors. As described earlier this dependency is what is reflected in the variation in the social cost of carbon (a shadow price) due to assumptions in scenarios of emission trajectories and other socio-economic factors.

Equation (1) represents the linear model used in practice, including the components identified in Figure 11: the actor footprint $\hat{f} - f$, the societal footprint f, and other external drivers s. **With a few exceptions that are noted, all the food system impact valuations case studies in Case Studies of Food System Impact Valuation use equation (1) to calculate a food system impact valuation.** It is the change in footprint due to the actor(s) in one dimension of footprint over the temporal scope of the valuation multiplied by shadow price for that dimension of footprint to get a change in value from that dimension, then value change from each of the dimensions of footprint are added together. The shadow prices in case studies are obtained from literature or from high level bodies such as the Carbon Pricing Leadership Coalition.

The error term in equation (1) needs consideration. First the linear terms.

[149] Dasgupta and Duraiappah (2012) define the shadow price or value of a capital asset as the monetary measure of the contribution a marginal unit of that asset is forecast to make to human well-being: Dasgupta and Duraiappah, "Well-being and wealth."

The determinants of value s include other economic quantities besides socio-economic drivers. Some of these determinants will change if footprint changes, such as commodities whose production created the footprint itself. Other socio-economic drivers may not change much with respect to changes in footprint. These could be omitted by a user as part of the impact valuation, since it is designed to value benefits and costs outside of production (e.g. external costs). If s changes with the societal footprint f the chain rule implies that the shadow price is composed of the changes in economic quantities associated to footprint changes, and a residual part that does not factor through the economic quantities included in s:

$$\frac{\partial V}{\partial f_1}(s(f),f) = \sum_{m=1} \frac{\partial V}{\partial s_m}(s(f),f) \times \frac{\partial s_m}{\partial f_1}(f) + \frac{\partial V}{\partial f_1}(s,f)\,. \tag{2}$$

The implications of what is included within s has been discussed already in detail. It relates primarily to the boundaries and scope of the impact pathways – what changes because footprint changes. Some of the effects mentioned as subsequent economic costs outside of direct health damage costs are any corrective effect of those costs, i.e. the adjustment of value when expenditure is added or removed from the health sector due to the production and consumption of food products. When economic quantities relevant to value are assumed not to change from the actor's contribution to footprint ($\frac{\partial s_m}{\partial f_1} = 0$), this is the same as assuming that they are constant determinants of value independent of footprint. One of the assumptions relating to using the linear model is that most of the major economic benefits and costs have been accounted for in the calculation of the shadow price of the footprint, any terms omitted are assumed to be insensitive to footprint changes. If subsequent economic effects have been missed, they are absorbed by the error term and it is unknown if they are of similar magnitude to the valuation without error estimates. This relates to the first mentioned point of ethical implications on p. 84: omitting some impact pathways of value loss and gain can distort impact valuation.

Scarcity and interaction terms

The error also absorbs non-linear terms. The second order terms in Taylor's expansion are

$$V(s(\hat{f}),\hat{f}) - V(s(f),f) = J_V(s(f),f)\cdot(\hat{f}-f) + \mathrm{H}_V(s(f),f)(\hat{f}-f)\cdot(\hat{f}-f) + error \tag{3}$$

where $\mathrm{H}_V(s(f),f)$ is the Hessian matrix:

$$\mathrm{H_V}(s(f),f)(\hat{f}-f)\cdot(\hat{f}-f) = \frac{1}{2}\sum_{i,j=1}^{n}\frac{\partial^2 V}{\partial f_i \partial f_j}(s(f),f)\times(\hat{f_i}-f_i)\times(\hat{f_j}-f_j).$$

Calculating second order effects requires the actor footprint $\hat{f}-f$ and estimating the Hessian. The terms when $i=j$,

$$\frac{\partial^2 V}{\partial f_i^2}(s(f),f),$$

represent resource scarcity. They are the change in the shadow prices for a footprint quantity as that footprint quantity changes. For example, if water is extracted from an already low capital stock of water in a location, then the impacts and costs increase at a disproportionate rate. This term reflects that the value of water is greater when there is less supply[150]. Similarly,

[150] S. Pfister, A. Koehler, and S. Hellweg, "Assessing the Environmental Impacts of Freshwater Consumption in LCA," *Environmental Science & Technology* 43, no. 11 (2009), https://doi.org/10.1021/es802423e. J. Allouche, "The sustainability and resilience of global water and food systems: Political analysis of the interplay between security, resource scarcity, political systems

the value of reducing CO2-eq emission increases the higher the amount of societal emissions. However, the level of individual actor's emissions compared to global emissions is usually quite low, and it is usually assumed the economic value loss with respect to global emissions is more sensitive to the stock of existing emission than the flow[151]. That extraction is more proportional to the stock will probably result in larger second order effects for other food impact footprints than for the social cost of carbon. The model of water scarcity of Pfister (2009) (footnote 150), widely used by the consultant TruCost for impact valuations, is non-linear in marginal extraction.

The terms in the Hessian when $i \neq j$,

$$\frac{\partial^2 V}{\partial f_i \partial f_j}(s(f), f),$$

correspond to interactions between footprints relating to value loss. They are the change in a shadow price of one footprint as other footprints change. For example, how a shadow price for obesity increases as CO2-eq emissions increase or how a shadow price for nutrient pollution increases as CO2-eq emissions increase. Unlike carbon costing, food impact costing features multiple footprints. Interactions terms of carbon, market prices (abatement of carbon can have a co-benefit of reducing prices) and marginal economic costs from other environmental and social footprints have been studied[152]. For example, Figure 5.16 of the IPCC Report *IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystem* examines the synergies and trade-offs between achieving targets within SDG 2 (zero hunger/food security) and SDG 13 (climate action). Interactions include that emissions through change in climate contribute to water scarcity (change in shadow prices for water) and acidification. Land-use and acidification contributions to acceleration of climate costs (changes in the shadow price for carbon) through effectively changing emission trajectories by reducing the ongoing potential for natural carbon sequestration[153]. DALYs saved increase population with potential scarcity effects. Radical changes in agricultural incomes (removing social costs of poverty) would have unknown effects in terms of displacing labour and production to or from lower emitting sectors and demographics to higher emitting sectors and demographics[154].

The first order effects of co-benefits or trade-offs on shadow pricing are part of the interaction terms $\frac{\partial^2 V}{\partial f_i \partial f_j}$ when the dependence on s is expanded by the chain rule. Synergies and trade-offs between the footprint categories and impact pathways of the food system are complex, and the author is unaware of quantitative estimates of the magnitude of potential interaction terms.

Whether the errors from non-linearity are significant, or will make a significant difference for economic food policy designed to reduce food system impacts, is unknown because they have

and global trade," *Food Policy* 36, Supp 1 (2011), https://doi.org/http://dx.doi.org/10.1016/j.foodpol.2010.11.013.

151 R. Clarkson and K. Deyes, *Estimating the social cost of carbon emissions*, Government Economic Service working paper, (London: HM Treasury, 2002).

152 For impact pathways of climate change see 3.6.3.2 of Kolstad et al., "Social, Economic and Ethical Concepts and Methods." See Chapter 7 also of IPCC, *IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems*., synergies and trade-offs are a central theme of the IPCC report. P. Smith and J. E. Olesen, "Synergies between the mitigation of, and adaptation to, climate change in agriculture," *J Agric Sci* 148 (2010// 2010), https://doi.org/10.1017/S0021859610000341.

153 https://www.ucsusa.org/resources/co2-and-ocean-acidification

154 Section 7.5.6.2: IPCC, *IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems*.

not been much investigated. Without including the second order effects it is hard to judge whether they are comparable to the first order terms. If economic value is non-linear (e.g. rapidly declining) with increasing footprint then these terms will count. They count increasingly more if the difference $\hat{f} - f$ is comparable to the societal footprint. That is, they are more, and likely manifestly, significant for impact valuations of significant changes to the food system.

For example, in the social case studies 1-3 the economic valuation of social costs would involve comparing the present economic value with the counterfactual represented by changes in food loss and waste, the global livestock sector, and the global food system respectively. Errors from second order effects including scarcity and interactions should be expected in these cases. The distortion effects of scarcity and interaction in equation (3) are among the non-linear effects that significantly affect the ability to add up (linearly aggregate) many valuations based on small footprint changes to obtain large scale valuations. Toman's critique of the total value of ecosystem services was based on this argument[155]. The valuation of sectors, and potentially large companies with large shares of societal footprint, may need to consider this effect.

Without further study it is difficult to recommend the degree to which standardisation of shadow prices should extend to the Hessian. Formalising conceptual impact pathways would assist in understanding synergies and trade-offs for economic value loss or gain along the impact pathways and provide a basis for estimating second order effects by concentrating on footprints that interact.

Economic analyses will often use the assumption of constant prices ($\frac{\partial^2 V}{\partial f_i \partial f_j} = 0$). The linear model in (1) removes the effects of resource scarcity and synergies and trade-offs. Wealth changes over small time periods are valued using linear approximation leading to assumptions that shadow prices are constant over those time periods[156].

Based purely on dependence of the error on the magnitude of footprint changes, the error terms are less significant for impact valuations of products. Aggregating impact valuations of products back to sector scale will reintroduce the significance of non-linear errors.

The marginal abatement case studies 4-9 are either of smaller scale operations or individual products. The first-order linear approximation in equation (1) is more likely to be valid in those cases. However, potential omission of relative terms from equation (2) feature as sources of error.

A food system non-financial capital standard that considers formalising conceptual impact pathways will assist in improving practical and comparable impact valuation by indicating the determinants s in equation (2) that should be included within the consideration of shadow pricing for impact valuation. Formally, impact pathways should specify the major determinants of shadow prices.

Optimal reduction and abatement costing

Multiple dimensions of footprint complicate the picture between the value of abating food system footprints and the portfolios of abatement measures and abatement costs for food

[155] M. Toman, " Why not to calculate the value of the world's ecosystem services and natural capital," *Ecological Economics* 25, no. 1 (1998), https://doi.org/10.1016/S0921-8009(98)00017-2.
[156] R. Yamaguchi, M. Islam, and S. Managi, "Inclusive wealth in the twenty-first century: a summary and further discussion of Inclusive Wealth Report 2018," *Letters in Spatial and Resource Sciences* 12, no. 2 (2019), https://doi.org/10.1007/s12076-019-00229-x.

impact. A key challenge is understanding co-benefit opportunities or trade-offs between the dimensions of food system impacts[157].

As discussed for costing carbon, social costs SC and abatement costs AC are two approaches to the valuation function V.

The interpretation of $V(f) = SC(f)$ is the total social costs incurred given present societal footprint f (loss of economic value in the trajectory of a baseline economy into the future). The impact valuation measures the change in social costs due to the actor (equation (1)). The Jacobian $J_{SC}(f)$ represents a vector of estimates of marginal social costs with respect to each footprint quantity. That is, the damage from one more unit of emission, etc. given the existing footprint f. The Hessian represents scarcity in terms of the larger the footprint the greater the marginal damage, and co-benefits and trade-offs in terms of the damage from increasing one unit of two footprint quantities at the same time may be more or less than the sum of their marginal damages.

The interpretation of $V(f) = AC(f, q\ )$ for abatement costs is the total cost of the least cost abatement portfolio that reduces the footprint from f to a footprint reduction target q (cost to achieve an abated economy with footprint $f - q$ obtained by substituting the abatement portfolio in the baseline economy with footprint f). The impact valuation estimates the change in abatement cost required to meet the footprint reduction target $q + \ \hat{f} - f$ (equation (1)). The Jacobian $J_{AC}(f)$ represents a vector of estimates of marginal abatements costs. That is, if one unit e_j of footprint is added in footprint dimension j, what is the cost of the abatement measure that needs to be added to the abatement portfolio to achieve footprint reduction $q + e_j$. The Hessian represents scarcity of abatement measures in terms of the larger footprint reduction required the more expensive the abatement measures become, and co-benefits and trade-offs in terms of the cost of an abatement measure that reduce two footprint quantities at the same time may be more and less than the sum of the cost of abatement measures that reduce the footprint quantities individually.

The building of an abatement cost function is conceptually the same as carbon costing, but harder to do in practice.

In Figure 16 there was one direction for reducing social costs: reducing carbon emissions. For food systems what is the optimal direction for reducing social costs? Should society or industry be focussed on reducing footprints associated to human health costs as a priority over abatement of environmental pollution? Co-benefits and trade-offs for both social costs and abatement measures make a difference; a point discussed in the chapter Economic Theory of Change. The vector of footprints relevant to food impacts means that there are different paths for footprint reduction. When footprint is a vector, multiple footprint reduction targets can offer the same abatement of social costs (an impact target), the optimal footprint reduction target should be chosen according to minimising the abatement cost (Figure 21).

The priority order in the portfolio of abatement measures achieving the optimal footprint reduction coincides with the path of steepest ascent in q directions on the surface $SC(f) - SC(f - q) - AC(f, q)$ where f is the current societal footprint and q is the variable reduction. Societal footprint reduction targets that are staged toward an optimal footprint should follow, as clearly as society can estimate, the path of steepest ascent. The direction of this path depends on co-benefits and trade-offs for social costs and abatement costs (Figure 21).

If trade-offs are prevalent then prioritising abatement of one footprint over another may be the optimal path. If co-benefits are prevalent an abatement portfolio of mixed measures achieving

[157] M. T. Niles et al., "Climate change mitigation beyond agriculture: a review of food system opportunities and implications," 33, no. 3 (2018), https://doi.org/10.1017/S1742170518000029.

reduction in multiple footprints may be optimal. Co-benefits here relate to both social costs and abatement. Co-benefit in abatement measures means that achieving footprint and social cost reduction can cost less than the most cost-effective reduction measure of individual footprints combined.

Affordable measures that achieve co-benefits in footprint reduction may be optimal paths to achieving reduction of social cost. Cheaper measures may exist for reduction of individual footprints, but the total cost along the trajectory to achieve the same reduction in social cost may be higher.

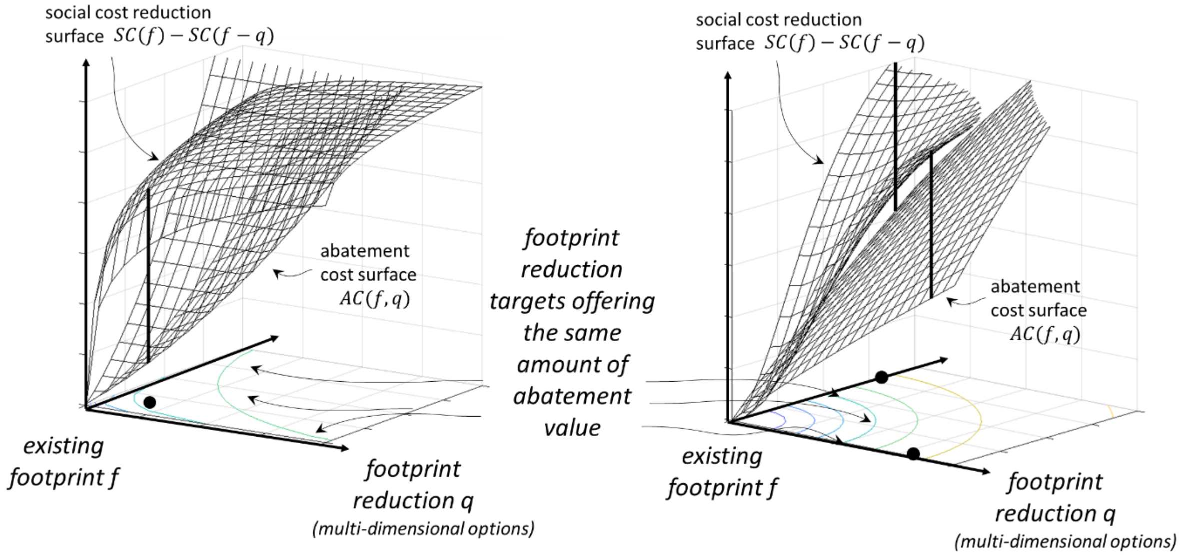

Figure 21: Complications from trade-offs in setting footprint reductions targets for food systems: finding the target associated to the most reduction of social costs for the least cost (optimality), and the different strategies for prioritising footprint reduction in competing dimensions in the presence of co-benefits and trade-offs. With co-benefits in the left panel footprint reduction is most effective with abatement portfolios of mixed measures. With trade-offs in the right panel footprint reduction is most effective with abatement portfolios prioritising one footprint that minimally effects other footprints. Optimal footprint reduction targets are large dots in either panel

Most food system actor impact valuations will not be concerned with optimal trajectories until engaged in a societal process for refining targets or policies on achieving impact reduction targets. Food sector sustainable products and sustainable practices are abatement measures. Their practical goal is to offer the most abatement value per unit of cost compared to the products and practices they substitute. Trajectories of footprint reduction become relevant in the demand of products and practices stimulated by social cost reduction policies. If strong trade-offs exist in the marginal social cost surface, products and practices that address the priority footprint direction efficiently may be incentivised over product and practices that attempt to abate several footprint dimensions at once.

Optimality is the conceptual basis for marginal abatement costing of food system impacts. The potential to achieve impact reduction from multiple footprint reduction targets, or multiple trajectories to achieve a set footprint target, makes building marginal abatement portfolios for food system impacts a complicated exercise. The many options available for abatement introduces uncertainty as to the completeness of the lowest cost abatement portfolio. In practice, as for carbon costing, a valuation of food system impacts based on abatement costing introduces uncertainty even though the abatement measures may be concrete and already on the market. The uncertainty in abatement cost is not just in the costs, but in the social cost being abated. Pricing uncertainty into valuations is not avoided by an abatement cost approach.

There is uncertainty in whether potential abatement will be realised. Research has identified diets that have lower impact on human and natural capital – clear co-benefits[158]. Using fiscal policy to push demand along this trajectory may not work if demand is not responsive and higher prices are mostly absorbed into household budgets. If this happens revenue could be pushed into lowest cost (more efficient on a per footprint basis) measures through offset markets. The overall social benefit achieved from the revenue compared to the dietary change may not be as great. The uncertainty in realising potential abatement measures and what baseline measures they displace, especially in the predominately private provision of food products, is discussed under abatement demand from p. 103 and in Case Studies of Food System Impact Valuation. This translates into uncertainty in the marginal abatement cost, explained from p. 103.

In summary, abatement costing for food system impacts is not developed like carbon costing. Energy is a traditional infrastructure, with large or at-scale capital investment and technological challenges (e.g. carbon capture). Food is much more heterogenous in abatement measures available. For the CO2-eq emissions dimension marginal abatement curves for agriculture have been developed at national and subnational scales[159]. In practice, existing emissions marginal abatement curves for the food system are not that easily transferrable. Co-benefits and trade-offs in other footprints have not generally been considered in the building of a least cost curve for emissions reduction. It also unclear what efficiency gains (negative abatement) would provide in terms of footprint reduction. This research question was already proposed on the chapter Economic Theory of Change.

More research, highlighted in the chapter Economic Theory of Change, is required to develop marginal abatement costing as a valuation method for food system impacts. Some abatement costs are used in the case studies 1-9. They are obtained from external studies and do not reflect a marginal abatement valuation for food system impact specifically in the sense above. They reflect least costing for abatement measures from individual footprints. From p. 103 we discuss the feasibility of mixing social and abatement cost estimates for shadow prices.

Attribution implicit in valuation factors and shadow prices of capital changes

A comment on attribution. When a valuation factor is given then attribution is split (Figure 22), and it is partly determined by footprint disclosure (by the company or a monitor) and partly determined within the calculation of the valuation factor. If the calculation of the valuation factor cannot be split apart (case studies below show the mixture of third-party calculated valuation

158 Afshin et al., "Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017."; Clark et al., "Multiple health and environmental impacts of foods."; W. Willett et al., "Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems," *The Lancet* 393, no. 10170 (2019), https://doi.org/https://doi.org/10.1016/S0140-6736(18)31788-4.,

159 L. Bockel et al., *Using Marginal Abatement Cost Curves to Realize the Economic Appraisal of Climate Smart Agriculture Policy Options*, Food and Agriculture Organization of the United Nations. (Rome, 2012); V. Eory et al., "Marginal abatement cost curves for agricultural climate policy: State-of-the art, lessons learnt and future potential," *Journal of Cleaner Production* 182 (2018), https://doi.org/10.1016/j.jclepro.2018.01.252; D. Moran et al., "Marginal Abatement Cost Curves for UK Agricultural Greenhouse Gas Emissions," *Journal of Agricultural Economics* 62, no. 1 (2011), https://doi.org/10.1111/j.1477-9552.2010.00268.x. R. H. Beach et al., "Mitigation potential and costs for global agricultural greenhouse gas emissions 1," *Agricultural Economics* 38, no. 2 (2008), https://doi.org/10.1111/j.1574-0862.2008.00286.x; R. H. Beach et al., "Global mitigation potential and costs of reducing agricultural non-CO2 greenhouse gas emissions through 2030," *Journal of Integrative Environmental Sciences* 12, no. sup1 (2015), https://doi.org/10.1080/1943815X.2015.1110183; K. Tang et al., "Marginal abatement costs of greenhouse gas emissions: broadacre farming in the Great Southern Region of Western Australia," *Australian Journal of Agricultural and Resource Economics* 60, no. 3 (2016), https://doi.org/10.1111/1467-8489.12135.

factors used in practice) the attribution cannot directly be calculated. Clear language should be used for the term attribution of what and valuation of what (Figure 22).

