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# Revisiting the promise of carbon labelling

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**Carbon labelling systems can inform individual and organizational choices, which potentially reduce the carbon footprints of goods and services. We review the ways labelling is conceptualized and operationalized, and the available evidence on effectiveness. The literature focuses mainly on how labelling affects retail consumer behaviour, but much less on how labelling affects the behaviour of the organizations that produce, transport and sell products despite preliminary research suggesting that the effects on corporate behaviour may be substantial even without strong consumer responses. We consider key challenges for carbon labelling systems related to standard setting, data collection and use, and label design. We summarize the available knowledge, identify key research questions and identify steps towards achieving the promise of carbon labelling.**

Carbon labelling summarizes data on the greenhouse gases (GHGs) emitted from the production, distribution and use ('carbon footprints') of a good or service in a simple indicator presented at the point of purchase. The goal is to facilitate choices that can rapidly reduce GHG emissions to meet the challenges posed by escalating anthropogenic climate change. Even increasingly aggressive national emissions reduction commitments fall far short of the levels needed to limit warming to 1.5 or 2 °C (ref. [1]). A commentary in the first volume of this journal[2] advocated the development of 'a global private carbon labelling system' as a low-cost, viable initiative to reduce the carbon footprints of consumer goods and services (hereafter referred to as products).

Feasibility is a primary rationale for carbon labelling. Unlike many other GHG mitigation initiatives, information disclosure does not require government actions such as regulations, taxation or financial incentives, each of which faces barriers in many political systems[2]. Emissions reductions from carbon labelling may also be more rapidly achievable than that from many technological innovations, which require time to develop, implement and diffuse[3–6].

Carbon labelling has also been advocated on the grounds of behavioural plasticity, the extent to which the intended responders to an initiative take action[7]. The argument is that information provided by well-designed labelling systems can, alone or combined with other initiatives, increase the responsiveness among the intended responders—households, companies and governments[8–12]. Labelling can help address several impediments to behavioural plasticity among responders, such as: (1) limited or incorrect understanding of the direct GHG emissions associated with products, sometimes misperceived by an order of magnitude or more[13–16]; (2) incomplete understanding of indirect GHG emissions, that is, those produced by other actors in product supply chains; and (3) difficulties finding or interpreting the available information.

Policy analyses of climate mitigation initiatives often apply economic cost–benefit analysis to assess the feasibility without analysing the political, social and behavioural issues that affect the feasibility of and response to these initiatives. This oversight may account for disappointments with the uptake of many initiatives of the past, from nuclear power to time-of-use electricity pricing to carbon taxes. Future mitigation initiatives, such as negative emission technologies, may suffer the same fate if behavioural plasticity and initiative feasibility are considered only narrowly or not at all[17–20]. These issues may also arise with carbon labels that incorporate carbon offsets, as these suffer from well-known methodological challenges and sometimes rely on unproved technologies that are poorly understood by most citizens and may raise public opposition.

## Labelling relative to other disclosure initiatives

As is the case for other kinds of environmental and social labelling (for example, organic, fair trade and animal welfare), carbon labelling depends on collecting and presenting information in ways intended to shape decisions[21]. The information collected to support the carbon labelling of products can also be used to support carbon taxes, carbon border adjustments and supply-chain contracting. Synergies and economies of scale may thus derive from efforts to design carbon disclosure systems with all these uses in mind, and from building labelling systems on well-designed disclosure protocols.

Environmental labelling (sometimes referred to as eco-labelling) systems vary in the extent to which they signal individual benefits (for example, financial or health, as with energy and organic labelling) or collective benefits (for example, societal protection from climate change or well-being of ecosystems, as with carbon and sustainability labelling). The benefits signalled by labels probably have heterogeneous effects on responders, depending on their familiarity and engagement with the labelling system, and thereby influence the effectiveness of labels over time[22].

Labelling systems also differ in whether they capture environmental footprints from the production of the product (typical of carbon labels), from product use (typical of energy labels), or from the entire product life cycle, which includes production, use and disposal. Some labels, such as the Greenhouse Gas Protocol's $CO_2$-Neutral label (https://www.co2-neutral-label.org/), also include emissions offsets. The GHG emissions from the use of a company's products (often called scope 3 emissions), the increased

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policy focus on reporting and reducing emissions elsewhere in product life cycles and the increased focus on net-zero commitments suggest that incentives to label may increase. Labels that address the full product life cycles may thus receive a greater emphasis.

Important insights may emerge from comparing labelling systems across environmental domains, and perhaps also from examining information disclosure initiatives in the health and social domains of products. Nevertheless, we restrict our focus here to carbon footprint labelling. We highlight important dimensions of developing and implementing new carbon labelling systems or modifying existing systems. These dimensions include who develops the systems, how system standards and criteria are negotiated, how and what information is presented, and the heterogeneity of users and their needs. Much of our analysis also applies to energy labels, although energy labels and carbon labels differ (for example, whether they emphasize individual or collective benefits). For simplicity, we refer to carbon labels unless making a specific distinction between the two.

Carbon labelling systems may be sponsored or implemented by governmental, corporate or non-profit organizations, or by collaborations of these organizations. They may target consumer or organizational behaviour and may influence users anywhere in product life cycles. The validity and effectiveness of carbon labelling systems depend on the characteristics of the targeted product or market, the availability and accuracy of data, the rules developed to convert data into labels and the procedures employed to develop rules, design labels and modify them as appropriate. The procedures often involve negotiation within and among organizations and can influence trust in the system, which shapes the impact of labels on users' behaviour[23–25]. A wide engagement of government, the private sector and non-governmental organizations can improve the accuracy and credibility of a labelling system. However, labelling also places a premium on technical expertise, and the distribution of power in negotiations has implications for the resulting labelling system[26,27]. Large organizations, through buying power, can use emissions data to push suppliers to reduce emissions. However, such organizations may also obstruct the consensus or shape it towards their interests. These possibilities may affect the trust in labelling systems. In general, the dynamics by which labelling systems are adopted and revised within and across organizations are complex and undoubtedly vary across jurisdictions and products[28–30].

Labels may provide information in a variety of formats and at different levels of resolution (Fig. 1 and Supplementary Table 1). A certificate or seal of approval marks labelled entities as meeting some standard; its absence signifies either failure to meet the standard or to apply for certification. Certificates may attest that a product is carbon neutral, or indicate that its footprint is measured and certified (for example, the Publicly Available Specification (PAS) 2050 and International Organisation for Standardization (ISO) 14067 standards), that its footprint is being reduced year by year or that it emits less $CO_2$ than comparable products[31,32]. Some labels provide ordinal rating scales analogous to the Michelin star ratings for restaurants or traffic light designations with products labelled as green, yellow or red. One limitation of such ordinal scales is that there is a tendency for efforts to stop at a point that just meets the criteria for a step on the scale[33]. Even finer resolution is offered by quantitative measures, such as fuel economy labels on automobiles or appliances. We argue that the most effective design may incorporate both ordinal and quantitative information to facilitate both simple and more detailed product comparisons (for example, the European Union (EU) energy label) by diverse consumers (retail, corporate and governmental) and corporate actors throughout the product supply chains[14,34,35].

As label users differ in the amount of detail they want or can use, labelling systems should offer a level of detail suited to their needs and capabilities. For example, retail consumers have very little time, energy, capability or interest in absorbing detailed information when deciding on a can of beans or a light bulb, so a simple certification or ordinal label may serve them well, given that it is accurate and credible[36–39]. For larger purchases, such as a vehicle, building or appliance, retail consumers may use more detailed information, especially if it is presented in a format that facilitates the kinds of comparisons being used in decision making (Fig. 1). For organizational consumers, retailers, producers and intermediaries in supply chains, and governments, all of which have more at stake and more ability to use detailed information than do retail consumers, quantitative information may be critical. The precision of the underlying data and information presented should reflect the function that the carbon labelling system is serving because to acquire and analyse the necessary data can be costly. For products with large carbon footprints, a high degree of precision may be useful to inform choices, but in other instances, less precision may be preferable. A 'good enough for the intended purpose' labelling approach may have substantial benefits, even as more refined efforts are developed[40].