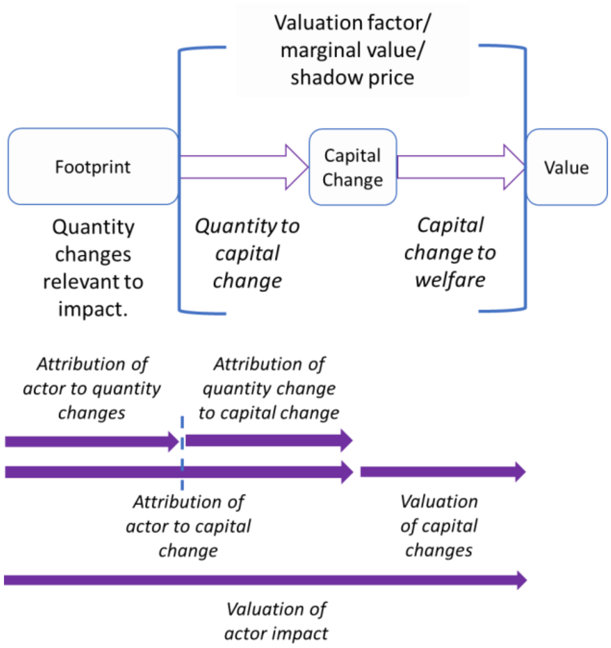

Figure 22: Highlighting the break within marginal valuation of the attribution of capital changes from Figure 11. Attribution of capital changes to actors is partly determined by footprint and partly determined within the calculation of the valuation factor

Valuation factors are a combination of: (a) determining how much capital change is attributable to a unit change in quantity; and (b) the valuation of capital changes from (a).

An attribution of capital changes to an actor is a function from that actor's footprint to capital changes. As we discussed for the valuation function, an attribution function would, and should, be dependent on the total footprint (e.g. ecosystem damage depends jointly on climatic changes and pollutants in a non-univariate way) of the actor, and of other actors, and is not just linear in the units (the extraction of a ten times more water is likely to cause more capital change than ten times the capital change of the original extraction of water). Complex biophysical models of climate, agriculture and ecosystems, across the literature, act as multi-variate, non-linear functions from quantities to capital change.

Valuation factors split the multi-variate (depending on all the quantities in footprint as a vector) and non-linear nature of attribution apart into a univariate (depending on each quantity separately, e.g. carbon footprint) and linear approximation of the attribution function in the total valuation of actor impact.

The change of climate parameters (statistics of weather) like temperature attributable to emissions of actors, can be intermediate within the valuation factor, e.g. a midpoint in the calculation of carbon footprint to natural capital change outside of the atmosphere. Attribution of climate change is partly within the calculation of the social cost of carbon (Figure 12 on p. 49). The case studies are not uniform in the footprint they measure, and sometimes attribution is ambiguous because of causal connections in capital change. So, the most general simple formula is attribution of a change of quantity to an actor, and a marginal value with respect to a change in that quantity. For example, some studies might attribute a temperature change to an actor or activity, and then associate an economic cost of lost value flows from land per degree Celsius of temperature change.

Attribution within valuation needs to specify what type of capital change or it is ambiguous (Figure 23). If the natural capital change is land degradation, then temperature is a midpoint in the previous example and part of the attribution of land degradation. If the natural capital change is atmospheric (temperature as a flow of atmosphere) then land degradation is pushed into the valuation of the atmospheric change and temperature change is a capital change. The end value of the actor's footprint should be agnostic to this ambiguity, but in practice the ambiguity leads to many versions of the same calculation factoring through different marginal valuations, e.g. the partial derivative of value with respect to deg C versus the partial derivative of value with respect to ha of land degradation. This is evident across the mixture of first and third-party calculated valuation factors used in case studies in the chapter Case Studies of Food System Impact Valuation, and in the different models for the social cost of carbon.

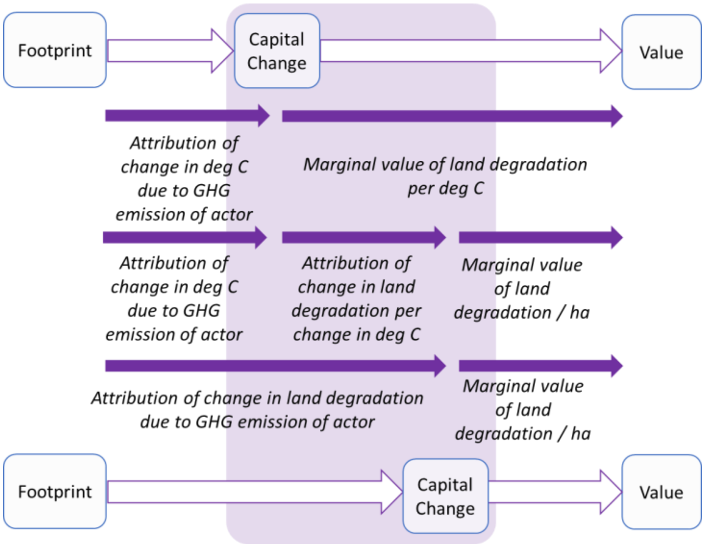

Figure 23: Ambiguity in attribution of capital change and valuation of capital change.

Some of the case studies use a shadow price for a capital change. That is, as a valuation factor is a combination of: (a) determining how much capital change is attributable to a unit change in quantity; and (b) the valuation of capital changes from (a), they use a shadow price in (b) and an estimate for (a). Mathematically, this is an application of the chain rule and footnote 164 indicates how to reframe the linear model of valuation explicit linear model to use shadow prices associated to capital change instead of footprint change.

The UNEP Inclusive Wealth Report methodology uses shadow prices with respect to the quantities of capital changes because it looks at global capital changes directly and has no need to attribute changes in those capitals to individual actor(s). The wealth of the global community is being measured and the global community is responsible for any attributable capital change[160].

It is recommended that practical and comparable valuation for users be based on shadow prices of footprint changes and not capital changes (Figure 20 and equation (1)):

- The actor is unlikely to be able to report on their capital changes, e.g. for climate change or for health changes. Footprint changes are more immediate to the activities of the actor. Attribution modelling as discussed above is difficult.

[160] Chapter 7 and Methodology Appendices: UNEP, *Inclusive wealth report 2018 : measuring progress towards sustainability*.; Yamaguchi, Islam, and Managi, "Inclusive wealth in the twenty-first century: a summary and further discussion of Inclusive Wealth Report 2018."

- Given the complex interactions between capitals it will be difficult for non-experts to use shadow prices with respect to capital, i.e. the additional ambiguity as above.
- It is natural to put the ambiguity and epistemological uncertainty of the complexity of capital changes into the uncertainty of the shadow prices of footprint quantities which should be priced by a societal process.

Shadow prices of capital changes play an important technical role in calculating shadow prices of footprint changes, e.g. within the social cost of carbon. An accounting framework formalising footprints and impact pathways would help to lessen the ambiguities in capital changes. The LCA community faced a similar issue on what are called midpoints and endpoints, which was partly resolved by the development of the ReCiPe method[161].

While marginal valuations of footprint are recommended for practical and comparable valuation of food system impacts, and attribution becomes implicit in food impact costing as part of the societal model building of shadow prices for footprint quantities, attribution remains important on its own. Parity measures based on capital changes and not just on national economies are a potential technical adjustment. Equity statistics on implicit substitutions of value derived from different capitals would be based technically on attribution and valuation of capital changes. Both shadow prices of capital changes and shadow prices of footprint changes are needed. The recommendation is that the former are more technical and an intermediary for the latter which is more direct to the domain of users and more direct for the purpose of changing a quantity controlled by humans.

Spatial, contextual, and temporal factors

When considering impact and footprint it was advocated to distinguish footprints spatially and contextually into “sources of impact now” and impact occurring in economies distinguished in space and time as “receivers of impact now and in the future”.

These distinctions lead to a refinement of the linear model on p. 90. This model is advocated as the basis for practical and comparable impact valuation. It has enough distinction to reduce gross errors in valuation of impacts. This model is also the basis recommended for societal development of shadow prices, for risk pricing, for an explicit formulation that allows clear comparability in parity and discounting and lastly, but not least important, for the ability to examine equity in implicit exchanges of non-financial value. The spatial and contextual distinction for footprints is no more detailed conceptually than present LCA.

As before denote a vector of footprint quantities

$$f = [f_1, \cdots, f_n].$$

The vector is now longer; the index $i = 1,2, \dots, n$ relates to a vector of footprint quantities such as emission of pollution, water extraction, etc. but each one may have further spatial and contextual footprints at the kind of resolution discussed on p. 77.

For instance, the first terms in the footprint $f_1, f_2, f_3, \dots$ may relate to GHG emission. We noted for climate change effects carbon emission has a global footprint. It could contextually be distinguished into tonnes of CO2 (Carbon Dioxide), CH4 (Methane), N2O (Nitrous Oxide) emitted. NOx from agriculture, as well as leading N2O emissions, can cause air pollution close to the source of emission[162]. This would be a separate impact pathway as it leads to different spatial and temporal changes in economies than its effects as a GHG (Figure 18). If NOx

[161] M. Huijbregts et al., *ReCiPe 2016 : A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterization*, National Institute for Public Health and the Environment (Bilthoven, The Netherlands, 2016), http://rivm.openrepository.com/rivm/handle/10029/620793.

[162] M. Almaraz et al., "Agriculture is a major source of NOx pollution in California," *Science Advances* 4, no. 1 (2018), https://doi.org/10.1126/sciadv.aao3477.

footprint were separated out, it would need to be spatially explicit to reflect differences in conditions for smog formation and affected populations. If each of the 320 food basins of global agricultural production used in the IMPACT model were used as the sources of NOx pollution then $f_1, f_2, f_3, \dots, f_{322}$ might relate to CO2 footprint (global), CH4 footprint (global), and then NOx spatially distinct footprints. The carbon component of shadow prices relating to $f_3, \dots, f_{322}$ are social costs of carbon since NOx leading to the GHG N2O has global impact. The air pollution component of shadow prices relating to $f_3, \dots, f_{322}$ are not identical, they will change depending on economic value change they cause in a national economy in a specified time period.

For economic value change, we advocate for an initially *undiscounted* vector of value output

$$V = \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_m \end{bmatrix}.$$

Each value function is an *undiscounted* monetary measure of welfare in a national economy in a time period in the future. There are 195 nations, $V_1, \dots, V_{195}$ might be the measure of welfare for all nations over a time period 2015-2020, $V_{196}, \dots, V_{390}$ might be the measure of welfare for all nations over a time period 2020-2030. The time period might cover 100 years (in which case $m \geq 1000$). These figures are illustrative only. The temporal scale should not be linear stretching into the future, 5 log-scaled time periods might be used, etc.

Besides footprint f, each value function for a national economy and time will also be a function of other determinants of value. These need only be formally recognised so we keep the notation $s(f)$. The determinants of value depending on present societal footprint levels play the same conceptual role. Their influence on value in the context of the footprint change could be refined to the national level if feasible. At least for scenarios this implies the opportunity for global socio-economic scenarios to be scaled down to regional or national effects; the effects at future time periods are usually already specified. Other economic determinants, e.g. in models of national economies and trade, will need separate consideration. The value function is then

$$V(s(\cdot),\cdot): \mathbb{R}^n \to \mathbb{R}^m.$$

The impact valuation, that is, the change in economic value in each nation in each time period due to an actor's contribution $\hat{f} - f$ to present spatial and contextual footprint f is the same formula as before

$$V\big(s(\hat{f}),\hat{f}\big) - V\big(s(f),f\big) = \begin{bmatrix} V_1\big(s(\hat{f}),\hat{f}\big) - V_1\big(s(f),f\big) \\ V_2\big(s(\hat{f}),\hat{f}\big) - V_2\big(s(f),f\big) \\ \vdots \\ V_m\big(s(\hat{f}),\hat{f}\big) - V_m\big(s(f),f\big) \end{bmatrix}. \quad (4)$$

The terms in the vector represent impact in a nation and over a time period. Note that impact in a nation might depend on spatial footprint well outside national boundaries. NOx pollution in food basin 2 might affect national economy 1, 2 and 3 in the next 5 years. The food basin might be in nation 1, or it might straddle nation 1 and 3, or it might be in none of the nations but plume from the emission source in food basin 2 drifts over nations 1, 2 and 3. These kinds of considerations are already well established in many of the existing models behind environmental pricing. The interactions between spatial and contextual footprint change and national and temporal impacts are the least resolution required of formal impact pathways. These pathways will also be represented in the matrix of shadow prices in the first order approximation of equation (4) below.

We introduce the full linear model of the process in Figure 11.

If a food system actor is responsible for a change in spatial and contextual footprint from f to $\hat{f}$ (say extraction of freshwater from the Paraná Basin in Brazil for the production of irrigated soy) then Taylor's theorem approximates the change in economic value, or impact, by

$$V\big(s(\hat{f}),\hat{f}\big) - V(s(f),f) = J_V(s(f),f)\big(\hat{f} - f\big) + error \qquad (1)$$

The difference in footprint, $\hat{f} - f$, is the spatial and contextual footprint of the actor produced now. The matrix of shadow prices

$$J_V(s(f),f) = \begin{bmatrix} \frac{\partial V_1}{\partial f_1}(s(f),f) & \cdots & \frac{\partial V_1}{\partial f_n}(s(f),f) \\ \vdots & \ddots & \vdots \\ \frac{\partial V_m}{\partial f_1}(s(f),f) & \cdots & \frac{\partial V_m}{\partial f_n}(s(f),f) \end{bmatrix}$$

is the Jacobian of the function $V(s(\cdot),\cdot)$. To be clear the shadow price

$$\frac{\partial V_i}{\partial f_j}(s(f),f), \quad i = 1,\ldots,m \;\; j = 1,\ldots n$$

represent the impact according to the monetary measure V_i (change of economic value in the a country, say Uruguay, in the period 2020-2030) per unit of the footprint f_j (which corresponds say to per m^3 of freshwater extracted now from the Paraná Basin in Brazil).

There are country estimates of the social cost of carbon[163]. From integrated assessment model calculations, the social costs in a time period without discounting can be extracted. For climate change impact and a few other environmental pollutants, the model does not require more information than already exists on footprints, impact pathways and shadow prices. For other dimensions of footprint the model is asking a lot more. This is the resolution required though to distinguish impact in the food sector's global but heterogenous value chains with footprints both upstream and downstream into waste and effects from human consumption. Determining the social costs at the coarse resolution discussed is not beyond a societal process and could bring together many of the modelling pieces across disciplines that the scientific community already has. There may be over a million shadow prices in the Jacobian. The Jacobian will generally be very sparse. For example, local effects in water basins are only going to affect a few countries and many effects will not appear in later time periods. There will likely be a repetition of terms. Tractability of the Jacobian relies on other computationally convenient assumptions. One of those conveniences is pure pragmatism. In the consideration of global impact due to food systems, it is the major social costs, and representations of the major impact pathways involving transfers of footprints to costs that need to be embodied in the Jacobian of shadow prices. Small costs and minor pathways should be absorbed as noise into the error term and dealt with by risk pricing, especially so for later time periods.

The impacts across nations and time periods are not yet compared a parity choice and discounting. They are not yet substituted if some are positive and some are negative. Denote the parity and discount vector

$$T = [T_1, \cdots, T_m].$$

The weightings in T can be decomposed into the usual forms of parity weighting terms $T_1, \cdots, T_{195}$. The rest of the terms can be obtained by compound growth using a social discount

[163] Ricke et al., "Country-level social cost of carbon."; Adler et al., "Priority for the worse-off and the social cost of carbon."; W. R. Cline, *Global Warming and Agriculture: Impact Estimates by Country* (Washington DC: Center for Global Development, 2007).

rate. At this level of resolution the discount rate can be country specific and it could involve a decreasing social discount rate as recommended in the discussion from p. 72. Using different parity weightings for different capital effects (e.g. PPP for produced capital and priority for human capital) is possible but not without a more complicated model[164].

Using matrix multiplication, the linear model of the valuation of impact associated to the actor with spatial and contextual footprint $\hat{f} - f$ is

$$T\ J_V(s(f), f)\ (\hat{f} - f). \tag{5}$$

To be explicit how this model is a linear model of the process in Figure 11 and Figure 17:

$$V(s(\hat{f}), \hat{f}) - V(s(f), f) \approx \begin{bmatrix} T_1 & \cdots & T_m \end{bmatrix} \begin{bmatrix} \frac{\partial V_1}{\partial f_1}(s(f), f) & \cdots & \frac{\partial V_1}{\partial f_n}(s(f), f) \\ \vdots & \ddots & \vdots \\ \frac{\partial V_m}{\partial f_1}(s(f), f) & \cdots & \frac{\partial V_m}{\partial f_n}(s(f), f) \end{bmatrix} \begin{bmatrix} \hat{f}_1 - f_1 \\ \vdots \\ \hat{f}_n - f_n \end{bmatrix}$$

Impact valuation
Marginal valuation
Actor footprint
Discounting and parity
National and temporal variation in value change
Spatial and contextual variation in footprint

Note that the present comparable value function

$$T\ V(s(f), f)$$

is not vector valued. It reverts to the scalar form on p. 90 with shadow price vector

$$J_{TV}(s(f), f) = T\ J_V(s(f), f).$$

What has been suggested is that it is most useful to deconstruct the calculation of the shadow prices discussed on p. 90 into a minimum level of national, temporal, spatial and contextual detail. The extra burden on actors is reporting spatial and contextual footprint. The extra burden overall is mostly on the calculation of shadow prices. Second order corrections to this linear model could proceed as before in terms of the Hessian, which can be constructed from $H_{TV} = T \cdot [H_{V_0}, \cdots, H_{V_m}]$. Hessians would be an extra burden on a societal process above the calculation of shadow prices. Pragmatism should again be the main computational consideration. If calculated, the Hessians should feature the major scarcity concerns, and the

[164] A further application of the chain rule provides a linear model of the process in Figure 17: assume a vector attribution function $C = [C_1(z(f), f), \ldots, C_p(z(f), f)]$ as a list of function of capital stocks changes against footprints given extra determinants of capital changes z. Assuming all footprint changes create value changes by factoring through capital changes then there is a valuation function $U = U(v(C), C)$ from capital stock changes to economic value such that

$$V(s(f), f)\ (\hat{f} - f) = U\left(v(C(z(f), f)), C(z(f), f)\right)\ (\hat{f} - f).$$

The undiscounted linear model is

$$J_V(s(f), f)\ (\hat{f} - f) = J_U(v(C), C)\ J_C(z(f), f)\ (\hat{f} - f).$$

The Jacobian J_U is the matrix of shadow prices with respect to capital changes, and J_C is the attribution matrix of rates of capital changes from footprint changes. These are first order estimates of the processes of valuation of capital changes and attribution of capital changes. The linear model has three terms corresponding to the three steps of the process in Figure 17. In this three-term model parity scaling based on the kind of capital changed could be implemented. It is also the conceptual basis for understanding potential substitutions of welfare from non-financial or non-produced capital changes in one location to welfare from financial or produced capital in another location.

major synergies and trade-offs that might distort policy choices. The Hessians should be very sparse, reflecting that all else being equal most shadow prices are approximately constant. Minor deviations, increasingly so for later time periods, should be absorbed as noise into the error term and dealt with by risk pricing.

The model in equation (5) relies on a choice of parity and discounting (potentially from a common set of choices linked to the socio-economic drivers embodied in s), a common Jacobian of shadow prices, and the spatial and contextual footprint of the actor[165].

Social costs or abatement costs

Abatement measures which reduce carbon footprint were discussed under the abatement cost of carbon on p. 54. Portfolios of abatement measures were discussed that result in achieving a total reduction target for carbon footprint.

Are sustainable products and practices in the food sector which offer reduction of food impact footprints compared to a baseline product or practice, abatement measures in a similar sense? If a target for food system transformation were represented by a footprint reduction target, what is the value of sustainable products and practices in the food sector as contributions toward that target?

Sustainable food products and practices as abatement measures

For sustainable products and practices that substitute a baseline product or practice to be abatement measures the assumption is that they offer, all else being equal, the same private value to consumers or procurers of goods as the baseline product or practice. The additional cost of the sustainable products and practices to match that value is the abatement cost. The reduction in footprint from substitution of the baseline product or practice is the abatement. The abatement value is the social benefit associated to the abatement.

To explain the relationship in basic terms. The difference between a social cost and abatement cost is the difference between incurring value loss in the baseline (a social cost) and averting that value loss by the cost of doing something (abatement). Suppose a \$100 visit to the doctor now saves a \$1000 operation in a year's time if nothing was done. Assume no pain and suffering over the year and the visit to the doctor is as traumatic as the operation. The abatement value is \$1000 (discounted back one year). The abatement cost is \$100. The visit to the doctor is the abatement of the operation. Outside of the cost, both have the same private value (fixing the medical problem).

The assumption that sustainable products and practices match the private value of baselines can be complicated to determine for the food sector. Unfortunately, all else is not equal.

Sustainable energy which offers the same number of kilowatts for a lower carbon footprint will be substitutable for consumers willing to pay the higher cost. Kilowatts represent approximately the same private value in use.

Sustainable food products offering the same number of calories and nutrients may not be considered to have the same private value in use. Consumers might react more strongly to other determinants of value compared to an energy product. The sustainability story attached to the product might make it more valuable to some consumers. The taste difference between a plant-based protein product and its equivalent animal-based protein product might make the

[165] This model approximates a conceptual model in space, time and context of higher resolution. Conceivably $V(y,t,s(y,t,f(x,c)),f(x,c))$ where (x,c,y,t) are spatial, temporal and contextual variables respectively. In the matrix model described the index m conflates the variation of monetary estimates in space and time (y,t) and the index n conflates the dependence of economic value change in spatial and contextual differences in footprint (x,c).

product less valuable to some consumers. For food products these are major factors in private value. Adjustments to economic value were raised when discussing the abatement cost of carbon. Sustainable food products and practices will often have a clear cost difference to baselines, in the sense of the cost difference between one litre of plant-based milk and animal-based milk, the cost difference to produce one kg liveweight of wholly grass-fed beef versus intensively finished beef, or the cost per ha to implement a sustainable farming practice versus the baseline practice. LCA and other methods can determine the footprint difference because there is a clear functional unit. What is not clear is whether, at that cost difference, the products have the same private value.

Regulatory measures based upon forcing demand change might not care about the private value. Many literature studies take the social value perspective on matching calorie and nutrient delivery at the scale of the global population. Voluntary measures based upon responding to changing demand, or the responses to attempts to force demand change, will be sensitive to private value. The provision of food is largely a private service.

There are several conceivable corrections when private value equivalence is hard to determine. One is the injection of additional investment costs – these costs are the additional amount required to develop the abatement products until they match the private value of the baselines. These costs could be added to the price difference to form the abatement cost. Another is social cost adjustment. An abatement product with price difference as the abatement cost would then provide social cost reduction from footprint reduction and an additional social cost correction from the difference in private value. This approach would require food system transformation targets to be stated in terms of social cost reduction instead of footprint reduction, which we discuss below. Another approach is discovery of equal value product substitution. This would require simulation or empirical research on the equilibrium abatement cost in market to understand the products and practices substituted by the sustainable product or practice at the price offered.

In trying to align the social value perspective (which should determine the abatement value) and the private value perspective (which will likely be a main determinant in abatement costs) we recommend a form of equilibrium abatement cost adjustment. The abatement of an abatement measure is dependent on the abatement portfolio(s) it appears in. The contribution of the abatement measure to an abatement portfolio is in the total amount of abatement it offers. This requires a projection of the demand of total substitution of the sustainable product for baselines. The private value matching is not per good or practice (some consumers will never find plant-based dairy equivalent to animal-based dairy even with a negative abatement cost), but in the total amount of substitution of present goods by the sustainable alternatives (how many consumers did find plant-based dairy equivalent or better than animal-based dairy at the abatement cost). From the products or practices displaced the total abatement cost and the total footprint abatement can be estimated. Marginal abatement costs and footprint abated per unit could then be calculated. To form an abatement portfolio with adjusted marginal abatement costs, this would have to be repeated for each abatement measure. Every time an adjusted marginal cost was calculated, the new demand profile (the substituted products and the previous baseline) become the new baseline. This is to ensure that the abatement is maximised for the abatement measures with the lowest adjusted marginal cost and substitution of a baseline product does not occur twice.

The same comments above apply to investment in companies and initiatives offering sustainable products and production practices. They, the companies and initiatives, represent portfolios of abatement measures.

In the total abatement method outlined, uncertainty in demand produces uncertainty in total abatement. This introduces uncertainty in the marginal abatement cost of an abatement portfolio designed to meet a footprint reduction target. To explain this in simple terms we revert to Figure 15. For food products which act as abatement measures (individual columns in the abatement curve in Figure 15), the height of the column, which is the marginal abatement cost of that measure, may be uncertain if price differences with equal value substitutes are unknown, the width of each column (now a volume in the several dimensions of footprint for food impact) is uncertain because of uncertainty in demand, and hence what is the next most expensive abatement measure in the directions of the individuals footprints once the footprint reduction target is met is uncertain. If such abatement portfolios could be constructed with their uncertainty, this would be the equivalent of marginal valuation of food impacts using abatement costing (and, without uncertainty, form the abatement surfaces in Figure 21).

We reiterate the difference between the marginal abatement cost of a product or practice (the height of a column in Figure 15) and the marginal abatement cost of a portfolio of products and practices (the height of the last column in Figure 15). The terminology is not inconsistent. The marginal abatement cost of a portfolio with one abatement measure in it is the marginal abatement cost of that measure. If the portfolio has more than one measure then there can be a difference between the marginal abatement cost of a measure in the portfolio, and the maximum marginal abatement cost of a measure in the portfolio (Figure 24).

One implication of the above discussion is that the smaller the correction to abatement costing, likely the lower the uncertainty in achieving abatement value. Products that offer, all else being equal, the same private value will likely have clearer demand trajectories by direct substitution. Costed investment in food technology that enables plant-based meat and dairy products to be direct substitutes (taste, experience, nutrition, etc.) to animal-based meat and dairy reverts the marginal abatement cost to the price difference between the direct substitutes[166].

Another implication from the difficulty in abatement costing for food products is zero-revenue taxation. Suppose that the marginal abatement cost of an abatement portfolio meeting a food impact footprint target was used as the basis for a tax on food sector activities that created footprints. Further, suppose the revenue from the tax was used to offset the total abatement cost of the portfolio to stimulate additional demand and achieve the footprint reduction target more rapidly. One way to allocate the revenue is based proportionally on the substitutes of the taxed product within the abatement portfolio. This allocation becomes much clearer with same private value direct substitutes versus discovering empirically an equal value basket of substitutes.

Footprint targets versus impact targets

Social costs and abatement costs are two approaches to valuation discussed for costing carbon. They use the same formula for impact valuation (equation (1) on p. 90), except the valuation factors substituted into the equation are either marginal social costs or marginal abatements costs.

Impact valuation using marginal social costs measures the change in social costs due to the actor. For a sustainable product or practice the impact valuation uses the abatement (footprint reduction) from substitution of a baseline as the footprint. The impact valuation would be the abatement value of the product or practice. If society had a target for reducing social costs from the food system (what we call an impact target), then the abatement value represents the contribution of the sustainable product or practice to that target. The incentive for

[166] There could be an opposite argument. Novel products will have greater uncertainty in which products they substitute, but their novelty may allow them to establish a displacement of baselines. It is unclear without further research if more expected total abatement would be achieved through novel products or direct substitution of existing products, or a mixed approach is complementary to balance abatement cost and risk to achieving abatement.

sustainable products or practices in this view depends on how much the abatement value is internalised into the value chain of those products and practices – either subsidies are received directly, or demand is increased, or costs lessened (discussed further in Case Studies of Food System Impact Valuation).

For a sustainable product or practice, impact valuation using marginal abatement costs and abatement as footprint calculates the money saved by that product or practice in abatement costs to achieve a footprint reduction target. This amount will be less than the abatement value of the product or practice (only at the optimal footprint reduction are marginal social costs and marginal abatement costs equal - Figure 16). If the impact valuation using marginal abatement costs is higher than the abatement costs of the product or practice, this indicates that sustainable product or practice should be part of an abatement portfolio to achieve the footprint reduction target. The incentive for sustainable products or practices in this view depends on how much achieving the footprint reduction target is incentivised through internalisation.

Why consider impact at all? Why not set a footprint target and assess sustainable products and practices purely on their footprint? Valuation is the economics required to incentivise achieving the footprint target. First, what should the targets be and where? Abatement value is a measure of the relative importance of footprint reduction which spatially and contextually varies as mentioned. Abatement costing indicates the cost effectiveness compared to other measures in achieving the footprint target.

In practice both points of view are valuable[167]. Without understanding the social costs, it is difficult to determine which footprint changes optimise welfare. Without abatement costs, it is difficult to determine what impact target optimises welfare. In terms of whether an impact valuation of sustainable products or practices should use marginal social costs or marginal abatement costs, it is presently unclear what will be the major viewpoint of those offering incentives – meeting footprint targets at least cost or achieving the most social benefit.

Damage costings associated to food system impacts are presently more developed than abatement costings. Case studies 4-9 involve mostly damage based valuation factors and we view them as estimates of marginal abatement value.

Are footprint reduction targets and impact targets interchangeable? Footprint reduction is a proxy for social cost reduction (Figure 16). From the perspective of economic food policy, the footprint reduction target should match the optimal reduction of social costs or is part of a graded set of targets toward the optimum.

Many different footprint targets could achieve the same impact target. The collection of abatement portfolios whose total abatement value achieves an impact target is different from the collection of abatement portfolios whose total abatement achieves a footprint target. The abatement portfolio that achieves an impact target at lowest cost will select out some of the footprint reduction targets that achieve the impact target.

The difference between footprint and impact highlighted on p. 77 mean that, in practice, going back and forth between footprint targets and impact targets is not straightforward. Footprint targets will have to be spatially and contextually disintegrated to associate them to an impact target. The many ways to do this mean that a global footprint reduction target (the food system should reduce globally this amount of CO_2-eq emissions, this amount of water extraction, this amount of nitrogen leaching, etc.) could be associated to several impact targets depending on where the reduction is achieved. Evidently the greatest of those impact targets (the most social

[167] LCA literature captures an extensive discussion distinguishes between attributional (footprint) and consequential (impact) LCA: J. Davis et al., *Generic strategy LCA and LCC : Guidance for LCA and LCC focused on prevention, valorisation and treatment of side flows from the food supply chain* (2017 2017), http://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-27973.

cost reduction) is the desirable way to disintegrate total footprint reduction into spatial and contextual footprint reduction. The configuration of the spatial and contextual footprint targets associated to the highest impact target will depend critically on parity and discounting. Therefore, whether the footprint reduction targets are viewed as equitable is unclear. To an impact target there could be a great many regional and production permutations.

This is a possible way to simplify target setting: a global footprint target, which is disintegrated into a spatial and contextual footprint target according to maximising the social benefit from that footprint reduction. At least as a start point for political agreement.

In the next section we discuss example footprint targets for food system transformation. In the case studies, we discuss an impact target from a 2019 FOLU report.

Mixing social and abatement costs in valuations

Some of the case studies in Case Studies of Food System Impact Valuation use a mixture of marginal social costs and marginal abatement costs in equation (1). It is not entirely clear how to interpret and use the valuation.

Suppose one of the footprints changes, say carbon emissions, is being priced for least cost achievement of a 2-degree target, while for the other footprints there is no target. The activity is being valued according to cost-effectiveness in one dimension of footprint and social benefit in others. Mixing costs and value is problematic for economics and accounting[168]. In practice marginal abatement costs can be viewed as lower bounds on marginal social costs, and marginal social costs as upper bounds of marginal abatement costs. This view is interpreting the mixed valuation as either a value or a cost. Viewed as a value, the valuation is ignoring the footprint reduction setting implicit in abatement costs. Viewed as a cost, the valuation has implicit footprint reduction targets.

For the case studies, the mixing does not change the valuation amount much. The marginal abatement costs used are mostly marginal abatement costs for carbon, and the values of carbon abatement costs are within the central to high ranges of the IWGSCC social cost of carbon. It is the interpretation which changes.

In an optimal economy the marginal social costs equal the marginal abatement costs. Is this an assumption that can be used to turn social costs into abatement costs and abatement costs into social costs? This also needs careful interpretation. For example, suppose the marginal abatement cost of carbon was calculated for an emissions target for a 2 deg world. Assuming that a 2 deg world is the optimal outcome (any less carbon emission and the social and human welfare of developing nations would have suffered from impaired use of carbon for production and growth, any more and climate change damages would start to outweigh the benefit gains), then the marginal abatement cost of carbon is equivalent to the social cost of carbon in a 2 deg world, i.e. the damages produced per tonne of extra emission in that world. This is not the marginal valuation of the social cost of carbon for other equilibrium temperature outcomes, but with a specific assumption about the future and the carbon emissions trajectory. At the optimum, marginal abatement costs are conceptually social costs but in futures where the optimal footprint reduction has been achieved, and achieved very rapidly in relation to the timescale of the impact pathway for the various footprints[169].

[168] p. 136 OECD et al., "System of Environmental Economic Accounting 2012 : Experimental Ecosystems Accounting," (2014), https://doi.org/10.1787/9789210562850-en.
[169] J. R. Lamontagne et al., "Robust abatement pathways to tolerable climate futures require immediate global action," *Nature Climate Change* 9, no. 4 (2019), https://doi.org/10.1038/s41558-019-0426-8.

Case study 3, an impact valuation of the global food system, uses some valuations that are not social costs. They provide examples to illustrate the difference between marginal social costs and abatement costs.

In case study 3 there is a valuation of rural welfare as an impact of the global food system. The footprint is the number of people working in agriculture below the World Bank poverty line of $5.50/day. The footprint reduction target is zero people working in agriculture below the World Bank poverty line. An annual marginal abatement cost is calculated at $5.50 x 0.4 x 365.25 /pp rural in poverty/yr (40% is the average rural poverty gap), which is the average annual cost to raise the income of one person below the World Bank poverty line above the poverty line. This is not a calculation of the social costs of poverty. The assumption is the social costs of poverty would be abated by this level of income.

Another valuation in case study 3 is of private benefits from overapplication of fertiliser. The footprint is a calculation of the global overapplication of fertiliser in tonnes. The average market price of fertiliser per tonne is used as the valuation factor. A correction to the additional welfare from the saved private costs against the welfare losses from decreased activity in the agriculture input sector is not applied. This private benefit is a social benefit when corrected. It can also be interpreted as a negative abatement cost if there was a target involving fertiliser overapplication reduction.

Adding marginal abatement costs with the same footprint dimension must be done with care. The same care as required for carbon emission reduction accounting[170]. Assumptions in the abatement portfolios and how to combine them together determines the marginal abatement costs of the combined portfolios. The ability to trade footprint reduction lowers marginal abatement costs and makes footprint reduction more efficient (Figure 24). This is the argument

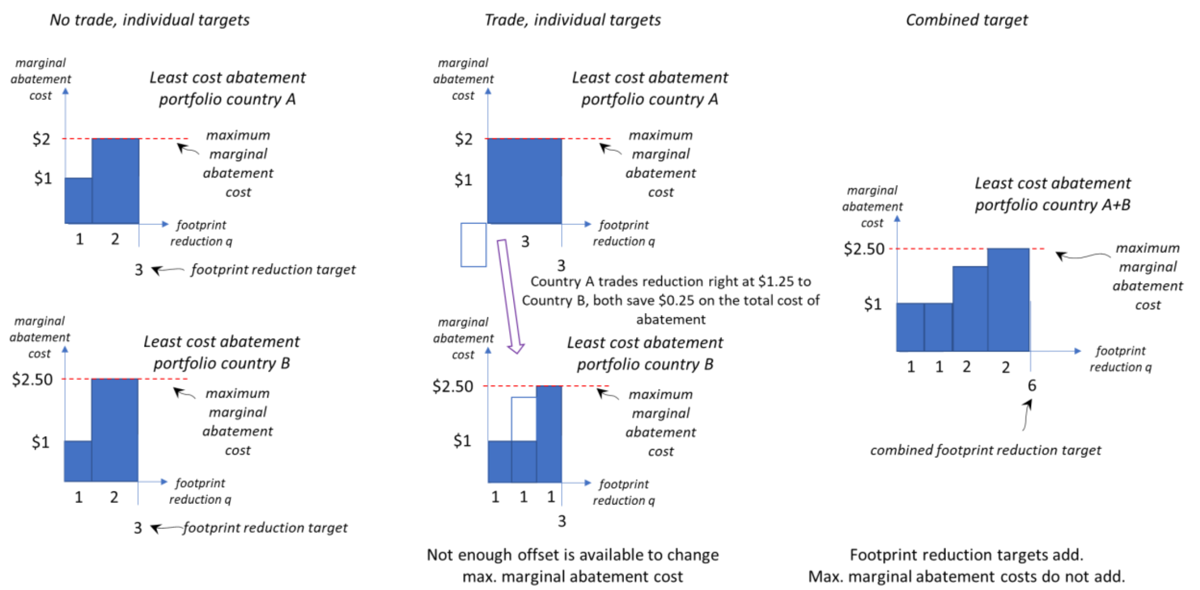

Figure 24: Simple illustration of efficiency in footprint reduction trading for footprints that can be offset, and that marginal abatement costs do not add when footprint reduction targets can be combined.

for the efficiency of carbon trading. The inability (or prohibitive cost) to trade non-carbon footprint reduction is one of the reasons for the disintegration of marginal valuations on p. 99 into a Jacobian matrix with spatial and contextual footprint distinctions. Is a cubic metre of water extraction saved in the UK going to offset the damages of a cubic metre of water extracted in Brazil? It is not only marginal social costs that require this breakup because of the

170 L. Schneider et al., "Double counting and the Paris Agreement rulebook," *Science* 366, no. 6462 (2019), https://doi.org/10.1126/science.aay8750.

different damages that the same footprint might occur. The inability to globally trade abatement measures or the adjustment to their costs to do so, makes calculating global portfolios of abatement measures applied to global footprint reduction targets very complicated outside of carbon.

There are limitations on how much technology and practice improvements, even at high costs, can enable footprint reduction in the production of food[171]. Likely some abatement costs in a food system abatement portfolio will be stimulus measures to change demand[172].

Adding together marginal abatement costs across different footprints dimensions also require corrections or understanding of the potential error in the valuation. Most of the marginal abatement costs are likely to be literature estimates of abatement portfolios for that footprint dimension singularly (carbon, reactive nitrogen, health care cost abatement, etc.). Abatement portfolios of mixed abatement measures with co-benefits addressing multiple footprints toward a food footprint reduction target may have lower marginal abatement costs.

Combining the footprint reduction targets from abatement portfolios that consider footprint singularly needs consideration. It is not as simple as adding targets together like they are orthogonal. That is, taking the marginal abatement cost for carbon from an abatement portfolio with 100Gt of CO2-eq reduction target by 2030 and the marginal abatement cost for nitrogen from an abatement portfolio of 1000 Tg N reduction target by 2030[173] provides the marginal abatement costs for carbon and nitrogen for a combined reduction target of 1000 Tg N and 100Gt Co2-eq by 2030. In addressing the global nitrogen challenge, other non-nitrogen footprints will increase or decrease (e.g. the energy used to produce nitrate fertiliser) and potentially alter whether footprint targets are being met in other dimensions[174].

Overall, because of the complexity in abatement costing and the need to be consistent about multidimensional targets for the food system and the underlying abatement portfolios, it is recommended to use social costs until abatement costings for food impacts are further developed and compiled.

Targets for food system transformation

Sustainable products and practices require footprint or impact reduction targets to be assessed as cost-effective abatement, or reducing social cost respectively, and proportionally incentivised. Setting consistent footprint or impact targets for food system transformation is a consensus exercise. There are several high-level reports indicating targets for footprint reduction for the global food system that add to or synthesise a large literature base. There exists no body like the United Nations Framework Convention on Climate Change (UNFCCC)

---

[171] C. M. Anderson et al., "Natural climate solutions are not enough," *Science* 363, no. 6430 (2019), https://doi.org/10.1126/science.aaw2741; B. Bajzelj et al., "Importance of food-demand management for climate mitigation," *Nature Clim. Change* 4, no. 10 (2014), https://doi.org/10.1038/nclimate2353.

[172] Bajzelj et al., "Importance of food-demand management for climate mitigation."

[173] UNEP Emission Gap report UNEP, *Emissions Gap Report 2019*, United Nations Environment Programme (Nairobi, 2019), https://www.unenvironment.org/resources/emissions-gap-report-2019. staying on the 2 deg C warming target requires a 20% reduction from present trajectory from 2020 to 2030, which amounts to 100 Gt CO2eq. Liu et al., "Reducing human nitrogen use for food production." estimated 171 Tg N / yr input into food production in 2015, which grows linearly to 100 Tg N/yr extra by 2030. It estimated 77% of N application lost based on present day. This is a 2000 Tg N loss of N from food production and consumption between 2020 and 2030. The International Nitrogen Initiative supports a global goal to halve reactive nitrogen waste by 2030 http://inms.international/news/ini-commits-support-global-goal-halve-nitrogen-waste-2030-support-inms-project. S. Reis et al., "Synthesis and review: Tackling the nitrogen management challenge: from global to local scales," *Environmental Research Letters* 11, no. 12 (2016), https://doi.org/10.1088/1748-9326/11/12/120205.

[174] Reis et al., "Synthesis and review: Tackling the nitrogen management challenge: from global to local scales."

that brings national bodies, international bodies and industry together to agree on the relevant food system footprints and coalesce the targets into scientifically informed reductions in those footprints[175]. This section reflects briefly on the question of whether the food system needs to set its own targets, or whether the food sector should look to proportional contribution to existing targets and where they might be compiled from.

The drafting and signing of The Paris Agreement within the UNFCCC set a physical target of 2-degree Celsius global average temperature with respect to mid-nineteenth century global average temperature. The temperature target is a proxy to avoid social costs of climate change that cannot be avoided by adaptation. Mitigation in the context of climate change is emissions reduction – footprint reduction. Adaptation in the context of climate change is avoidance of social costs but not through footprint reduction. Mitigation and adaptation together achieve impact reduction. Translating the temperature target is not straightforward. The Paris Agreement set the 2 deg target and a desire for a 1.5 deg target. Subsequent work by the climate science community after 2015 is the latest science on what emissions targets accord with 2 deg and 1.5 deg. There is large uncertainty because of modelling assumptions[176]. Bodies like UNEP, with the Emission Gap report, act to synthesis the scientific literature into a footprint reduction target, which is roughly a 100 Gt CO2eq reduction (16%) from a baseline business-as-usual scenario over 2020-2030 for the 2 deg target, and 200 Gt CO2eq (32%) for the 1.5 deg target, with further large reductions after 2030[177].