Although the responses of retail consumers to labels have been the main subject of labelling research, consumers are not the only, or perhaps even the most promising, target for carbon labels. Labelling can reduce GHG emissions without directly affecting retail consumers' choices[2], such as by inducing changes in supply chains, production processes and product mix to improve companies' reputations or to achieve efficiency gains[40–42]. Labels may also affect governments in their roles as regulators, standard setters and consumers of products. Thus, labels can have effects on organizational behaviour beyond those that arise from retail consumer behaviour. Labels, as for other mitigation initiatives, can be assessed in terms of how much effect they could ideally have, the feasibility of their adoption and the degree to which they produce the intended responses when implemented[3].

## Carbon labelling efforts to date

Carbon labelling systems have been developed for a wide variety of products[31]. Ecolabel Index (http://www.ecolabelindex.com/) reports 455 ecolabels in 199 countries across 25 different sectors, which include 31 carbon footprint labels. Carbon Trust, for example, has labelled hundreds of thousands of products, from cement to bank accounts. Some early efforts were undertaken by large European retailers—such as Tesco, Casino, E.Leclerc and RAISIO—which labelled thousands of products through self-initiated systems[31,43,44]. However, not all these efforts remain in place. For example, Tesco announced plans to label all of its 70,000 products, yet had to abandon the project due to the high associated costs[45]. Casino's carbon label was gradually replaced by a broader environmental index that considers products' GHG emissions, water consumption and aquatic pollution over their life cycle. Meanwhile, other actors in the food sector have adopted labelling systems, such as restaurants (for example, the Swedish burger chain, Max), food producers (for example, Unilever) and other corporations. Carbon labelling systems have also been implemented in domains such as tourism, hospitality, transport and housing[46–50].

The efforts of Tesco and Casino suggest the importance of avoiding the high cost of attempting to label all products, even those with complex carbon footprints and low emissions. Shewmake et al.[51] suggested four criteria for selecting the most promising products for carbon labelling: (1) the amount of GHG emissions; (2) the availability of data on life-cycle emissions; (3) the ability of companies to adjust their activities to reduce emissions; and (4) the responsiveness of consumers by switching to lower-carbon products. To this list, we would add (5) the responsiveness of corporations to reputational, efficiency and other pressure to reduce emissions.

Carbon and other environmental disclosure systems have increased market penetration in some domains. For example,