In many national emission reduction and trade schemes agriculture is currently excluded, or is delayed from being included, from carbon accounts[178]. It is unclear then what proportion of a 100 Gt CO2eq target should be assigned to food system impact reduction. Proportionally the food system should have a 21-37 Gt CO2eq reduction target based on current contribution to global emissions (21-37%), with 14-30 Gt CO2eq of that total the contribution of agriculture and associated land-use. Contextually, if associated land-use is to become a carbon sink to achieve 2 deg targets, the target by 2050 will be a 100% reduction (carbon neutral) for associated land-use and no growth in CH4 and N2O emissions from present day[179]. What the spatial and further contextual breakdown of this footprint should be is part of an agreement process, acknowledging the larger social and human wellbeing benefits from carbon production in developing countries.

Similar targets come from global nitrogen reduction initiatives, of which agriculture contributes a tremendous share of global N pollution (mineral fertilizer production alone accounts for 53% of the present total human creation of reactive nitrogen)[180]. The International Nitrogen Initiative supports a global goal to halve reactive nitrogen waste by 2030. If applied proportionally to food production and consumption losses, over 2020-2030 this would equate to a reduction target of 1000 Tg N for the global food system compared to business as usual[181]. Like carbon, the spatial and contextual breakdown of nitrogen reduction is also varied when social and human wellbeing are considered. Some parts of the world are recommended to increase their

---

[175] p. 484: Willett et al., "Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems."
[176] R. J. Millar et al., "Emission budgets and pathways consistent with limiting warming to 1.5 °C," *Nature Geoscience* 10, no. 10 (2017), https://doi.org/10.1038/ngeo3031, https://doi.org/10.1038/ngeo3031.
[177] Figure ES.4: UNEP, *Emissions Gap Report 2019*.
[178] https://theconversation.com/why-agricultural-groups-fiercely-oppose-the-carbon-tax-110248 https://theconversation.com/nz-introduces-groundbreaking-zero-carbon-bill-including-targets-for-agricultural-methane-116724 https://www.simpsongrierson.com/articles/2019/major-developments-for-the-zero-carbon-and-emissions-trading-reform-bills
[179] Figure 2, p. 463: Willett et al., "Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems."
[180] Liu et al., "Reducing human nitrogen use for food production."
[181] Liu et al., "Reducing human nitrogen use for food production."

nitrogen footprint for food security and development, and other parts to drastically reduce their nitrogen footprint[182].

The food system inherits targets from existing global societal initiatives in carbon, nitrogen, and water. For impacts from pesticides it is the main contributor, and its contribution to obesity and other disease could potentially be extracted from national health targets where they exist. High level reports on the food system aim to synthesise societal initiatives such as the UN Sustainable Development Goals (SDGs), The Paris Agreement, and planetary boundaries, with food system transformation targets.

Target setting is a priority for food system transformation research. From the introduction of the "Food in the Anthropocene" report of the EAT–Lancet Commission on healthy diets from sustainable food systems:

> "The absence of scientific targets for achieving healthy diets from sustainable food systems has been hindering large-scale and coordinated efforts to transform the global food system. This Commission brings together 19 Commissioners and 18 coauthors from 16 countries in various fields of human health, agriculture, political sciences, and environmental sustainability to develop global scientific targets based on the best evidence available for healthy diets and sustainable food production. These global targets define a safe operating space for food systems that allow us to assess which diets and food production practices will help ensure that the UN Sustainable Development Goals (SDGs) and Paris Agreement are achieved."[183]

The EAT–Lancet Commission report provides global targets for CO2-eq emissions, biodiversity loss, freshwater use, reactive nitrogen and soluble phosphorus leakage, and land-use change. It also provides a reference diet which equates to a global malnutrition footprint reduction target for food consumption categories[184].

The targets can be compared with present day amounts to understand footprint reduction targets by 2050 compared to present day footprint. Health and environmental targets are integrated together. The EAT–Lancet Commission report provides global targets and indicates the need to regionalise and contextualise footprint reduction targets according to impact through an agreement process.

The Eat-Lancet targets are not targets across all material issues associated to food system impact. There are other approaches to setting targets including inferring targets from physical boundaries such as land boundaries[185]. Even though targets can be set with reference to the SDGs, it is not clear that the food system can achieve them. While co-benefits exist between physical environmental footprints (carbon, nitrogen, land-use, water), trade-offs exist between social and environmental goals[186]. While pushing down one target, another may rise. In terms of most environmental factors and health, the EAT-Lancet Commission report demonstrates win-wins. Assuming the global diet targets are achieved, environmental footprint reduction

[182] B. Z. Houlton et al., "A World of Cobenefits: Solving the Global Nitrogen Challenge," *Earth's Future* 7, no. 8 (2019), https://doi.org/10.1029/2019EF001222. C. Lu and H. Tian, "Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: Shifted hot spots and nutrient imbalance," *Earth System Science Data Discussions* 9, no. 1 (2016), https://doi.org/10.5194/essd-2016-35.
[183] p. 447: Willett et al., "Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems."
[184] p. 448: Willett et al., "Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems."
[185] H. H. E. van Zanten et al., "Defining a land boundary for sustainable livestock consumption," *Glob Chang Biol* 24, no. 9 (Sep 2018), https://doi.org/10.1111/gcb.14321.
[186] L. Scherer et al., "Trade-offs between social and environmental Sustainable Development Goals," *Environmental Science and Policy* 90 (2018), https://doi.org/10.1016/j.envsci.2018.10.002. Chapter 7: IPCC, *IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems*.

targets and preventable death and disease reduction targets can be achieved together. While international agreements can cap physical emissions and extractions, there is large uncertainty in the achievement of dietary targets. Strategies, including many internalisations (soft approaches to demand change, fiscal incentives, and fiscal penalties), are recommended in the EAT–Lancet Commission report[187]. Work on food system impact valuation, in terms of the underlying basis for social and abatement costing, is part of the follow-on work to investigate the means to achieve food system transformation to the targets identified.

The FABLE Consortium also identified global footprint targets in their report "Pathways to Sustainable Land-Use and Food Systems"[188]. Consisting of health and environmental targets like the Eat-Lancet Commission report it covers malnutrition (zero hunger and a target for dietary related preventable death), CO2-eq emissions, biodiversity and ecosystem services, freshwater use, reactive nitrogen and soluble phosphorus leakage, and land-use change. Except for the phrasing of the malnutrition footprint (the FABLE report does not recommend a detailed reference diet to achieve the DALY reduction), the global footprint categories and 2050 target values are very similar to the EAT-Lancet Commission targets (some of the FABLE targets are for 2030).

The FABLE targets are global. The main feature of the FABLE report is to identify pathways to the targets in the 18 countries that are part of the consortium. The pathways give detailed context over time indicating how the targets can be achieved, ultimately to build consensus for food system transformation. The FABLE targets do not currently include social capital targets as discussed in the FABLE report. The FABLE targets concentrate presently on health, environment and economics. The FABLE pathways offer potential skeletons for subsequent development of abatement portfolios, demonstrating feasibility and considering co-benefits and trade-offs amongst the three dimensions of health, environment, and economics. Potential costings of broad investment for the pathways and policies are taken up by the later FOLU report which we discuss in Case Studies of Food System Impact Valuation. The modelling in the FABLE report shows the criticality of Chinese demand trajectories on achieving dietary and environmental targets[189].

In summary, there is enough scientific work to inform food system impact or footprint targets. The gap is in the political and societal process and structures to enable that process to develop agreement. For social cost reduction, impact targets indicate what should be achieved and where. Impact targets guide impact reduction incentives for sustainable products and practices. Abatement costings provide direction for fiscal, policy and market incentives amenable to national accounting. With the global value chains of the food system, it would be very difficult to consistently account and apply incentives to sustainable food products and practices based on abatement costings without global agreed footprint targets broken down spatially and contextually with consideration of impact pathways.

Variability and uncertainty

This section summarises the variation and uncertainty that has been highlighted in the previous sections. Each stage of the valuation process in Figure 17 has variation and uncertainty and it compounds from footprint to valuation (Figure 25). The compounding

---

187 Table 6, p. 478: Willett et al., "Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems."

188 p. 14: FABLE, *Pathways to Sustainable Land-Use and Food Systems. 2019 Report of the FABLE Consortium.*, International Institute for Applied Systems Analysis (IIASA) and Sustainable Development Solutions Network (SDSN) (Laxenburg and Paris, 2019).

189 p. 45: FABLE, *Pathways to Sustainable Land-Use and Food Systems. 2019 Report of the FABLE Consortium.*

uncertainty manifests as enormous variation and uncertainty for valuation factors (Figure 20). Valuation factors concentrate into one numerical value a large part of the valuation process.

The choices of data, models, scenarios, assumptions about including scarcity and interaction corrections, welfare measure, discount rate, and choice of parity, result in different valuations.

The data on the actor's footprint is often incomplete, either through lack of knowledge or lack of disclosure. Some footprint information is directly measured by the actor in their own operations or in their supply chain. Other actor footprint information, such as carbon emissions and nitrogen footprint, need the assistance of tools and third-party databases as discussed from p. 63. Variance exists across databases and different tools. The database and tools themselves have error bars relating to the footprint they are measuring. Lack of disclosure is a separate issue discussed below.

Calculating the societal emission footprint for carbon has large uncertainty by itself[190]. This is in addition to the uncertainty in what level of emissions relates to what level of warming, see footnote 176. Other societal footprint information is less monitored, with a range of estimates across literature. Approximating capital changes for the global, systemic, and long-term effects along impact pathways has inherent ambiguity and uncertainty from the use of models as discussed from p. 64 and p. 96. This results in modelling and modelling structure error[191]. In a practical sense, using a range of different models provides an estimate for modelling structure

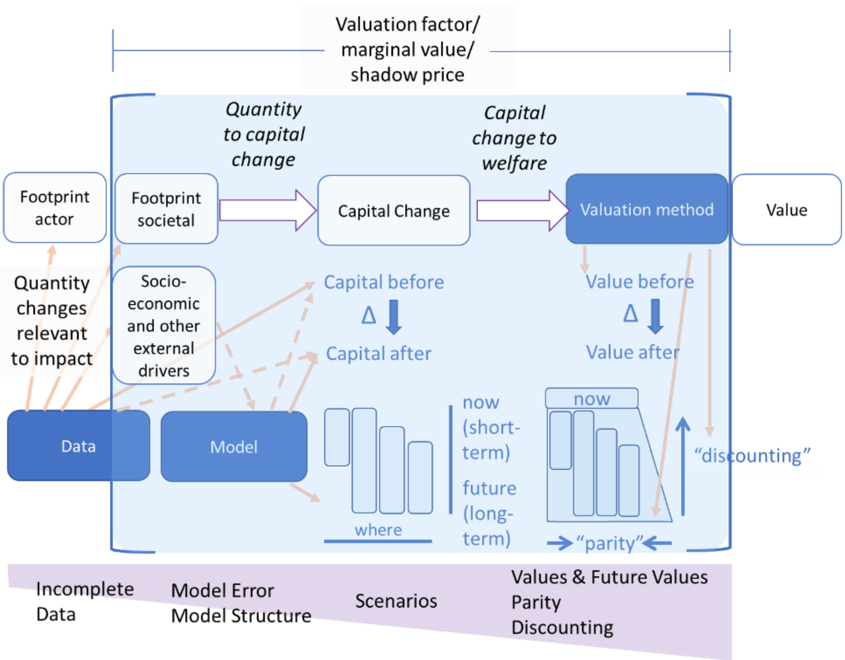

Figure 25: Compounding uncertainty along the valuation steps

[190] M. Jonas et al., "Quantifying greenhouse gas emissions," *Mitigation and Adaptation Strategies for Global Change* 24, no. 6 (2019), https://doi.org/10.1007/s11027-019-09867-4. https://ghgprotocol.org/calculation-tools

[191] K. Beven, "On the concept of model structural error," *Water Sci Technol* 52, no. 6 (2005); Stern, "The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models."; M. G. Morgan and M. Henrion, *Uncertainty: a guide to dealing with uncertainty in quantiative risk and policy analysis* (Cambridge, UK: Cambridge University Press, 1990); R. Knutti, "Should we believe model predictions of climate change," *Philosophical Transactions: Mathematical, Phsyical and Engineering Sciences* 366, no. 1855 (2008); D. A. Stainforth et al., "Confidence, uncertainty and decision-support relevance in climate predictions," *Phil. Trans. R. Soc. A* 365 (2007); L. A. Cox, "Confronting Deep Uncertainties in Risk Analysis," *Risk Analysis* 32, no. 10 (2012), https://doi.org/10.1111/j.1539-6924.2012.01792.x.

error. Four models were used for the US IWGSCC estimates of the social cost of carbon[192] discussed from p. 49.

Long-term external drivers lead to a range of possible future impacts. Short-term uncertainty where responses are unknown also leads to a range of potential impacts. For example, responses of the economy to large production and consumption changes[193]. The uncertainty due to scenarios was discussed on p. 82.

The variation from choices, and the uncertainty within those choices, ascends from footprint to attribution of capital changes to valuation. Choices in welfare, discounting and parity were all shown to create significant uncertainty in the discussion from p. 67 and p. 84. For social costs of carbon, the combined tail variation toward higher values from discounting and parity can be several orders of magnitude. This variation is on top of that from footprint and modelling. Ambiguity in mixing social and abatement costs also creates error bars in valuations.

Within choosing a valuation factor there is an implicit choice of economic model and environmental, or social, or health models. Implicit choices of data relevant to other business and other sector footprints. Implicit choices of scenarios, values, discounting rate, and targets. Consideration in the choices spans food system theory, economic theory, and their interface. The number of permutations in all the choices is the significant. A valuation factor represents a highly uncertain number.

What does a valuation factor look like when treated as an uncertain number? Figure 14 on p. 51 shows the social costs of carbon emission as a distribution of numerical values. Figure 14 is interpreted by the possible numerical values on the x-axis, and how likely that the social cost of carbon is that numerical value on the y-axis. This is the distribution of the social cost of carbon treated as an uncertain number. The (right-sided) tail of the distribution is the shape of the distribution as it moves to the right along the x-axis toward increasingly higher monetary values for the social cost of carbon. As the possible monetary values for the social cost of carbon get larger, the chance that such a large value will be realised as the cost incurred by society into the future gets less. The shape of the tail is always decreasing toward zero (under the assumptions in Alignment of Impact Frameworks). Larger values get less likely. The rate at which the tail decreases toward zero is critical for understanding the risk posed to society by the possibility of larger than expected values. The rate at which the tail decreases as the uncertain cost gets larger is called the “fatness” of the tail.

The discussion and references from p. 49 evidence that the ascending uncertainty described above does accumulate in valuation factors in practice. The references in footnote 18 describe how the distribution for the social cost of carbon in Figure 14 is likely a sub-sample of the uncertainty, and the spread of estimates is conceivably larger. The marginal abatement costs of carbon are also uncertain numbers because it is unknown whether abatement measures will be adopted to the degree assumed in a marginal abatement curve. Even if adopted, it is uncertain of abatement measures will achieve the given level of abatement at that abatement cost. Discounting uncertainties are still present in abatement costing.

The marginal social and abatement costs of carbon are not unique in being uncertain. The debate on valuation given large uncertainty is also not unique to carbon. Literature evidences

---

[192] Dietz, "The Treatment of Risk and Uncertainty in the US Social Cost of Carbon for Regulatory Impact Analysis."

[193] S. Wynes et al., "Measuring what works: quantifying greenhouse gas emission reductions of behavioural interventions to reduce driving, meat consumption, and household energy use," *Environmental Research Letters* 13, no. 11 (2018), https://doi.org/10.1088/1748-9326/aae5d7. F. Brunner et al., "Carbon Label at a University Restaurant – Label Implementation and Evaluation," *Ecological Economics* 146 (2018), https://doi.org/https://doi.org/10.1016/j.ecolecon.2017.12.012.

a spread of nitrogen pricing estimates[194], a spread of ecosystem service pricing estimates[195], a spread of health valuation estimates[196], etc.

Inherently, costing non-financial food system impacts involves not only society eventually absorbing the damages or paying to avert them, but taking on risk because of the uncertainty in what those damages or payments will turn out to be. The risk is being transferred from business activity to society. Business get a certain outcome in terms of financial value from the production creating the footprint and society gains uncertainty in the damages or payments associated to that production in return. The countering risk is that society will lose welfare enabled by production if it reduces footprints. However, with present major food impact costs it is strongly expected that, like the distribution for the social cost of carbon in Figure 14, the uncertainty is skewed to the right-side, that is toward higher marginal costs from incurring footprint rather than marginal benefits.

We view non-financial valuation as inherently uncertainty, and take the position that it is more efficient to accept the uncertainty and cost it in, in practice and in theory, rather than make non-financial valuation like financial valuation where centralisation from many transactions in known exchange markets reduces the variation to practically zero. Even for financial capital where there are few transactions, valuations price in risk. Pricing in risk will involve adding a risk premium to the central values. In the presence of skewed distributions to the right (the greater weight of uncertainty is toward higher estimates of the social or abatement costs) this means the risk premium will increase the food impact costing. This also has the effect of making sustainable food products and practices more valuable as abatement measures. More valuable in terms in the reduction of damages (marginal abatement value) and in their cost-effectiveness in abating footprint (marginal abatement costing).

The UN 2018 Inclusive Wealth report, p. 107 comments:

> “The major challenge, however, is to estimate the shadow prices of the natural and ecosystem capital assets. For example, we do not have full knowledge of the production functions of life-supporting systems. Dasgupta and Duraiappah (2012) recognize that we may never get the shadow prices “right”, instead we can simply try to estimate the range in which they lie.”[197]

Can the uncertainty be reduced?

It is unclear at present where the major sensitivities lie for practical estimation of error bars. Variation does exist across different LCA databases in determining actor footprint, but is it a major contribution to the variance of the impact valuation? Similarly, outside of the lock-in effects of carbon, more research is required on the timeframe of food system impacts. Obesity effects are intergenerational, and they are major sources of impact from food systems, but how large is the intergenerational effect into the future? Is it significant enough to increase the sensitivity of the final impact valuation to discount rate?

---

[194] van Grinsven et al., "Costs and Benefits of Nitrogen for Europe and Implications for Mitigation." L. Jones et al., "A review and application of the evidence for nitrogen impacts on ecosystem services," *Ecosystem Services* 7 (2014), https://doi.org/https://doi.org/10.1016/j.ecoser.2013.09.001.

[195] de Groot et al., "Global estimates of the value of ecosystems and their services in monetary units." P. Hamel and B. P. Bryant, "Uncertainty assessment in ecosystem services analyses: Seven challenges and practical responses," *Ecosystem Services* 24 (2017), https://doi.org/https://doi.org/10.1016/j.ecoser.2016.12.008. K. A. Johnson et al., "Uncertainty in ecosystem services valuation and implications for assessing land use tradeoffs: An agricultural case study in the Minnesota River Basin," *Ecological Economics* 79 (2012), https://doi.org/https://doi.org/10.1016/j.ecolecon.2012.04.020.

[196] Neumann et al., "A Systematic Review of Cost-Effectiveness Studies Reporting Cost-per-DALY Averted."

[197] p. 107: UNEP, *Inclusive wealth report 2018 : measuring progress towards sustainability*. Dasgupta and Duraiappah, "Well-being and wealth."

A feature of our recommendation for food impact costing, discussed further in Implications, is that marginal social and abatement costs need to be regularly updated. This updating affects the uncertainty as well. Over time the epistemological uncertainty will decrease, and more information is revealed. However, there are core ethical choices described on p. 84 which cannot be removed. We view the uncertainty as unavoidable.

Estimating uncertainty and pricing risk makes determining valuation factors and impact valuations harder. Below we outline a simple technical approach to risk pricing attached to the linear model described from p. 99. The approach would make it no more difficult for business and society to calculate risk pricing. It would be simple to implement in software packages. It relies though on the distributions of individual shadow prices and their correlations being determined and agreed through a societal process. The latter is the burden in risk pricing.

Users can choose to ignore the uncertainty. The implicit nature of the choices behind valuation factors makes impact valuations done by different users who make their own, or pull them from different sources of literature, very difficult to compare and in some cases difficult to validate. The case studies in Case Studies of Food System Impact Valuation evidence the variation in shadow prices used and in choices of footprint. Even if choices were interoperable, and different parameters for discounting, parity, and even different models could be substituted in and out of calculations so that two impact valuations could be compared on the same set of choices, there is still inherent and large uncertainty in many of the models. Insurance industry standards such as Solvency II increasingly require portfolios to be tested against multiple models. The catastrophe risk modelling community has responded[198]. It is a large effort to make "plug-and-play" integrated modelling platforms in this way. It is argued in Inventory and Development of Methods that an estimation of the uncertainty in shadow prices by scientific consensus across modelling studies would be a faster route to agreement and use than a user themselves having the capability to substitute different models of ecosystem damages, etc.