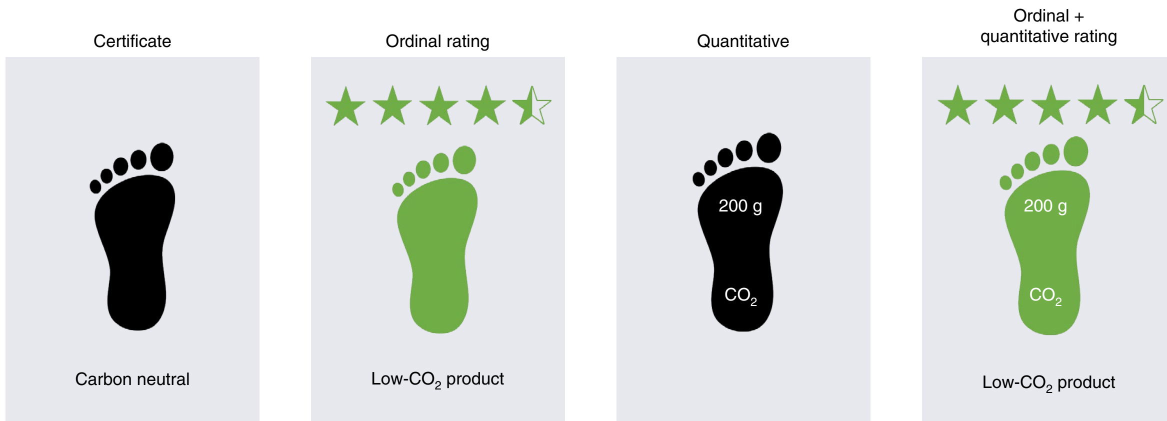


**Fig. 1 | Illustrative examples of resolution levels offered by carbon labels.** Labels at all resolution levels shown are currently in use. Some examples are identified, with links, in Supplementary Table 1. Certificate labels indicate that the labelled products meet some standard, ordinal ratings differentiate among several levels of carbon footprints of the same product, quantitative labels offer numerical measurements of carbon footprints and some labels combine quantitative and ordinal ratings. The design of labels should be informed by research on what means of conveying information is the most effective, particularly for retail consumers. The available data are inadequate to choose among logo types (we use footprints here) or among ways to represent ordinal differences (for example, stars or letter grades). Research suggests that ordinal labels that employ the familiar red–yellow–green distinction in traffic lights may be effective for many retail choices[35]. In the figure, we apply that insight by colouring the footprints green in the ordinal representations to indicate low-footprint products. Yellow or red can be used to indicate intermediate- or high-footprint products. Icon credits: Roselin Christina.S (stars) and iconoci (footprints), Noun Project (https://thenounproject.com/).

environmental and energy certification for commercial buildings, such as LEED (Leadership in Energy and Environmental Design), increased in the largest US markets from about 5% in 2005 to about 40% in 2014[52]. The Greenhouse Gas Protocol (https://ghgprotocol.org/) reports that 92% of Fortune 500 companies use this protocol. Although most corporations report only emissions from their facilities (called scope 1 emissions) and the off-site facilities that provide energy to them (scope 2), the protocol includes a tool to calculate emissions 'throughout their value chains' and provides a basis for its $CO_2$-neutral label.

Carbon labelling, however, remains less widespread than energy labelling. Thanks to the implementation of mandatory energy labelling systems in the EU, United States and other areas, labels have long existed for many energy-consuming products (for example, electric appliances, commercial buildings, housing and motor vehicles). Consequently, retail consumers generally report a much greater familiarity with and usage of energy labels than of carbon labels. For example, according to the Special Barometer 492 survey, the EU energy label is recognized by 93% of consumers, and 79% report considering the label when purchasing new electric appliances[53]. Environmental and carbon labelling are dynamic areas with a great deal of ongoing research, and many labelling systems are underway or in planning. For example, Foundation Earth, a non-profit organization, is currently undertaking a pilot carbon labelling system using traffic light 'eco-scores' for food and drinks with a plan for Europe-wide rollout in 2022[54]. The importance of environmental and carbon labelling for informed consumer, corporate and government procurement decisions is also gaining an increasing attention at the policy level in, for example, the United Kingdom[55] and United States[56,57].

The Internet may also increase opportunities for carbon labelling, and digital carbon labelling may be cheaper, easier and more effective than labelling for traditional brick-and-mortar-based commerce[58]. For example, PANGAIA clothing has initiated a 'digital passport' (QR code and cloud-hosted digital twin) printed on clothing to indicate its carbon and water footprints, and Sheep Inc. uses a bio-based near-field communication tag that details the carbon footprint at each stage of the supply chain. Other recent advancements, such as block-chain technology, may also improve the tools for supply-chain management and carbon footprinting[59]. Although digital carbon labelling is promising, further research is needed to explore how it can be applied across an array of GHG-intensive production and consumption activities.

Retail consumers' responsiveness to labels may be limited unless enough products are labelled to enable consumers to readily compare among them. Nevertheless, corporations may gain an advantage by displaying a favourable carbon label that suggests to consumers, who are often using cognitive shortcuts, that the labelled product has lower emissions than an unlabelled product. In addition, as we discuss below, even without major shifts in consumer behaviour, the process to gather and analyse the data for labelling and the prospect of publicly disclosing product emissions can create corporate incentives for emissions reductions.

## Evidence of effectiveness

An effective carbon label can be defined as one that decreases GHG emissions in a non-trivial, cost-effective way compared with efforts that lack a labelling feature and that does not negatively affect other mitigation initiatives. Carbon labels can increase behavioural plasticity among retail consumers by encouraging them to select low-carbon products. Carbon labelling can also induce retailers and others in the supply chain (for example, corporate buyers, transporters and producers) to provide consumers with low-carbon products because attention to labelling data can make these organizations more aware of GHG emissions and inefficiencies associated with their products or more concerned about naming-and-shaming or reputation campaigns. The effects of labels may vary over time, across types of products and across types of producers and consumers. We discuss behavioural plasticity for retail consumers and then turn to corporations and other actors.