The uncertainty embedded in different models is inherently a representation of human lack of knowledge (Table 3). Many authors distinguish between stochastic or aleatory uncertainty (random processes), epistemological uncertainty (lack of knowledge) and ambiguity[199]. Decision making under these different types of risk is a developed area[200]. Pricing risk is a form of decision making – it favours some options over others because the uncertainty is reflected in additional cost which is least preferred. We remain pragmatic and use probability theory to represent uncertainty despite other conceivable risk pricing mechanisms[201].

---

[198] https://oasislmf.org/ P. McSharry, "Chapter 12 - Parsimonious Risk Assessment and the Role of Transparent Diverse Models," in *Risk Modeling for Hazards and Disasters*, ed. G. Michel (Elsevier, 2018). K. R. Royse et al., "The application of componentised modelling techniques to catastrophe model generation," *Environmental Modelling & Software* 61 (2014), https://doi.org/https://doi.org/10.1016/j.envsoft.2014.07.005.

[199] M. E. Pate-Cornell, "The Engineering Risk Analysis Method and Some Applications," in *Advances in Decision Analysis*, ed. W. Edwards, R. F. Miles, Jr., and D. Von Winterfeldt (Cambridge, UK: Cambridge University Press, 2007). D. Ellsberg, "Risk, Ambiguity, and the Savage Axioms," *The Quarterly Journal of Economics* 75, no. 4 (1961), https://doi.org/10.2307/1884324.

[200] Cox, "Confronting Deep Uncertainties in Risk Analysis." G. Loomes and R. Sugden, "Regret theory: An alternative theory of rational choice under uncertainty," *Economic Journal* 92, no. 4 (1982). R. J. Lempert and M. T. Collins, "Managing the risk of uncertain threshold response: comparison of robust, optimum, and precautionary approaches," *Risk Analysis* 27, no. 4 (2007). J. Rosenhead, "Robustness Analysis: Keeping your options open," in *Rational Analysis for a Problematic World Revisited: Problem Structuring Methods for Complexity, Uncertainty, and Conflict*, ed. J. Rosenhead and J. Mingers (Chichester, UK: Wiley, 2001).

[201] E. T. Jaynes and G. L. Bretthorst, *Probability theory: the logic of science* (Cambridge: Cambridge University Press, 2003). R. J. Lempert, M. E. Schlesinger, and S. C. Bankes, "When we don't know the

Table 3: The uncertainties mentioned for valuation factors involve different categories and degrees of uncertainty identified in the study of decision-making under uncertainty.

Degree	Data	Model
Almost certain	Observation	
Mild uncertainty (observed stable random processes) (established knowledge) (low ambiguity)	Interpolated, extrapolated, proxy	Well established models of physical processes. Predictable demographic trends. Statistical models of stable processes with sufficient data on populations
Deep uncertainty (rarely observed or non-stable random processes) (lack of knowledge) (ambiguity)		Integrated models. Speculative socio-economic drivers. Statistical models of non-stable processes, or with insufficient data, or applied to subpopulations. Bayesian modelling. Robust criteria.

Pragmatic spatial and temporal resolution for impacts were advocated on p. 77 and p. 99. There is a large amount of variance in marginal social and abatement costs at smaller resolutions than those advocated. Individuals projects may collect data on the ground to assess costs at this small resolution. As stated previously, this report focusses on larger scale assessment for first order corrections of economic activity toward global footprint reduction. The conclusion that greater spatial, temporal, and contextual resolution implies greater certainty needs strong caveats. For example, benefit transfer of valuations creates the impression of spatial resolution but are likely increasing uncertainty[202]. Benefit transfer might help estimate mean changes but should be treated as increasing the error bars around that mean.

There is a final argument for removing the uncertainty in valuation factors that we discuss again in Case Studies of Food System Impact Valuation. It is the argument that the central value of the distribution of valuation estimates can be taken (the average value). The argument is that, because there are many individual point sources of pollutants and many individual receivers of doses from those pollutants, the effects could be treated as independent. So, at aggregated scales, by the central limit theorem the variation averages out and the central value of a valuation factor can be used. This is a very strong assumption on impact pathways. To apply it *carte blanche* to valuation, assumes, at the least, no co-dependency of the individual receivers on variation in discount rates and socio-economic drivers – which have been observed to dominate the uncertainty in some marginal value estimates. The

costs or the benefits: Adaptive strategies for abating climate change," *Climatic Change* 33 (1996). J. W. Hall et al., "Robust climate policies under uncertainty: a comparison of robust decision making and info-gap methods," *Risk Analysis* 32 (2012). Kriegler et al., "Imprecise probability assessment of tipping points in the climate system."

[202] Schmidt, Manceur, and Seppelt, "Uncertainty of Monetary Valued Ecosystem Services – Value Transfer Functions for Global Mapping." COWI, *Assessment of potentials and limitations in valuation of externalities*.

centralisation also removes the risk premium. The centralisation assumption may apply to some food system impact pathways, but we reject it without greater evidence. It does not apply to climate change. Correlations make it unclear where it would apply without further evidence.

The next section is technical. It briefly describes implementing risk pricing practically in the linear model of valuation described in equation (5) on p. 102. To summarise the implications of risk pricing without technical details:

- The uncertainty has three main components, uncertainty in valuation conditional on attribution of capital change, uncertainty in attribution of capital change conditional on footprint, and the uncertainty in footprint. The uncertainty in the first two components is measured by, or in the control of, the societal process for setting marginal social or abatement costs associated to footprints. The uncertainty in footprint is measured by, or in the control of, business.
- One way to incorporate the uncertainty in an impact valuation into a single value is with a risk premium.
- The risk premium is how much society should “charge” to take on the uncertainty in impact associated to the footprint produced by a product, practice, or company.
- The premium is a further chance for credibility and agreement in impact valuation – if set in collaboration with civil society and government who are the bearers, or represent the bearers, of risk.
- Businesses in the same sector have the same playing field if marginal social or abatement costs and their uncertainty were agreed. This incentivises the sector to invest in the societal process for better information about impacts and valuation to reduce the uncertainty and so reduce the risk premium.
- Businesses in the same sector can compete on impact reduction and on disclosure (more information about footprint reduces the uncertainty in footprint, which through the pricing mechanism, reduces the premium on the valuation for that company).
- It is more efficient to communicate uncertainty quantitatively in the distribution of valuations.
- It makes the valuation of less studied localised impacts, known to have large error bars, more credible as issues in methods such as benefit transfer are acknowledged in the distribution and become part of the pricing.
- The uncertainty is highly likely to be right-skewed (Figure 14), meaning a greater chance of higher costs. The risk premium will then be a positive amount added on to the expected impact cost.
- Care must be taken in consideration of the aggregated premium. There are correlated chances of above or below expected impact. If environmental damage such as that from climate change is high, then social damage and health damage is likely to be exacerbated or social benefits not as likely to be as great. The risk premium is not applied to shadow prices individually and risk premiums do not add. In short, the risk premium on the total impact of ten products may be more than ten times the risk premium attached to each product.
- Assumptions valid for market exchange value about centralising prices are unlikely to hold. Impact must be valued differently from expected and central limit theorem assumption on normal financial markets. Uncertainty in impact costing is likely to exhibit a long tail from coincident and correlated impact– tipping points, coincidence of social and environmental damage (e.g. greatest impacts from climate change

expected in the tropical zones, which are least developed, energy-water and food couplings, livelihood and resource changes)[203].

- Risk premiums are likely to be dominated by uncertainty and correlations between the greatest impacts, e.g. carbon and health. Major non-market costs that pose significant joint risk to global welfare. Lesser considerations should be absorbed into standard errors. Research is required to: understand the lock-in generational effects from other footprints associated to major impact besides CO2-eq emissions; local effects occurring simultaneously globally (especially by the same physical or social mechanism); develop further quantitative estimates of synergies and trade-offs between the impacts created by food's multiple footprints as initiated in the 2019 IPCC report[204].
- Summing uncertain benefits and costs, even if they have the same expected benefit or expected cost, does not cancel the uncertainty out. Substitution of economic value is a consideration in summing uncertain benefits and costs.

Linear model with risk pricing

Figure 20 provides a conceptual conditional sequence of random variables on which to build a simple approach to risk pricing. Uncertainty methods exist for actor footprint calculation, e.g. uncertainty in lifecycle assessment[205]. There will uncertainty in the footprint associated to an actor denoted by the random variable

$$footprint(actor).$$

Given a certain footprint of one unit, denote the uncertain marginal valuation by

$$valuation \mid footprint.$$

Approximate the uncertain valuation of the actor by the product of the random variables

$$valuation(actor) = (valuation \mid footprint) \times footprint(actor).$$

A similar sequence can be used to express the linear model in footnote 164 which has explicit shadow prices of capital changes[206]. This product model assumes that the footprint random variable and the marginal valuation random variable are independent. What this means is that when a footprint is observed, none of the marginal valuation numbers are observed to occur more frequently than others. It is unclear if this would be strictly observed. Likely those actors that are less willing to report, or less able to measure their footprint accurately, are associated

[203] Weitzman, "On Modeling and Interpreting the Economics of Catastrophic Climate Change."; Weitzman, "Fat-tailed uncertainty in the economics of catastrophic climate change."

[204] IPCC, *IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems*.

[205] S. M. Lloyd and R. Ries, "Characterizing, Propagating, and Analyzing Uncertainty in Life-Cycle Assessment: A Survey of Quantitative Approaches," *Journal of Industrial Ecology* 11, no. 1 (2007), https://doi.org/10.1162/jiec.2007.1136. R. Heijungs and M. Lenzen, "Error propagation methods for LCA—a comparison," *The International Journal of Life Cycle Assessment* 19, no. 7 (2014), https://doi.org/10.1007/s11367-014-0751-0. R. Heijungs and M. Huijbregts, "A Review of Approaches to Treat Uncertainty in LCA," *Complexity and Integrated Resources Management*.

[206] Figure 17 provides the following conceptual conditional sequence. There will uncertainty in the footprint associated to an actor, denote the vector of random variables

$$footprint(actor).$$

Given a footprint of one unit, denote the uncertainty in the attributable capital changes by

$$capital\ change \mid footprint.$$

Given a capital change of one unit, denote the uncertainty in the valuation of the capital changes by

$$valuation \mid capital\ change.$$

Approximate the uncertainty in the valuation of the actor by the product of the random variables

$$(valuation \mid capital\ change) \times (capital\ change \mid footprint) \times footprint(actor).$$

to impacts that are higher than average, or less well known and likely underestimated. However, the major variance in shadow prices observed in practice are economic parameters weakly influence by individual actors. That footprint due to actor and shadow prices are treated as independent random variables simplifies a basic risk model.

Previous studies of impact valuation have noted that the uncertainty in the valuation can be approximated by a product of the uncertainty in footprint and the uncertainty in marginal valuation[207].

In the matrix model in equation (5) we used undiscounted national economic value in a time period into the future, and then applied a vector T of discounting and parity weights to turn the undiscounted national economic value into present comparable value and add them together to obtain the valuation. We also broke apart the footprint into spatial and contextual footprints.

We adjust the specification. Denote the uncertain footprint within a specific spatial boundary and context (corresponding to the index n) as a random variable

$$footprint_n(actor).$$

Given a certain footprint of one unit within a specific spatial boundary and context, denote the uncertain undiscounted national marginal valuation (corresponding to the index m) by

$$valuation_m \mid footprint_n.$$

Given a certain change in national economic value of one unit in a future time period, denote the uncertain discount rate or parity weight to compare national economies in present value by

$$present\ parity \mid valuation_m.$$

Multiplying these three random variables approximates the uncertainty in one of the terms in the sum represented by equation (5)

$$valuation_{m,n}(actor) = present\ parity \mid valuation_m$$

$$\times (valuation_m \mid footprint_n) \times footprint_n(actor)$$

We argue again that we should treat the uncertainty in discounting and parity as independent of the economic change in a national economy in a future time period due to the lock-in impacts of the footprint occurred by an actor now. This is not strictly going to be observed, but the discounting term will depend on growth up until the future time period and depend little on the future time period itself. For parity, we also assume that the economic effects of the actor are small enough that global distribution of wealth is dependent more on societal footprint and other exogenous assumptions.

We interpret the matrix model in equation (5) now in terms of the algebra of random variables. The Jacobian matrix of shadow prices is now a matrix of random variables reflected uncertain shadow prices

$$J_V = [J_V]_{m,n} = [valuation_m \mid footprint_n]_{m,n}\ .$$

[207] COWI, *Assessment of potentials and limitations in valuation of externalities*. The comment of the reference p. 30, Section 4.3 about the uncertainty "Assuming that the assessment of the impact [footprint] and the assessment of the unit values [marginal valuation] are independent the overall level of uncertainty will be more or less similar to the most uncertain component…" is a little mystifying. The standard deviation of the product of two independent random variables is dominated below by the product of standard deviations. Therefore, the uncertainties in marginal valuation and footprint multiply and orders of magnitude add.

We argued above that this matrix of random variables should not be replaced by the expected values of its terms, but that the shadow prices should be kept as random variables. A scientific process collating literature can estimate distributions for the uncertain shadow prices. Many of the literature studies indicate errors to valuations as well as central values. Using these error estimates or performing additional simplified error estimation, log-normal or similar right skewed distributions can be used to simplify the representation of shadow prices as random variables[208]. The vector of random variables representing uncertain footprint produced by the actor is

$$\hat{f} - f = \left[\hat{f}_n - f_n\right]_{n,1} = [footprint_n(actor)]_{n,1}.$$

The vector of random variables representing uncertainty or variation in discounting rate and parity

$$T = [T_m]_{1,m} = [present\ parity \mid valuation_m]_{1,m}.$$

The approximation to the impact valuation given by equation (5) when there is uncertainty in discount rate, parity, shadow prices, and footprint measurement, is

$$V(\hat{f}) - V(f) \approx T\, J_V\, (\hat{f} - f) = \textstyle\sum_{m,n} valuation_{m,n}(actor) \quad (6)$$

The assumptions above calculate $valuation_{m,n}(actor)$ as the product of three random variables assumed to be independent. This product can be standardised. For example, not much additional uncertainty is introduced into a log-normal approximation of this product if footprint uncertainty is standardised to uniform distributions over ranges. There are ways that these random variables can be calculated efficiently, assuming the matrices of random variables J_V and T are given with a simplified and standard form for specifying the uncertainty in footprint. The most important aspect we want to sketch is adding the random variables $valuation_{m,n}(actor)$ across the indices n and m. We *do not* assume that the random variables $valuation_{m,n}(actor)$ are independent.

For serious effects of global impact from the food system, we argue that there will be positive correlations that increase the uncertainty in the impact valuation estimate in (6). The correlations create additional risk. First, it is not entirely clear that discounting and parity terms over time should be treated as independent, general time series analysis of periods of low or high GDP growth indicate autocorrelation. If global inequality is worse than expected, it is more likely to be that way in the next time period rather than a not infeasible, but less likely, global structural break. It is also not clear the impact across nations should be treated independent for global material issues for society. If impact is worse than expected from climate change in one country and at one time period, it will more than likely be worse than expected for other countries and neighbouring time periods. The same is likely to apply where we have underestimated the physical impacts of underlying biophysical and chemical processes. Those processes will largely cause shifts in impact in the same direction wherever they occur spatially. While it is less clear that footprints in different contexts such as environmental footprints and dietary footprints will have a correlated impact, it is to be suspected that worse than expected impacts from emissions will correlate in worse than expected health outcomes (potentially due to auxiliary worsening of general public health in some countries from tropical diseases, desertification, heat stress, which amplifies dietary health impacts)[209].

---

[208] E. L. Crow and K. Shimizu, *Lognormal distributions : theory and applications*, Statistics, textbooks and monographs, (New York: M. Dekker, 1988).

[209] A. J. McMichael, R. E. Woodruff, and S. Hales, "Climate change and human health: present and future risks," *The Lancet* 367, no. 9513 (2006), https://doi.org/10.1016/S0140-6736(06)68079-3. IPCC, *Climate Change 2014 – Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects:*

There are effective analytic formulas for summing log-normal random variables with assumed covariance and estimating their statistics. As a simple example, assume the risk premium to be added onto the expected value

$$E\left(T\,J_V\,(\hat{f}-f)\right)$$

is the right side standard deviation

$$\sigma_+\left(T\,J_V\,(\hat{f}-f)\right).$$

The model described above, provided the matrices J_V and T were given, and provided two $m \times m$ and one $n \times n$ correlation matrix describing the correlations between discount and parity factors, between national impact within and between time periods, and between impacts from different footprints were given, could calculate a risk adjusted food impact costing

$$(E+\sigma_+)\left(T\,J_V\,(\hat{f}-f)\right) \tag{7}$$

given the footprint $\hat{f}-f$. The risk premium is calculated for each actor depending only on their footprint $\hat{f}-f$. The terms T, J_V with correlations and the choice of the risk measure, which we chose as $E+\sigma_+$ as an illustration, should be determined by society as the risk bearer. That is, how much society is going to "charge" to take on the risk associated to the footprint $\hat{f}-f$.

Even though equation (5) is a linear model in actor footprint, meaning that the sum of the impact valuations is equal to the impact valuations of the sum of the footprints, the risk adjusted impact valuation (7) is not linear in actor footprint. Statistics of sums of correlated random variables are generally not linear. The risk adjusted impact valuation of the sum of two actor footprints may be higher than the sum of the risk adjusted impact valuations associated to each footprint individually.

The purpose of this section was to sketch technical details of an approach to standardising risk pricing for impact valuation. The technical difficulty and modelling choices for computational efficiency rest with the standardisation of shadow prices. Users of valuations from this method of risk pricing will not be working with distributions of shadow prices. Calculation involving distributions and correlations occurs "back-end" in software or calculation tools. The user obtains from the method a single numerical value (the output of equation (7)), which is the risk adjusted impact valuation. Food system actors provide their footprint in the form required by the user, which may require them to specify uncertainty in calculation of footprint.

Carbon footprint protocols provide advice on reporting uncertainty in carbon footprint[210]. Estimates of uncertainty in carbon footprints from common methods such as LCA have been studied[211]. Discussions of uncertainty in footprint measurement can be found for most other environmental footprints of concern for food impact costing[212]. Without more research on the

Volume 1, Global and Sectoral Aspects: Working Group II Contribution to the IPCC Fifth Assessment Report (Cambridge, UK: Cambridge University Press, 2014).

210 https://ghgprotocol.org/calculation-tools

211 P. J. G. Henriksson et al., "Product Carbon Footprints and Their Uncertainties in Comparative Decision Contexts," *PLOS ONE* 10, no. 3 (2015), https://doi.org/10.1371/journal.pone.0121221.

212 E. Solazzo et al., "Evaluation and uncertainty estimation of the impact of air quality modelling on crop yields and premature deaths using a multi-model ensemble," *Science of The Total Environment* 633 (2018), https://doi.org/https://doi.org/10.1016/j.scitotenv.2018.03.317; P. Holnicki and Z. Nahorski, "Emission Data Uncertainty in Urban Air Quality Modeling—Case Study," *Environmental Modeling & Assessment* 20, no. 6 (2015), https://doi.org/10.1007/s10666-015-9445-7; T. P. Tomich et al., "Food and agricultural innovation pathways for prosperity," *Agricultural Systems* 172 (2019), https://doi.org/https://doi.org/10.1016/j.agsy.2018.01.002; E. A. Davidson and D. Kanter, "Inventories

uncertainty in footprint estimation, it is unclear whether it is a major component of risk premiums.

A simple but direct use of the risk premium is to incentivise disclosure of footprints. Non-disclosure pushes risk onto society in the form of an inability to cost food system impacts and enable economic correction.

The user of a valuation can input the numerical value of disclosed actor footprints. The user can pre-assign a distribution to represent undisclosed footprints. This could be a uniform distribution associated to products in the same category. This represents not knowing what the footprint is, but assuming it sits somewhere in the range already observed for the activities whose impact is being valued. The user could apply the maximal entropy distribution given only the average footprint observed for that product or activity[213]. This represents not knowing what the footprint is given only the observed average for the industry. If the user wanted to penalise non-disclosure, they could condition either of these distributions on the maximum footprint observed. Conditioning the maximal entropy distribution associated to non-disclosure on the maximum observed, associates to the undisclosed footprint the maximum footprint observed for that activity, and uncertainty whether the non-disclosing actor's footprint is actually above the maximum (which may be why they choose not to disclose it). The conditioned maximum distribution would add a risk premium above the impact valuation associated to the maximum footprint. A higher value for the impact valuation could mean less incentives, failure to meet regulation, or more fiscal penalties. The consequences of the additional risk premium for non-disclosure compared to disclosure would act as an incentive to disclose. It could also incentivise companies moving through stages of better measurement of their footprint. Disclosure reduces the uncertainty in footprint, which through the pricing mechanism, reduces the risk price.

It does not matter for the method described whether footprint is disclosed in some dimensions e.g. carbon, and footprint not disclosed in others, e.g. nitrogen. The risk pricing method can compute a risk adjusted impact valuation with a mixture of disclosure and non-disclosure in footprints.

The model sketched approximates the compounding of uncertainties in Figure 25 by products and sums of random variables. We briefly discuss computation efficiency. The Jacobian of shadow prices from the linear model on p. 102 is replaced by a Jacobian of random variables representing uncertain shadow prices. The model we described on p. 102 might have n and m of the order of 1000. The Jacobian is a relatively sparse matrix for the reasons discussed on p. 102, but there are still many non-zero entries. Given the unavoidable uncertainty in shadow prices, the consideration of uncertainty should be performed, even in a simple way utilising log-normal approximation, within any process to establish shadow prices. That is, if society was going to invest in food impact costing, we have argued for the resolution required, and the effort to generate and consider the Jacobian of shadow prices as simplified random variables is a small add to the effort to formulate a Jacobian of best guess single prices.

The correlation matrices, which are important, are new for the risk pricing approach. A pragmatic approach to correlation in the first instance would feature sparse correlation matrices, rough estimates, and concentration on correlation between the largest shadow prices. Analytic approximations to stochastic algebra are favoured over Monte Carlo simulation at this stage. Most users that want to substitute in footprints to compare them may not be able to simulate or implement "back-ends" that can perform the Monte Carlo simulation.

---

and scenarios of nitrous oxide emissions," *Environmental Research Letters* 9, no. 10 (2014), https://doi.org/10.1088/1748-9326/9/10/105012.

[213] S. Guiasu and A. Shenitzer, "The principle of maximum entropy," *The Mathematical Intelligencer* 7, no. 1 (1985).

Risk premiums based on other statistics such as the finance industry standard VaR would likely require importance sampling to gain additional confidence and computational efficiency[214].

The number of summands in equation (6) is very large. Without correlation the distribution of the impact valuation as a random variable (the total of the summands on the left-hand side of equation (6)) would likely tend to a normal shape with a potentially small standard deviation compared to the expected value (a negligible risk premium). This would be an artefact of the modelling. Arbitrary choices, such as increasing the resolution from national down to subnational, would introduce more terms in the summand and the tendency to normality is strengthened further. This is only valid under increased decoupling of variance in impact at lower resolutions. We reject the position that environmental prices centralise for the type of global issues of concern in food system impact valuation. Correlation of global and national activities means that it is likely that correlation will feature in the summation, leading to a retention of right-skew and non-trivial risk premium for the total of the summands.

We have not discussed substitution in the Jacobian of shadow prices. That is, when some shadow prices have probabilities of negative values (marginal social benefits or negative marginal abatement cost) and are being added to shadow prices with probabilities of positive values. Statistics of equity in implicit exchange of a gain in economic value for one party for a loss of economic value for another party are discussed in Implications. Uncertainty in substitutability is an additional consideration which would increase the risk premium in an impact valuation[215].

[214] S. T. Tokdar and R. E. Kass, "Importance sampling: a review," *WIREs Computational Statistics* 2, no. 1 (2010), https://doi.org/10.1002/wics.56. P. J. Smith, M. Shafi, and G. Hongsheng, "Quick simulation: a review of importance sampling techniques in communications systems," *IEEE Journal on Selected Areas in Communications* 15, no. 4 (1997), https://doi.org/10.1109/49.585771.
[215] Gollier, "Valuation of natural capital under uncertain substitutability."

REFERENCES

Aalbers, R., G. Renes, and G. Romijn. *WLO-klimaatscenario's en de waardering van CO2-uitstoot in MKBA's.* Centraal Planbureau (CPB), Planbureau voor de Leefomgeving (PBL) (Den Haag: 2016).

Abhishek, C., G. David, and M. Alexander. "Multi-indicator sustainability assessment of global food systems." *Nature Communications* 9, no. 1 (2018): 1-13. https://doi.org/10.1038/s41467-018-03308-7.

Acemoglu, D., and M. Dell. "Productivity Differences between and within Countries." *American Economic Journal: Macroeconomics* 2, no. 1 (2010): 169-88. https://doi.org/10.1257/mac.2.1.169.

Ackerman, F., and E. Stanton. "Climate Risks and Carbon Prices: Revising the Social Cost of Carbon." *Economics* 6, no. 10 (2012): 0_1-26.

Addicott, E. T., and E. P. Fenichel. "Spatial aggregation and the value of natural capital." *Journal of Environmental Economics and Management* 95 (2019): 118-32. https://doi.org/https://doi.org/10.1016/j.jeem.2019.03.001.

Adler, M., D. Anthoff, V. Bosetti, G. Garner, K. Keller, and N. Treich. "Priority for the worse-off and the social cost of carbon." *Nature Climate Change* 7, no. 6 (2017). https://doi.org/10.1038/nclimate3298.

Afshin, A., P. J. Sur, K. A. Fay, L. Cornaby, G. Ferrara, J. S. Salama, E. C. Mullany, *et al.* "Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017." *The Lancet* 393, no. 10184 (2019): 1958-72. https://doi.org/https://doi.org/10.1016/S0140-6736(19)30041-8.

Allouche, J. "The sustainability and resilience of global water and food systems: Political analysis of the interplay between security, resource scarcity, political systems and global trade." *Food Policy* 36, Supp 1 (2011): S3-S8. https://doi.org/http://dx.doi.org/10.1016/j.foodpol.2010.11.013.

Almaraz, M., E. Bai, C. Wang, J. Trousdell, S. Conley, I. Faloona, and B. Z. Houlton. "Agriculture is a major source of NOx pollution in California." *Science Advances* 4, no. 1 (2018): eaao3477. https://doi.org/10.1126/sciadv.aao3477.

Anderson, C. M., R. S. DeFries, R. Litterman, P. A. Matson, D. C. Nepstad, S. Pacala, W. H. Schlesinger, *et al.* "Natural climate solutions are not enough." *Science* 363, no. 6430 (2019): 933. https://doi.org/10.1126/science.aaw2741.

Anderson, V., ed. *Debating Nature's Value: The Concept of 'Natural Capital'*. Cham: Springer International Publishing, 2018.

Arnesen, T., and E. Nord. "The value of DALY life: problems with ethics and validity of disability adjusted life years." *BMJ (Clinical research ed.)* 319, no. 7222 (1999): 1423-25. https://doi.org/10.1136/bmj.319.7222.1423.

Arrow, K. J., M. L. Cropper, C. Gollier, B. Groom, G. M. Heal, R. G. Newell, W. D. Nordhaus, *et al.* "Should Governments Use a Declining Discount Rate in Project Analysis?". *Review of Environmental Economics and Policy* 8, no. 2 (2014): 145-63. https://doi.org/10.1093/reep/reu008.

Arrow, K. J., P. Dasgupta, L. H. Goulder, K. J. Mumford, and K. Oleson. "Sustainability and the measurement of wealth." *Environment and Development Economics* 17, no. 3 (2012): 317-53. https://doi.org/10.1017/S1355770X12000137.

Bachmann, T. M. "Optimal pollution: the welfare economic approach to correct market failures." In *Encyclopedia on Environmental Health.*, edited by J. Nriagu, 264-74. Burlington: Elsevier, 2011.

Bajzelj, B., K. S. Richards, J. M. Allwood, P. Smith, J. S. Dennis, E. Curmi, and C. A. Gilligan. "Importance of food-demand management for climate mitigation." *Nature Clim. Change* 4, no. 10 (2014): 924-29. https://doi.org/10.1038/nclimate2353.

Barrett, C. B., M. E. Bachke, M. F. Bellemare, H. C. Michelson, S. Narayanan, and T. F. Walker. "Smallholder Participation in Contract Farming: Comparative Evidence from Five Countries." *World Development* 40, no. 4 (2012): 715-30. https://doi.org/10.1016/j.worlddev.2011.09.006.

Beach, R. H., J. Creason, S. B. Ohrel, S. Ragnauth, S. Ogle, C. Li, P. Ingraham, and W. Salas. "Global mitigation potential and costs of reducing agricultural non-CO2 greenhouse gas emissions through 2030." *Journal of Integrative Environmental Sciences* 12, no. sup1 (2015): 87-105. https://doi.org/10.1080/1943815X.2015.1110183.

Beach, R. H., B. J. Deangelo, S. Rose, C. Li, W. Salas, and S. J. Delgrosso. "Mitigation potential and costs for global agricultural greenhouse gas emissions 1." *Agricultural Economics* 38, no. 2 (2008): 109-15. https://doi.org/10.1111/j.1574-0862.2008.00286.x.

Beddington, J. R. *The future of food and farming : challenges and choices for global sustainability ; [final project report of the UK Government Foresight Global Food and Farming Futures].* London, UK: The Government Office for Science, 2011.

Bernard, L., and W. Semmler. *The Oxford handbook of the macroeconomics of global warming.* Handbook of the macroeconomics of global warming. New York: Oxford University Press, 2015.

Beven, K. "On the concept of model structural error." *Water Sci Technol* 52, no. 6 (2005): 167-75.

Bockel, L., P. Sutter, O. Touchemoulin, and M. Jonsson. *Using Marginal Abatement Cost Curves to Realize the Economic Appraisal of Climate Smart Agriculture Policy Options.* Food and Agriculture Organization of the United Nations. (Rome: 2012).

Boyle, K. J., N. V. Kuminoff, C. F. Parmeter, and J. C. Pope. "The Benefit-Transfer Challenges." *Annual Review of Resource Economics* 2, no. 1 (2010): 161-82. https://doi.org/10.1146/annurev.resource.012809.103933.

Brunner, F., V. Kurz, D. Bryngelsson, and F. Hedenus. "Carbon Label at a University Restaurant – Label Implementation and Evaluation." *Ecological Economics* 146 (2018): 658-67. https://doi.org/https://doi.org/10.1016/j.ecolecon.2017.12.012.

Carey, R., M. Caraher, M. Lawrence, and S. Friel. "Opportunities and challenges in developing a whole-of-government national food and nutrition policy: lessons from Australia's National Food Plan." *Public Health Nutr* 19, no. 1 (2016): 3-14. https://doi.org/10.1017/s1368980015001834.

Carole, D., W. Yoshihide, K. Thomas, and J. P. Michael. "Groundwater depletion embedded in international food trade." *Nature* 543, no. 7647 (2017): 700. https://doi.org/10.1038/nature21403.

CCE. *Carbon valuation in UK policy appraisal: a revised approach.* UK Department of Energy and Climate Change. (London: 2009). https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/245334/1_20090715105804_e____carbonvaluationinukpolicyappraisal.pdf.

Choudhry, M. *An Introduction to Value-at-Risk.* Wiley, 2012. doi:10.1002/9781119208037.ch3.

Clark, M. A., M. Springmann, J. Hill, and D. Tilman. "Multiple health and environmental impacts of foods." *Proceedings of the National Academy of Sciences* (2019): 201906908. https://doi.org/10.1073/pnas.1906908116.

Clarkson, R., and K. Deyes. *Estimating the social cost of carbon emissions.* Government Economic Service working paper. London: HM Treasury, 2002.

Cline, W. R. *Global Warming and Agriculture: Impact Estimates by Country.* Washington DC: Center for Global Development, 2007.

Conley, D., and J. Thompson. *Health Shocks, Insurance Status and Net Worth: Intra- and Inter-Generational Effects.* National Bureau of Economic Research (Cambridge, MA: 2011).

COWI. *Assessment of potentials and limitations in valuation of externalities.* The Danish Environmental Protection Agency (Copenhagen: 2014).

Cox, L. A. "Confronting Deep Uncertainties in Risk Analysis." *Risk Analysis* 32, no. 10 (2012): 1607-29. https://doi.org/10.1111/j.1539-6924.2012.01792.x.

CPLC. *Report of the High-Level Commission on Carbon Prices.* Carbon Pricing Leadership Coalition (Washington DC: 2017). https://www.carbonpricingleadership.org/report-of-the-highlevel-commission-on-carbon-prices.

Crawford, I., and B. De Rock. "Empirical Revealed Preference." *Annual Review of Economics* 6, no. 1 (2014): 503-24. https://doi.org/10.1146/annurev-economics-080213-041238.

Crenna, E., M. Secchi, L. Benini, and S. Sala. "Global environmental impacts: data sources and methodological choices for calculating normalization factors for LCA." *The International Journal of Life Cycle Assessment* 24, no. 10 (2019): 1851-77. https://doi.org/10.1007/s11367-019-01604-y.

Crow, E. L., and K. Shimizu. *Lognormal distributions : theory and applications.* Statistics, textbooks and monographs. New York: M. Dekker, 1988.

Čuček, L., J. J. Klemeš, and Z. Kravanja. "A Review of Footprint analysis tools for monitoring impacts on sustainability." *Journal of Cleaner Production* 34 (2012): 9-20. https://doi.org/https://doi.org/10.1016/j.jclepro.2012.02.036.

Dasgupta, P. *Human Well-Being and the Natural Environment.* Oxford: Oxford University Press, 2002.

———. "Nature's role in sustaining economic development." *Philosophical Transactions of the Royal Society B* 365, no. 1537 (2010): 5-11. https://doi.org/10.1098/rstb.2009.0231.

———. "The Stern Review's economics of climate change." *National Institute Economic Review* 199, no. 1 (2007): 4-7. https://doi.org/10.1177/0027950107077111.

Dasgupta, P., and A. Duraiappah. "Well-being and wealth." In *Inclusive Wealth Report 2012: measuring progress toward sustainability*, edited by IHDP-UNU and UNEP, 13-26. Cambridge: Cambridge University Press, 2012.

Davidson, E. A., and D. Kanter. "Inventories and scenarios of nitrous oxide emissions." *Environmental Research Letters* 9, no. 10 (2014): 105012. https://doi.org/10.1088/1748-9326/9/10/105012.

Davis, J., F. De Menna, N. Unger, K. Östergren, M. Loubiere, and M. Vittuari. *Generic strategy LCA and LCC : Guidance for LCA and LCC focused on prevention, valorisation and treatment of side flows from the food supply chain.* (2017 2017). http://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-27973.

De Backer, K., and S. Miroudot. *Mapping Global Value Chains, OECD Trade Policy Papers, No. 159.* OECD Publishing (Paris: 2013).

de Bruyn, S., S. Ahdour, M. Bijleveld, L. de Graaff, E. Schep, A. Schroten, and R. Vergeer. *Environmental Prices Handbook EU28 Version.* CE Delft (Delft, The Netherlands: 2018). https://www.cedelft.eu/en/publications/2113/envionmental-prices-handbook-2017.

de Groot, R., L. Brander, S. van Der Ploeg, R. Costanza, F. Bernard, L. Braat, M. Christie*, et al.* "Global estimates of the value of ecosystems and their services in monetary units." *Ecosystem Services* 1, no. 1 (2012): 50-61. https://doi.org/10.1016/j.ecoser.2012.07.005.

de Schutter, O., C. Hawkes, J. Hugh, K. Clancy, M. Anderson, and B. Athreya. *Advancing Health and Well-Being in Food Systems.* Global Alliance for the Future of Food (Toronto: 2015).

Dietz, S. "The Treatment of Risk and Uncertainty in the US Social Cost of Carbon for Regulatory Impact Analysis." *Economics* 6, no. 18 (2012): 0_1-12A.

Dietz, S., and S. Fankhauser. "Environmental prices, uncertainty, and learning." *Oxford Review of Economic Policy* 26, no. 2 (2010): 270-84. https://doi.org/10.1093/oxrep/grq005.

Dietz, S., and E. Neumayer. "Weak and strong sustainability in the SEEA: Concepts and measurement." *Ecological Economics* 61, no. 4 (2007): 617-26. https://doi.org/https://doi.org/10.1016/j.ecolecon.2006.09.007.

Dietz, S., and N. Stern. "Endogenous Growth, Convexity of Damage and Climate Risk: How Nordhaus' Framework Supports Deep Cuts in Carbon Emissions." *The Economic Journal* 125, no. 583 (2015): 574-620. https://doi.org/10.1111/ecoj.12188.

Drewnowski, A. "Obesity, diets, and social inequalities." *Nutrition Reviews* 67, no. suppl_1 (2009): S36-S39. https://doi.org/10.1111/j.1753-4887.2009.00157.x.

Ellsberg, D. "Risk, Ambiguity, and the Savage Axioms." *The Quarterly Journal of Economics* 75, no. 4 (1961): 643-69. https://doi.org/10.2307/1884324.

Eory, V., S. Pellerin, G. Carmona Garcia, H. Lehtonen, I. Licite, H. Mattila, T. Lund-Sørensen*, et al.* "Marginal abatement cost curves for agricultural climate policy: State-of-the art, lessons learnt and future potential." *Journal of Cleaner Production* 182 (2018): 705-16. https://doi.org/10.1016/j.jclepro.2018.01.252.

FABLE. *Pathways to Sustainable Land-Use and Food Systems. 2019 Report of the FABLE Consortium.* International Institute for Applied Systems Analysis (IIASA) and Sustainable Development Solutions Network (SDSN) (Laxenburg and Paris: 2019).

Fantke, P., and O. Jolliet. "Life cycle human health impacts of 875 pesticides." *The International Journal of Life Cycle Assessment* 21, no. 5 (2016): 722-33. https://doi.org/10.1007/s11367-015-0910-y.

FAO. *Food wastage footprint: full-cost accounting.* Food and Agriculture Organization of the United Nations (Rome: 2014).

———. *The State of Agricultural Commodity Markets 2018. Agricultural trade, climate change and food security.* The Food and Agriculture Organization of the United Nations (Rome: 2018). http://www.fao.org/3/I9542EN/i9542en.pdf.

Fenichel, E. P., and Y. Hashida. "Choices and the value of natural capital." *Oxford Review of Economic Policy* 35, no. 1 (2019): 120-37. https://doi.org/10.1093/oxrep/gry021.

Figge, F. "Capital Substitutability and Weak Sustainability Revisited: The Conditions for Capital Substitution in the Presence of Risk." *Environmental Values* 14, no. 2 (2005): 185-201. https://doi.org/10.3197/0963271054084966.

Fleurbaey, M., M. Ferranna, M. Budolfson, F. Dennig, K. Mintz-Woo, R. Socolow, D. Spears, and S. Zuber. "The Social Cost of Carbon: Valuing Inequality, Risk, and Population for Climate Policy." *The Monist* 102, no. 1 (2018): 84-109. https://doi.org/10.1093/monist/ony023.

Folloni, G., and G. Vittadini. "Human capital measurement: a survey." *Journal of Economic Surveys* 24, no. 2 (2010): 248-79. https://doi.org/10.1111/j.1467-6419.2009.00614.x.

FOLU. *Growing Better: Ten Critical Transitions to Transform Food and Land Use, The Global Consultation Report of the Food and Land Use Coalition.* Food and Land Use Coalition (New York: 2019). https://www.foodandlandusecoalition.org/global-report/.

Freidberg, S. "Big Food and Little Data: The Slow Harvest of Corporate Food Supply Chain Sustainability Initiatives." *Annals of the American Association of Geographers* 107, no. 6 (2017): 1389-406. https://doi.org/10.1080/24694452.2017.1309967.

Galloway, J. N., W. Winiwarter, A. Leip, A. M. Leach, A. Bleeker, and J. W. Erisman. "Nitrogen footprints: past, present and future." *Environmental Research Letters* 9, no. 11 (2014): 115003. https://doi.org/10.1088/1748-9326/9/11/115003.

Garnett, T., C. Godde, A. Muller, E. Röös, P. Smith, d. I. J. M. Boer, z. E. Ermgassen*, et al. Grazed and confused? : Ruminating on cattle, grazing systems, methane, nitrous oxide, the soil carbon sequestration question - and what it all means for greenhouse gas emissions.* Food Climate Research Network (London: 2017). https://www.fcrn.org.uk/sites/default/files/project-files/fcrn_gnc_report.pdf.

Gillingham, K., and J. H. Stock. "The Cost of Reducing Greenhouse Gas Emissions." *Journal of Economic Perspectives* 32, no. 4 (2018): 53-72. https://doi.org/10.1257/jep.32.4.53.

Godfray, H. C. J., I. R. Crute, L. Haddad, D. Lawrence, J. F. Muir, N. Nisbett, J. Pretty*, et al.* "The future of the global food system." *Philosophical Transactions of the Royal Society of London B: Biological Sciences* 365, no. 1554 (2010): 2769-77. https://doi.org/10.1098/rstb.2010.0180.

Gollier, C. "On the Underestimation of the Precautionary Effect in Discounting." *The Geneva Risk and Insurance Review* 36, no. 2 (2011): 95-111. https://doi.org/10.1057/grir.2011.6.

———. *Pricing the planet's future : the economics of discounting in an uncertain world.* University Press Scholarship Online. Princeton: Princeton University Press, 2017.

———. "Valuation of natural capital under uncertain substitutability." *Journal of Environmental Economics and Management* 94 (2019): 54-66. https://doi.org/10.1016/j.jeem.2019.01.003.

Gollier, C., and M. L. Weitzman. "How should the distant future be discounted when discount rates are uncertain?". *Economics Letters* 107, no. 3 (2010): 350-53. https://doi.org/10.1016/j.econlet.2010.03.001.

Greenville, J., K. Kawasaki, and M.-A. Jouanjean. *Dynamic Changes and Effects of Agro-Food GVCS, OECD Food, Agriculture and Fisheries Papers, No. 119.* OECD Publishing (Paris: 2019).

Grout, P. A. "Public and private sector discount rates in public–private partnerships." *Economic Journal* 113, no. 486 (2003): C62-C68. https://doi.org/10.1111/1468-0297.00109.

Guiasu, S., and A. Shenitzer. "The principle of maximum entropy." *The Mathematical Intelligencer* 7, no. 1 (1985): 42-48.