**Effectiveness with retail consumers.** Many studies have examined the effectiveness of carbon labels on retail consumer choices[46] (Box 1 reviews work on vehicle labels, and Box 2 examines the labelling of buildings and their effectiveness with both retail and organizational consumers). Our broad review of such studies (Supplementary Information) shows that consumer disposable products are most extensively studied. Most studies that examined consumer responses

**Box 1 | Responses to labels for motor vehicles**

The choice of motor vehicles is one of the most climate consequential decisions for households and many organizations. It is also a complex decision that involves a relatively large financial commitment (among households, usually second only to the purchase of a home), a complex variety of practical and symbolic features of the vehicle and efforts by the industry to shape decisions[117]. For many retail consumers, carbon or energy labels are not likely to be the dominant influence on a motor vehicle purchase decision. Nonetheless, the rise in popularity of hybrid and all-electric vehicles through a period of historically modest gasoline prices suggests that environmental impacts, which include climate change concerns, do have a substantial impact on vehicle purchases. Certainly, the stark contrasts among the carbon footprints of all-electric, hybrid and conventional vehicles suggests that information on labels reflects something that matters to many retail consumers. However, beyond that categorical distinction, do labels matter?

In many countries, fuel-efficiency labels on new vehicles are mandated. As fuel-efficiency translates rather directly into GHG emissions, these labels are a reasonable surrogate for carbon labels as an influence on vehicle purchases. Indeed, one could view carbon labels and fuel-efficiency labels on vehicles as alternative ways to present essentially the same information to consumers, although fuel-efficiency labels signal both individual and collective benefits, whereas carbon labels mainly signal collective benefits. Of course, with plug-in hybrid or all-electric vehicles, the GHG emissions depend on the source of electricity.

Several studies document the effects of vehicle labels on retail consumer choice. Much of this literature relies on self-reports of behavioural intentions, so the usual cautions apply. It does seem clear that the way information is presented makes a difference. For example, Brazil et al.[118] found that information presented as a monthly fuel cost has a larger impact on the stated preferences than information presented as fuel consumption. In a direct comparison of fuel efficiency and cost information with environmental impact information, Codagnone et al.[119] found that fuel-efficiency labelling had the greatest impact (see also Andor et al.[120]). Galarraga et al.[121] found that both relative (compared with those of other vehicles) and absolute ratings of fuel efficiency can matter, but their influence depends on whether consumers are making choices within a class of vehicles (for example, sedans) or across all classes, an indication of the complexities that have to be considered in the design of effective labelling strategies (see also Hille et al.[122]). A variety of other studies found that labels can have an impact on the willingness to spend more for a fuel-efficient vehicle but, again, the results are complex, with the effect of energy efficiency or carbon labels depending on factors such as the kind of benefits from low fuel consumption that were signalled[123,124]. The effects on manufacturers and dealers are less studied; some reports show that dealers steer retail customers away from electric vehicles[103], which may suggest the need for research and policy initiatives that focus on these actors.

**Box 2 | Responses to building labels**

The purchase, lease or rental of a dwelling is the largest item in the budget of most households. The costs of buildings also represent an important expenditure for most organizations. It is therefore not surprising that building energy ratings and labels have a considerable history. Many jurisdictions have mandates for labels or rating and voluntary systems are also used extensively. As with the work on vehicles discussed in Box 1, this literature has evolved independently of the work on low-footprint consumer products, which is the major focus of the section 'Evidence of effectiveness'. Experiments with hypothetical real-estate advertisements suggest that energy ratings could influence home-purchase decisions, although, as with all results about labels, the impacts may vary across segments of the population[125]. There is also evidence that energy-efficient homes and homes equipped with solar photovoltaics appraise and sell for higher prices, so labels may facilitate signalling these features of a home, at least in the places where they have been studied most, such as California[126].