Hall, J. W., R. J. Lempert, K. Keller, A. Hackbarth, C. Mijere, and D. J. McInerney. "Robust climate policies under uncertainty: a comparison of robust decision making and info-gap methods." *Risk Analysis* 32 (2012): 1657-72.

Hamel, P., and B. P. Bryant. "Uncertainty assessment in ecosystem services analyses: Seven challenges and practical responses." *Ecosystem Services* 24 (2017): 1-15. https://doi.org/https://doi.org/10.1016/j.ecoser.2016.12.008.

Heijungs, R., and M. Huijbregts. "A Review of Approaches to Treat Uncertainty in LCA." *Complexity and Integrated Resources Management* (2004): 332.

Heijungs, R., and M. Lenzen. "Error propagation methods for LCA—a comparison." *The International Journal of Life Cycle Assessment* 19, no. 7 (2014): 1445-61. https://doi.org/10.1007/s11367-014-0751-0.

Helm, D. *Carbon valuation in UK policy appraisal: a revised approach and peer reviews. Peer review Dieter Helm.* Natural Capital Comittee. UK Department of Energy & Climate Change. (London: 2009). https://www.gov.uk/government/publications/carbon-valuation-in-uk-policy-appraisal-a-revised-approach.

Henriksson, P. J. G., R. Heijungs, H. M. Dao, L. T. Phan, G. R. de Snoo, and J. B. Guinée. "Product Carbon Footprints and Their Uncertainties in Comparative Decision Contexts." *PLOS ONE* 10, no. 3 (2015): e0121221. https://doi.org/10.1371/journal.pone.0121221.

Hepburn, C. "Climate change economics: Make carbon pricing a priority." *Nature Climate Change* 7, no. 6 (2017). https://doi.org/10.1038/nclimate3302.

Hillier, J., C. Walter, D. Malin, T. Garcia-Suarez, L. Mila-i-Canals, and P. Smith. "A farm-focused calculator for emissions from crop and livestock production." *Environmental Modelling & Software* 26, no. 9 (2011): 1070-78. https://doi.org/http://dx.doi.org/10.1016/j.envsoft.2011.03.014.

Hoekstra, A. Y., A. K. Chapagain, M. M. Aldaya, and M. M. Mekonnen. *The Water Footprint Assessment Manual: Setting the Global Standard.* London: Earthscan, 2011.

Holnicki, P., and Z. Nahorski. "Emission Data Uncertainty in Urban Air Quality Modeling—Case Study." *Environmental Modeling & Assessment* 20, no. 6 (2015): 583-97. https://doi.org/10.1007/s10666-015-9445-7.

Holzer, H. J., D. W. Schanzenbach, G. J. Duncan, and J. Ludwig. *The economic costs of poverty in the United States : subsequent effects of children growing up poor. Institute for Research on Poverty Discussion Paper no. 1327-07.* Center for American Progress (Washington DC: 2007). https://irp.wisc.edu/publications/dps/pdfs/dp132707.pdf.

Houlton, B. Z., M. Almaraz, V. Aneja, A. T. Austin, E. Bai, K. G. Cassman, J. E. Compton*, et al.* "A World of Cobenefits: Solving the Global Nitrogen Challenge." *Earth's Future* 7, no. 8 (2019): 865-72. https://doi.org/10.1029/2019EF001222.

Huang, S. K., L. Kuo, and K.-L. Chou. "The applicability of marginal abatement cost approach: A comprehensive review." *Journal of Cleaner Production* 127 (2016): 59-71. https://doi.org/10.1016/j.jclepro.2016.04.013.

Huijbregts, M., Z. Steinmann, P. Elshout, G. Stam, F. Verones, M. Vieira, A. Hollander, M. Zijp, and R. van Zelm. *ReCiPe 2016 : A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterization.* National Institute for Public Health and the Environment (Bilthoven, The Netherlands: 2016). http://rivm.openrepository.com/rivm/handle/10029/620793.

Hulme, D., K. Moore, and A. Shepherd. "Chronic Poverty: Meanings and Analytical Frameworks." [In eng]. *SSRN Electronic Journal* (2001). https://doi.org/10.2139/ssrn.1754546.

IPCC. *Climate Change 2014 – Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects: Volume 1, Global and Sectoral Aspects: Working Group II Contribution to the IPCC Fifth Assessment Report.* Cambridge, UK: Cambridge University Press, 2014.

———. *IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems.* Intergovernmental Panel on Climate Change (2019). https://www.ipcc.ch/report/srccl/.

IPES-Food. Unravelling the food-health nexus: addressing practices, political economy, and power relations to build healthier food systems. 2017. Global Alliance For The Future of Food and IPES-Food.

IWGSCGG. *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis.* Interagency Working Group on Social Cost of Greenhouse Gases, United States Government (Washington DC: 2016). https://www.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf.

Jaynes, E. T., and G. L. Bretthorst. *Probability theory: the logic of science.* Cambridge: Cambridge University Press, 2003.

Johnson, K. A., S. Polasky, E. Nelson, and D. Pennington. "Uncertainty in ecosystem services valuation and implications for assessing land use tradeoffs: An agricultural case study in the Minnesota River Basin." *Ecological Economics* 79 (2012): 71-79. https://doi.org/https://doi.org/10.1016/j.ecolecon.2012.04.020.

Jonas, M., R. Bun, Z. Nahorski, G. Marland, M. Gusti, and O. Danylo. "Quantifying greenhouse gas emissions." *Mitigation and Adaptation Strategies for Global Change* 24, no. 6 (2019): 839-52. https://doi.org/10.1007/s11027-019-09867-4.

Jones, C., and P. Klenow. *Beyond GDP? Welfare across Countries and Time.* National Bureau of Economic Research (Cambridge, MA: 2010).

Jones, L., A. Provins, M. Holland, G. Mills, F. Hayes, B. Emmett, J. Hall*, et al.* "A review and application of the evidence for nitrogen impacts on ecosystem services." *Ecosystem Services* 7 (2014): 76-88. https://doi.org/https://doi.org/10.1016/j.ecoser.2013.09.001.

Jørgensen, A., A. Le Bocq, L. Nazarkina, and M. Hauschild. "Methodologies for social life cycle assessment." *The international journal of life cycle assessment* 13, no. 2 (2008): 96.

Kaplan, S., and B. J. Garrick. "On the quantitative definition of risk." *Risk Analysis* 1, no. 1 (1981): 11-27.

Kaul, S., K. J. Boyle, N. V. Kuminoff, C. F. Parmeter, and J. C. Pope. "What can we learn from benefit transfer errors? Evidence from 20 years of research on convergent validity." *Journal of Environmental Economics and Management* 66, no. 1 (2013): 90-104. https://doi.org/10.1016/j.jeem.2013.03.001.

Kayatz, B., G. Baroni, J. Hillier, S. Lüdtke, R. Heathcote, D. Malin, C. van Tonder*, et al.* "Cool Farm Tool Water: A global on-line tool to assess water use in crop production." *Journal of Cleaner Production* 207 (2019): 1163-79. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.09.160.

Keeler, B. L., S. Polasky, K. A. Brauman, K. A. Johnson, J. C. Finlay, A. O'Neill, K. Kovacs, and B. Dalzell. "Linking water quality and well-being for improved assessment and valuation of ecosystem services." *Proceedings of the National Academy of Sciences* 109, no. 45 (2012): 18619-24. https://doi.org/10.1073/pnas.1215991109.

Kenny, C. "A Note on the Ethical Implications of the Stern Review on the Economics of Climate Change." *The Journal of Environment & Development* 16, no. 4 (2007): 432-40. https://doi.org/10.1177/1070496507308576.

Kesicki, F., and P. Ekins. "Marginal abatement cost curves: a call for caution." *Climate Policy* 12, no. 2 (2012): 219-36. https://doi.org/10.1080/14693062.2011.582347.

Knutti, R. "Should we believe model predictions of climate change." *Philosophical Transactions: Mathematical, Phsyical and Engineering Sciences* 366, no. 1855 (2008): 4647-64.

Kolstad, C., K. Urama, J. Broome, A. Bruvoll, M. Cariño Olvera, D. Fullerton, C. Gollier *, et al.* "Social, Economic and Ethical Concepts and Methods." In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler*, et al.*, 207-82. New York, NY: Cambridge University Press, 2014.

Kotchen, M. J. "Which Social Cost of Carbon? A Theoretical Perspective." *Journal of the Association of Environmental and Resource Economists* 5, no. 3 (2018): 673-94. https://doi.org/10.1086/697241.

Kriegler, E., J. W. Hall, H. Held, R. Dawson, and H. Schnellnhuber, J. "Imprecise probability assessment of tipping points in the climate system." *Proceedings of the National Academy of Sciences* 106, no. 13 (2009): 5041-46.

Kubiszewski, I., R. Costanza, S. Anderson, and P. Sutton. "The future value of ecosystem services: Global scenarios and national implications." *Ecosystem Services* 26 (2017): 289-301. https://doi.org/10.1016/j.ecoser.2017.05.004.

Lamontagne, J. R., P. M. Reed, G. Marangoni, K. Keller, and G. G. Garner. "Robust abatement pathways to tolerable climate futures require immediate global action." *Nature Climate Change* 9, no. 4 (2019): 290-94. https://doi.org/10.1038/s41558-019-0426-8.

Leach, A. M., K. A. Emery, J. Gephart, K. F. Davis, J. W. Erisman, A. Leip, M. L. Pace*, et al.* "Environmental impact food labels combining carbon, nitrogen, and water footprints." *Food Policy* 61 (2016): 213-23. https://doi.org/https://doi.org/10.1016/j.foodpol.2016.03.006.

Leip, A., A. Leach, P. Musinguzi, T. Tumwesigye, G. Olupot, J. Stephen Tenywa, J. Mudiope*, et al.* "Nitrogen-neutrality: a step towards sustainability." *Environmental Research Letters* 9, no. 11 (2014): 115001. https://doi.org/10.1088/1748-9326/9/11/115001.

Lempert, R. J., and M. T. Collins. "Managing the risk of uncertain threshold response: comparison of robust, optimum, and precautionary approaches." *Risk Analysis* 27, no. 4 (2007): 1009-26.

Lempert, R. J., M. E. Schlesinger, and S. C. Bankes. "When we don't know the costs or the benefits: Adaptive strategies for abating climate change." *Climatic Change* 33 (1996): 235-74.

Lenton, T. M. "Arctic Climate Tipping Points." *Ambio* 41, no. 1 (2012): 10-22. https://doi.org/10.1007/s13280-011-0221-x.

Levihn, F. "On the problem of optimizing through least cost per unit, when costs are negative: Implications for cost curves and the definition of economic efficiency." *Energy* 114 (2016): 1155-63. https://doi.org/https://doi.org/10.1016/j.energy.2016.08.089.

Liu, J., K. Ma, P. Ciais, and S. Polasky. "Reducing human nitrogen use for food production." *Scientific Reports* 6, no. 1 (2016): 30104. https://doi.org/10.1038/srep30104.

Lloyd, S. M., and R. Ries. "Characterizing, Propagating, and Analyzing Uncertainty in Life-Cycle Assessment: A Survey of Quantitative Approaches." *Journal of Industrial Ecology* 11, no. 1 (2007): 161-79. https://doi.org/10.1162/jiec.2007.1136.

Loomes, G., and R. Sugden. "Regret theory: An alternative theory of rational choice under uncertainty." *Economic Journal* 92, no. 4 (1982): 805-24.
Loomis, J. "What's to know about hypothetical bias in stated preference valuation studies?". Article. *Journal of Economic Surveys* 25, no. 2 (2011): 363-70. https://doi.org/10.1111/j.1467-6419.2010.00675.x.
Lowe, J. *Intergenerational wealth transfers and social discounting: Supplementary Green Book guidance.* HM Treasury (London: 2008).
Lu, C., and H. Tian. "Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: Shifted hot spots and nutrient imbalance." *Earth System Science Data Discussions* 9, no. 1 (2016): 1-33. https://doi.org/10.5194/essd-2016-35.
MacDonald, G. K., K. A. Brauman, S. Sun, K. M. Carlson, E. S. Cassidy, J. S. Gerber, and P. C. West. "Rethinking Agricultural Trade Relationships in an Era of Globalization." *BioScience* 65, no. 3 (2015): 275-89. https://doi.org/10.1093/biosci/biu225.
Manfredi, S., K. Allacker, N. Pelletier, E. Schau, K. Chomkhamsri, R. Pant, and D. Pennington. "Comparing the European Commission product environmental footprint method with other environmental accounting methods." *The International Journal of Life Cycle Assessment* 20, no. 3 (2015): 389-404. https://doi.org/10.1007/s11367-014-0839-6.
Mathieu, S., M. Bernhard, N. Bernard, P. Gilles, and M. André. "Long-term fate of nitrate fertilizer in agricultural soils." *Proceedings of the National Academy of Sciences* 110, no. 45 (2013): 18185. https://doi.org/10.1073/pnas.1305372110.
McGregor, J. A., and N. Pouw. "Towards an economics of well-being." *Cambridge Journal of Economics* 41, no. 4 (2016): 1123-42. https://doi.org/10.1093/cje/bew044.
McKinsey & Company. *Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve.* McKinsey & Company,, (New York NY: 2019). https://www.mckinsey.com/~/media/McKinsey/Business%20Functions/Sustainability/Our%20Insights/Pathways%20to%20a%20low%20carbon%20economy/Pathways%20to%20a%20low%20carbon%20economy.ashx.
McMichael, A. J., R. E. Woodruff, and S. Hales. "Climate change and human health: present and future risks." *The Lancet* 367, no. 9513 (2006): 859-69. https://doi.org/10.1016/S0140-6736(06)68079-3.
McSharry, P. "Chapter 12 - Parsimonious Risk Assessment and the Role of Transparent Diverse Models." In *Risk Modeling for Hazards and Disasters*, edited by G. Michel, 263-69: Elsevier, 2018.
Metcalf, G. E., and J. H. Stock. "Integrated Assessment Models and the Social Cost of Carbon: A Review and Assessment of U.S. Experience." *Review of Environmental Economics and Policy* 11, no. 1 (2017): 80-99. https://doi.org/10.1093/reep/rew014.
Miljkovic, D. "The Law of One Price in International Trade: A Critical Review." *Review of Agricultural Economics* 21, no. 1 (1999): 126-39. https://doi.org/10.2307/1349976.
Millar, R. J., J. S. Fuglestvedt, P. Friedlingstein, J. Rogelj, M. J. Grubb, H. D. Matthews, R. B. Skeie*, et al.* "Emission budgets and pathways consistent with limiting warming to 1.5 °C." *Nature Geoscience* 10, no. 10 (2017): 741-47. https://doi.org/10.1038/ngeo3031. https://doi.org/10.1038/ngeo3031.
Montalbano, P., S. Nenci, and L. Salvatici. *Trade, value chains and food security. Background paper prepared for The State of Agricultural Commodity Markets 2015–16.* Food and Agriculture Organization of the United Nations (Rome: 2015). http://www.fao.org/3/a-i5220e.pdf.
Moore, M. A., A. E. Boardman, A. R. Vining, D. L. Weimer, and D. H. Greenberg. ""Just Give Me a Number!" Practical Values for the Social Discount Rate." *Journal of Policy Analysis and Management* 23, no. 4 (2004): 789-812. https://doi.org/10.1002/pam.20047.
Moran, D., M. Macleod, E. Wall, V. Eory, A. McVittie, A. Barnes, R. Rees, C. F. E. Topp, and A. Moxey. "Marginal Abatement Cost Curves for UK Agricultural Greenhouse Gas Emissions." *Journal of Agricultural Economics* 62, no. 1 (2011): 93-118. https://doi.org/10.1111/j.1477-9552.2010.00268.x.
Morgan, M. G., and M. Henrion. *Uncertainty: a guide to dealing with uncertainty in quantiative risk and policy analysis.* Cambridge, UK: Cambridge University Press, 1990.
Mozaffarian, D., S. Y. Angell, T. Lang, and J. A. Rivera. "Role of government policy in nutrition—barriers to and opportunities for healthier eating." *BMJ* 361 (2018): k2426. https://doi.org/10.1136/bmj.k2426.

Narassimhan, E., K. S. Gallagher, S. Koester, and J. R. Alejo. "Carbon pricing in practice: a review of existing emissions trading systems." *Climate Policy* 18, no. 8 (2018): 967-91. https://doi.org/10.1080/14693062.2018.1467827.

National Research Council. *Framework for Assessing Effects of the Food System.* National Academies Press (Washington: 2015).

Neff, R. *Introduction to the US Food System: Public Health, Environment, and Equity.* Wiley, 2014.

Neufeldt, H., M. Jahn, B. M. Campbell, J. R. Beddington, F. DeClerck, A. De Pinto, J. Gulledge*, et al.* "Beyond climate-smart agriculture: toward safe operating spaces for global food systems." *Agric Food Secur* 2 (2013). https://doi.org/10.1186/2048-7010-2-12.

Neumann, P. J., T. Thorat, Y. Zhong, J. Anderson, M. Farquhar, M. Salem, E. Sandberg*, et al.* "A Systematic Review of Cost-Effectiveness Studies Reporting Cost-per-DALY Averted." *PLOS ONE* 11, no. 12 (2016): e0168512. https://doi.org/10.1371/journal.pone.0168512.

Ng, S. W., J. A. Rivera, B. M. Popkin, and M. A. Colchero. "Did high sugar-sweetened beverage purchasers respond differently to the excise tax on sugar-sweetened beverages in Mexico?". *Public Health Nutrition* 22, no. 4 (2019): 750-56. https://doi.org/10.1017/S136898001800321X.

Niles, M. T., R. Ahuja, T. Barker, J. Esquivel, S. Gutterman, M. C. Heller, N. Mango*, et al.* "Climate change mitigation beyond agriculture: a review of food system opportunities and implications." 33, no. 3 (2018): 297-308. https://doi.org/10.1017/S1742170518000029.

Niles, M. T., R. Ahuja, J. M. Esquivel, N. Mango, M. Duncan, M. Heller, and C. Tirado. *Climate change and food systems: Assessing impacts and opportunities.* Meridian Institute (Washington DC: 2017).

Nordhaus, W. D. "Revisiting the social cost of carbon." *Proceedings of the National Academy of Sciences of the United States of America* 114, no. 7 (2017): 1518. https://doi.org/10.1073/pnas.1609244114.

Notarnicola, B., S. Sala, A. Anton, S. J. McLaren, E. Saouter, and U. Sonesson. "The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges." *Journal of Cleaner Production* 140 (2017): 399-409. https://doi.org/10.1016/j.jclepro.2016.06.071.

OECD, UN, EU, FAO, and World Bank. "System of Environmental Economic Accounting 2012 : Experimental Ecosystems Accounting." (2014). https://doi.org/10.1787/9789210562850-en.

Parfit, D. *Equality or priority?* Lindley lecture. Lawrence, Kan.: Dept. of Philosophy, University of Kansas, 1995.

Parks, S., and J. Gowdy. "What have economists learned about valuing nature? A review essay." *Ecosystem Services* 3 (2013): e1-e10. https://doi.org/https://doi.org/10.1016/j.ecoser.2012.12.002.

Parsons, K., and C. Hawkes. *Brief 5: Policy Coherence in Food Systems. In: Rethinking Food Policy: A Fresh Approach to Policy and Practice.* Centre for Food Policy (London UK: 2019).

Pate-Cornell, M. E. "The Engineering Risk Analysis Method and Some Applications." In *Advances in Decision Analysis*, edited by W. Edwards, R. F. Miles, Jr. and D. Von Winterfeldt, 302-24. Cambridge, UK: Cambridge University Press, 2007.

Peano, L., X. Bengoa, S. Humbert, Y. Loerincik, J. Lansche, G. Gaillard, and T. Nemecek. "The World Food LCA Database project: towards more accurate food datasets." Paper presented at the Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector (LCA Food 2014), San Francisco, CA, 8-10 October, 2014. 2014.

Pearce, D. "The Social Cost of Carbon and its Policy Implications." *Oxford Review of Economic Policy* 19, no. 3 (2003): 362-84. https://doi.org/10.1093/oxrep/19.3.362.

Pelenc, J., and J. Ballet. "Strong sustainability, critical natural capital and the capability approach." *Ecological Economics* 112 (2015): 36-44. https://doi.org/10.1016/j.ecolecon.2015.02.006.

Pezzey, J. C. V. "Why the social cost of carbon will always be disputed." *Wiley Interdisciplinary Reviews: Climate Change* 10, no. 1 (2019): e558. https://doi.org/10.1002/wcc.558.

Pfister, S., A. Koehler, and S. Hellweg. "Assessing the Environmental Impacts of Freshwater Consumption in LCA." *Environmental Science & Technology* 43, no. 11 (2009): 4098-104. https://doi.org/10.1021/es802423e.

Pimentel, D., B. Berger, D. Filiberto, M. Newton, B. Wolfe, E. Karabinakis, S. Clark*, et al.* "Water Resources: Agricultural and Environmental Issues." *BioScience* 54, no. 10 (2004): 909-18. https://doi.org/10.1641/0006-3568(2004)054[0909:WRAAEI]2.0.CO;2.

Pindyck, R. S. "The social cost of carbon revisited." *Journal of Environmental Economics and Management* 94 (2019): 140-60. https://doi.org/https://doi.org/10.1016/j.jeem.2019.02.003.

———. "The Use and Misuse of Models for Climate Policy." *Review of Environmental Economics and Policy* 11, no. 1 (2017): 100-14. https://doi.org/10.1093/reep/rew012. https://doi.org/10.1093/reep/rew012.

Pizzol, M., B. Weidema, M. Brandão, and P. Osset. "Monetary valuation in Life Cycle Assessment: a review." *Journal of Cleaner Production* 86 (2015): 170-79. https://doi.org/10.1016/j.jclepro.2014.08.007.

Plummer, M. L. "Assessing benefit transfer for the valuation of ecosystem services." *Frontiers in Ecology and the Environment* 7, no. 1 (2009): 38-45. https://doi.org/10.1890/080091.

Porfirio, L. L., D. Newth, J. J. Finnigan, and Y. Cai. "Economic shifts in agricultural production and trade due to climate change." *Palgrave Communications* 4, no. 1 (2018): 111. https://doi.org/10.1057/s41599-018-0164-y.

Porkka, M., M. Kummu, S. Siebert, and O. Varis. "From food insufficiency towards trade dependency: a historical analysis of global food availability." *PloS one* 8, no. 12 (2013): e82714-e14. https://doi.org/10.1371/journal.pone.0082714.

Prosperi, P., T. Allen, B. Cogill, M. Padilla, and I. Peri. "Towards metrics of sustainable food systems: a review of the resilience and vulnerability literature." *Environment Systems and Decisions* 36, no. 1 (2016): 3-19. https://doi.org/10.1007/s10669-016-9584-7.

Prugh, T., R. Costanza, J. H. Cumberland, H. Daly, R. Goodland, and R. B. Noordgard. *Natural capital and human economic survival.* Boca Raton: Lewis Publishers, 1999.

Ready, R., S. Navrud, B. Day, R. Dubourg, F. Machado, S. Mourato, F. Spanninks, and M. Rodriquez. "Benefit Transfer in Europe: How Reliable Are Transfers between Countries?". *The Official Journal of the European Association of Environmental and Resource Economists* 29, no. 1 (2004): 67-82. https://doi.org/10.1023/B:EARE.0000035441.37039.8a.

Rebecca, C.-K., S. Sarah, H. Perrine, B. Benjamin, N. Ryan, M. Carina, R. Giles*, et al.* "Life cycle assessment needs predictive spatial modelling for biodiversity and ecosystem services." *Nature Communications* 8 (2017). https://doi.org/10.1038/ncomms15065.

Rehman, A., L. Jingdong, B. Shahzad, A. A. Chandio, I. Hussain, G. Nabi, and M. S. Iqbal. "Economic perspectives of major field crops of Pakistan: An empirical study." *Pacific Science Review B: Humanities and Social Sciences* 1, no. 3 (2015): 145-58. https://doi.org/https://doi.org/10.1016/j.psrb.2016.09.002.

Reig, P., W. Larson, S. Vionnet, and J. B. Bayar. *Volumetric Water Benefit Accounting (VWBA): A Method for Implementing and Valuing Water Stewardship Activities. Working paper.* World Resources Institute (Washington DC: 2019). https://wriorg.s3.amazonaws.com/s3fs-public/volumetric-water-benefit-accounting.pdf.

Reilly, M., and D. Willenbockel. "Managing uncertainty: a review of food system scenario analysis and modelling." *Philosophical transactions of the Royal Society of London. Series B, Biological sciences* 365, no. 1554 (2010): 3049-63. https://doi.org/10.1098/rstb.2010.0141.

Reis, S., M. Bekunda, C. M. Howard, N. Karanja, W. Winiwarter, X. Yan, A. Bleeker, and M. A. Sutton. "Synthesis and review: Tackling the nitrogen management challenge: from global to local scales." *Environmental Research Letters* 11, no. 12 (2016): 120205. https://doi.org/10.1088/1748-9326/11/12/120205.

Revkin, A. "Trump's attack on social cost of carbon could end up hurting his fossil fuel push." *Science* (2017). https://doi.org/10.1126/science.aap7709.

Ricke, K., L. Drouet, K. Caldeira, and M. Tavoni. "Country-level social cost of carbon." *Nature Climate Change* 8, no. 10 (2018): 895-900. https://doi.org/10.1038/s41558-018-0282-y.

Ridgway, E. M., M. A. Lawrence, and J. Woods. "Integrating Environmental Sustainability Considerations into Food and Nutrition Policies: Insights from Australia's National Food Plan." *Front Nutr* 2 (2015): 29. https://doi.org/10.3389/fnut.2015.00029.

Robert, E. K., and K. M. Bryan. "The U.S. Government's Social Cost of Carbon Estimates after their First Year: Pathways for Improvement." *Economics : the Open-Access, Open-Assessment e-Journal* (2011).

Robinson, S., D. Mason d'Croz, S. Islam, T. B. Sulser, R. D. Robertson, T. Zhu, A. Gueneau, G. Pitois, and M. W. Rosegrant. *The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model description for version 3.* International Food Policy Research Institute (IFPRI) (Washington, DC: 2015). http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/129825.

Roche, J. "Intergenerational equity and social discount rates: what have we learned over recent decades?". *International Journal of Social Economics* 43, no. 12 (2016): 1539-56. https://doi.org/10.1108/IJSE-07-2015-0193.

Rosenhead, J. "Robustness Analysis: Keeping your options open." In *Rational Analysis for a Problematic World Revisited: Problem Structuring Methods for Complexity, Uncertainty, and Conflict*, edited by J. Rosenhead and J. Mingers. Chichester, UK: Wiley, 2001.

Rosenzweig, C., J. Elliott, D. Deryng, A. C. Ruane, C. Müller, A. Arneth, K. J. Boote*, et al.* "Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison." *Proc Natl Acad Sci U S A* 111 (2014). https://doi.org/10.1073/pnas.1222463110.

Royse, K. R., J. K. Hillier, L. Wang, T. F. Lee, J. O'Niel, A. Kingdon, and A. Hughes. "The application of componentised modelling techniques to catastrophe model generation." *Environmental Modelling & Software* 61 (2014): 65-77. https://doi.org/https://doi.org/10.1016/j.envsoft.2014.07.005.

Rutten, M. M. "What economic theory tells us about the impacts of reducing food losses and/or waste: implications for research, policy and practice." *Agriculture & Food Security* 2, no. 1 (2013): 1-13. https://doi.org/10.1186/2048-7010-2-13.

Sala, S., E. Crenna, M. Secchi, and R. Pant. *Global normalisation factors for the Environmental Footprint and Life Cycle Assessment.* Publications Office of the European Union (Luxembourg: 2017).

Sandelin, B., H.-M. Trautwein, and R. Wundrak. *A short history of economic thought.* 3rd ed. London: Routledge, 2014.

Scherer, L., P. Behrens, A. de Koning, R. Heijungs, B. Sprecher, and A. Tukker. "Trade-offs between social and environmental Sustainable Development Goals." *Environmental Science and Policy* 90 (2018): 65-72. https://doi.org/10.1016/j.envsci.2018.10.002.

Schmidt, S., A. M. Manceur, and R. Seppelt. "Uncertainty of Monetary Valued Ecosystem Services – Value Transfer Functions for Global Mapping." *PLOS ONE* 11, no. 3 (2016): e0148524. https://doi.org/10.1371/journal.pone.0148524.

Schneider, L., M. Duan, R. Stavins, K. Kizzier, D. Broekhoff, F. Jotzo, H. Winkler*, et al.* "Double counting and the Paris Agreement rulebook." *Science* 366, no. 6462 (2019): 180. https://doi.org/10.1126/science.aay8750.

Silver, M. *IMF Applications of Purchasing Power Parity Estimates.* International Monetary Fund (Washington DC: 2010).

Smith, P., and J. E. Olesen. "Synergies between the mitigation of, and adaptation to, climate change in agriculture." *J Agric Sci* 148 (2010// 2010). https://doi.org/10.1017/S0021859610000341.

Smith, P. J., M. Shafi, and G. Hongsheng. "Quick simulation: a review of importance sampling techniques in communications systems." *IEEE Journal on Selected Areas in Communications* 15, no. 4 (1997): 597-613. https://doi.org/10.1109/49.585771.

Sobota, D. J., J. E. Compton, M. L. McCrackin, and S. Singh. "Cost of reactive nitrogen release from human activities to the environment in the United States." *Environmental Research Letters* 10, no. 2 (2015): 025006. https://doi.org/10.1088/1748-9326/10/2/025006.

Solazzo, E., A. Riccio, R. Van Dingenen, L. Valentini, and S. Galmarini. "Evaluation and uncertainty estimation of the impact of air quality modelling on crop yields and premature deaths using a multi-model ensemble." *Science of The Total Environment* 633 (2018): 1437-52. https://doi.org/https://doi.org/10.1016/j.scitotenv.2018.03.317.

Stainforth, D. A., M. R. Allen, E. Tredger, and L. A. Smith. "Confidence, uncertainty and decision-support relevance in climate predictions." *Phil. Trans. R. Soc. A* 365 (2007): 2145-61.

Stanley, P. L., J. E. Rowntree, D. K. Beede, M. S. Delonge, and M. W. Hamm. "Impacts of soil carbon sequestration on life cycle greenhouse gas emissions in Midwestern USA beef finishing systems." *Agricultural Systems* 162 (2018): 249-58. https://doi.org/10.1016/j.agsy.2018.02.003.

Stern, N. *The economics of climate change: the Stern review.* Cambridge, UK: Cambridge University Press, 2007.

———. "The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models." *Journal of Economic Literature* 51, no. 3 (2013): 838-59. https://doi.org/10.1257/jel.51.3.838.

Stiglitz, J. E., A. Sen, and J. P. Fitoussi. *The measurement of economic performance and social progress revisited. Reflections overview.* Commission on the measurement of Economic Performance and Social Progress (Paris: 2009).

https://wedocs.unep.org/bitstream/handle/20.500.11822/19041/Report_by_the_Commission_on_the_Measurement_of.pdf?sequence=1.

Swinburn, B. A., V. I. Kraak, S. Allender, V. J. Atkins, P. I. Baker, J. R. Bogard, H. Brinsden, *et al.* "The Global Syndemic of Obesity, Undernutrition, and Climate Change: The Lancet Commission report." *The Lancet* 393, no. 10173 (2019): 791-846. https://doi.org/10.1016/S0140-6736(18)32822-8.

Tang, K., A. Hailu, M. E. Kragt, and C. Ma. "Marginal abatement costs of greenhouse gas emissions: broadacre farming in the Great Southern Region of Western Australia." *Australian Journal of Agricultural and Resource Economics* 60, no. 3 (2016): 459-75. https://doi.org/10.1111/1467-8489.12135.

TEEB. *TEEB for Agriculture & Food: Scientific and Economic Foundations.* UN Environment (Geneva: 2018).

Tinch, R. "Debating Nature's Value: The Role of Monetary Valuation." In *Debating Nature's Value: The Concept of 'Natural Capital'*, edited by V. Anderson, 39-47. Cham: Springer International Publishing, 2018.

Tokdar, S. T., and R. E. Kass. "Importance sampling: a review." *WIREs Computational Statistics* 2, no. 1 (2010): 54-60. https://doi.org/10.1002/wics.56.

Tol, R. S. J. "On the Uncertainty About the Total Economic Impact of Climate Change." *Environmental and Resource Economics* 53, no. 1 (2012): 97-116. https://doi.org/10.1007/s10640-012-9549-3.

Toman, M. " Why not to calculate the value of the world's ecosystem services and natural capital." *Ecological Economics* 25, no. 1 (1998): 57-60. https://doi.org/10.1016/S0921-8009(98)00017-2.

Tomich, T. P., P. Lidder, M. Coley, D. Gollin, R. Meinzen-Dick, P. Webb, and P. Carberry. "Food and agricultural innovation pathways for prosperity." *Agricultural Systems* 172 (2019): 1-15. https://doi.org/https://doi.org/10.1016/j.agsy.2018.01.002.

Tremmel, M., U.-G. Gerdtham, P. M. Nilsson, and S. Saha. "Economic Burden of Obesity: A Systematic Literature Review." *International journal of environmental research and public health* 14, no. 4 (2017): 435. https://doi.org/10.3390/ijerph14040435.

TruCost. *Top-down methodology TEEB Animal Husbandry.* TruCost (London: 2016). http://www.teebweb.org/wp-content/uploads/2017/08/Top-down-methodology_TEEB-Animal-Husbandry_v2.pdf.

———. *TruCost's Valuation Methodology.* TruCost (2015). https://www.gabi-software.com/fileadmin/GaBi_Databases/Thinkstep_Trucost_NCA_factors_methodology_report.pdf.

Tubiello, F. N., M. Salvatore, A. F. Ferrara, J. House, S. Federici, S. Rossi, R. Biancalani, *et al.* "The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990–2012." *Global Change Biology* 21, no. 7 (2015): 2655-60. https://doi.org/10.1111/gcb.12865.

Turner, R. K., I. Bateman, and D. W. Pearce. *Environmental economics : an elementary introduction.* New York-London: Harvester Wheatsheaf, 1994.

UN, European Commission, Eurostat, FAO, IMF, OECD, and World Bank. *System of environmental-economic accounting 2012 : experimental ecosystem accounting.* United Nations Organization (New York: 2014).

UNEP. *Emissions Gap Report 2019.* United Nations Environment Programme (Nairobi: 2019). https://www.unenvironment.org/resources/emissions-gap-report-2019.

———. *Guidelines for social life cycle assessment of products: social and socio-economic LCA guidelines complementing environmental LCA and Life Cycle Costing, contributing to the full assessment of goods and services within the context of sustainable development.* UNEP DTIE Sustainable Consumption and Production Branch (Paris: 2009). http://hdl.handle.net/20.500.11822/7912.

———. *Inclusive wealth report 2018 : measuring progress towards sustainability.* Cambridge: Cambridge University Press, 2018.

Valdivia, R. O., J. M. Antle, C. Rosenzweig, A. C. Ruane, J. Vervoort, M. Ashfaq, I. Hathie, *et al.* "Representative Agricultural Pathways and Scenarios for Regional Integrated Assessment of Climate Change Impacts, Vulnerability, and Adaptation." In *Handbook of Climate Change and Agroecosystems*, edited by C. Rosenzweig and D. Hillel. Series on Climate Change Impacts, Adaptation, and Mitigation, 101-45. London UK: Imperial College Press, 2014.

van den Bergh, J. C. J. M., and W. J. W. Botzen. "A lower bound to the social cost of CO2 emissions." Perspective. *Nature Climate Change* 4 (2014): 253. https://doi.org/10.1038/nclimate2135.

van Grinsven, H. J. M., M. Holland, B. H. Jacobsen, Z. Klimont, M. a. Sutton, and W. Jaap Willems. "Costs and Benefits of Nitrogen for Europe and Implications for Mitigation." *Environmental Science & Technology* 47, no. 8 (2013): 3571-79. https://doi.org/10.1021/es303804g.

van Zanten, H. H. E., M. Herrero, O. Van Hal, E. Roos, A. Muller, T. Garnett, P. J. Gerber, C. Schader, and I. J. M. De Boer. "Defining a land boundary for sustainable livestock consumption." *Glob Chang Biol* 24, no. 9 (Sep 2018): 4185-94. https://doi.org/10.1111/gcb.14321.

Vanessa, B., L. Annekatrin, G. Marcel, and F. Matthias. "Product Environmental Footprint (PEF) Pilot Phase—Comparability over Flexibility?". *Sustainability* 10, no. 8 (2018): 2898. https://doi.org/10.3390/su10082898.

Vermeulen, S. J., B. M. Campbell, and J. S. I. Ingram. "Climate Change and Food Systems." *Annual Review of Environment and Resources* 37, no. 1 (2012): 195-222. https://doi.org/10.1146/annurev-environ-020411-130608.

Vermeulen, S. J., A. J. Challinor, P. K. Thornton, B. M. Campbell, N. Eriyagama, J. M. Vervoort, J. Kinyangi*, et al.* "Addressing uncertainty in adaptation planning for agriculture." *Proceedings of the National Academy of Sciences* 110, no. 21 (2013): 8357. https://doi.org/10.1073/pnas.1219441110.

Victora, C. G., L. Adair, C. Fall, P. C. Hallal, R. Martorell, L. Richter, and H. S. Sachdev. "Maternal and child undernutrition: consequences for adult health and human capital." *The Lancet* 371, no. 9609 (2008): 340-57. https://doi.org/https://doi.org/10.1016/S0140-6736(07)61692-4.

Vidal Legaz, B., D. Maia De Souza, R. F. M. Teixeira, A. Antón, B. Putman, and S. Sala. "Soil quality, properties, and functions in life cycle assessment: an evaluation of models." *Journal of Cleaner Production* 140, no. P2 (2017): 502-15. https://doi.org/10.1016/j.jclepro.2016.05.077.

Vogt-Schilb, A., and S. Hallegatte. "Marginal abatement cost curves and the optimal timing of mitigation measures." *Energy Policy* 66, no. C (2014): 645-53. https://doi.org/10.1016/j.enpol.2013.11.045.

WEF, and Deloitte Consulting. *Shaping the Future of Global Food Systems: A Scenarios Analysis.* World Economic Forum (Geneva: 2017).

Weidema, B. P., M. Thrane, P. Christensen, J. Schmidt, and S. Løkke. "Carbon Footprint." *Journal of Industrial Ecology* 12, no. 1 (2008): 3-6. https://doi.org/10.1111/j.1530-9290.2008.00005.x.

Weitzman, M. "Fat-tailed uncertainty in the economics of catastrophic climate change." *Rev. Environ. Econ. Policy.* 5 (2011): 275-92.

———. "On Modeling and Interpreting the Economics of Catastrophic Climate Change." *The Review of Economics and Statistics* 91, no. 1 (2009): 1-19. https://doi.org/10.1162/rest.91.1.1.

———. "Risk-adjusted gamma discounting." *Journal of Environmental Economics and Management* 60, no. 1 (2010): 1-13. https://doi.org/10.1016/j.jeem.2010.03.002.

Wellesley, L., C. Happer, and A. Froggatt. *Changing climate, changing diets : pathways to lower meat consumption.* Chatham House report. London: The Royal Institute of International Affairs, Chatham House, 2015.

Werners, S. E., S. Pfenninger, E. van Slobbe, M. Haasnoot, J. H. Kwakkel, and R. J. Swart. "Thresholds, tipping and turning points for sustainability under climate change." *Current Opinion in Environmental Sutainability* 5 (2013): 334-40.

Whitaker, K. L., M. J. Jarvis, R. J. Beeken, D. Boniface, and J. Wardle. "Comparing maternal and paternal intergenerational transmission of obesity risk in a large population-based sample." *The American Journal of Clinical Nutrition* 91, no. 6 (2010): 1560-67. https://doi.org/10.3945/ajcn.2009.28838.

Wiebe, K., H. Lotze-Campen, R. Sands, al, S. Frank, P. Havlík, H. van Meijl*, et al.* "Comparing impacts of climate change and mitigation on global agriculture by 2050." *Environmental Research Letters* 13 (2018): 1748-9326.

Wiebe, K., M. Zurek, S. Lord, N. Brzezina, G. Gabrielayan, J. Libertini, A. Loch*, et al.* "Scenario development and foresight analysis: exploring options to inform choices." *Annual Review of Environment and Resources* 43 (2018). https://doi.org/10.1146/annurev-environ-102017-030109.

Wiedmann, T., and J. Minx. "A Definition of 'Carbon Footprint'." Chap. 1 In *Ecological Economics Research Trends*, edited by C. C. Pertsova, 1-11. Hauppauge NY: Nova Science Publishers, 2008.

Willett, W., J. Rockström, B. Loken, M. Springmann, T. Lang, S. Vermeulen, T. Garnett*, et al.* "Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems." *The Lancet* 393, no. 10170 (2019): 447-92. https://doi.org/https://doi.org/10.1016/S0140-6736(18)31788-4.

WRAP. *Food futures: from business as usual to business unusual.* The Waste and Resources Action Programme (Banbury: 2016).

Wynes, S., K. A. Nicholas, J. Zhao, and S. D. Donner. "Measuring what works: quantifying greenhouse gas emission reductions of behavioural interventions to reduce driving, meat consumption, and household energy use." *Environmental Research Letters* 13, no. 11 (2018): 113002. https://doi.org/10.1088/1748-9326/aae5d7.

Yamaguchi, R., M. Islam, and S. Managi. "Inclusive wealth in the twenty-first century: a summary and further discussion of Inclusive Wealth Report 2018." *Letters in Spatial and Resource Sciences* 12, no. 2 (2019): 101-11. https://doi.org/10.1007/s12076-019-00229-x.

Zurek, M., A. Hebinck, A. Leip, J. Vervoort, M. Kuiper, M. Garrone, P. Havlík*, et al.* "Assessing Sustainable Food and Nutrition Security of the EU Food System—An Integrated Approach." *Sustainability* 10, no. 11 (2018). https://doi.org/10.3390/su10114271.

PREVIOUS SECTION: 5. ALIGNMENT OF IMPACT FRAMEWORKS

Valuing the impact of food:

Towards practical and comparable monetary valuation of food system impacts

A report of the Food System Impact Valuation Initiative (FoodSIVI)

May 2020

FoodSIVI

www.foodsivi.org @foodsivi

Download all sections and the full report at www.foodsivi.org/what-we-do/publications

NEXT SECTION: 7. CASE STUDIES OF FOOD SYSTEM IMPACT VALUATION