For commercial buildings, it appears that environmental certification (which includes energy efficiency, but other factors as well) leads to increased rental prices, lower vacancy rates, greater occupant satisfaction[52,127] and decreased energy use[128]. As with much of the literature on labelling, experiments that allow detailed assessments of the impact of a label mainly rely on hypothetical responses. Experiments using data from actual purchases or rentals to assess the impacts of a labelling or certification scheme over and above the features of the building itself are methodologically challenging. However, we suggest that a labelling system may draw attention to and encourage improvements in building characteristics that might not otherwise be visible. For buildings, as for vehicles, the most effective strategies to increase the impact of labels may come from targeting key actors who influence consumer and producer decisions. For buildings, these include real-estate agents, appraisers, corporate tenants and mortgage lenders[129].

or behavioural plasticity found a small, positive effect of carbon labels in guiding consumer selection, purchase or consumption towards lower-carbon products[14,35,60–65]. However, null effects are not uncommon (see Supplementary Table 3 for a summary of major findings over the past ten years)[66–68]. For energy labels on household equipment, such as electrical appliances or light bulbs, the evidence on behavioural plasticity similarly includes many studies that report small positive effects[69–71], but some report null effects[50,67].

Evidence from numerous studies suggests that design features of a carbon label, which include image, colour, size and location on the product, can significantly influence visual attraction, comprehension and ultimately engagement with the label[8,10,14,72]. However, the importance of different design features often varies across product types, decision environments and the deliberateness of the decision-making process. For example, when consumers make decisions with limited deliberation and in stimulus-intensive environments, such as when grocery shopping, the label must attract visual attention and be easy to understand[73,74].

For carbon labels on food products, several studies found that certificates (Fig. 1) are often not very effective in influencing behaviour, whereas ordinal (for example, traffic light) labels are more effective, particularly when coupled with quantitative information[10,35,75,76]. The observed benefits of traffic light designations are often attributed to their visual attractiveness and, especially, their ease of understanding and use for product comparisons[38,48]. A recent systematic review of six studies also found that presenting GHG emissions information using both a logo and text (for example, a traffic light designation and quantitative information) was the most effective design to influence consumer choices[60]. Additionally, a recent qualitative study found carbon labels are more likely to be noticed when presented as a warning of an environmental hazard[72], a finding consistent with evidence from health labelling[77,78]. Finally, studies on the EU energy label indicate that shifting from the original A–G ordinal ranking to a A$^{+++}$–D ranking reduced its effectiveness among retail consumers by lowering the perceived importance of energy efficiency in product choices[79,80]. Consequently, the original A–G ranking was recently reinstated alongside greater energy efficiency expectations for each ranking level.

Although research to date supports the promise of labelling, the literature has several noteworthy limitations. Perhaps the most important is that the vast majority of studies were conducted in artificial settings using hypothetical choice experiments[10,35,60,69,73], small-scale field experiments (for example, in one canteen or restaurant[55,56]) or cross-sectional surveys[8,81,82]. The generalizability of such evidence remains uncertain and the estimated effects may not match real-world outcomes. Moreover, studies typically focus on a particular product (for example, coffee, tomatoes, light bulbs or washing machines) or product category (for example, meat, dairy products, home appliances or building materials), which permits assessing within-product (category) effects, but not substitution and spillover effects. Another important limitation is that most studies evaluated labelling effects as a self-reported willingness to pay, purchase intention, noticeability or visual attention, and preference for label designs[10,64,72,73,83]. Limited evidence is available for assessing the effects of carbon and energy labelling on actual purchasing and consumption behaviour for products with a high technical potential to reduce emissions (for example, air travel), perhaps due to the difficulty of accessing actual sales data. Online purchasing may provide opportunities for the measurement of actual purchasing behaviour and for experimentation with label design and consumer targeting[58]. Finally, the literature has examined how different labelling approaches might appeal to different market segments. This includes the differing effect on consumer segments of communicating individual versus collective benefits[22], which plays a prominent role in the psychology of environmental decision making[84].

Taken together, the available evidence finds some effects of carbon and energy labels on retail consumer purchases, over and above the effects of other initiatives. However, these effects are probably context and actor dependent. For example, the effects may vary with the perceived importance of non-environmental product attributes, socio-economic factors, political views, environmental concern, business domain, presence of competing labels or prevalence of norms about purchases that might be signalled by labels. Information provision has been found effective in influencing the selection phase of decision making, after a consumer has decided to choose among particular products, and when the information source is highly credible to the consumer[12].

**Effectiveness with other life-cycle actors.** Relatively little research has focused on the impact of carbon labelling on the carbon footprint of retailers, producers, intermediaries and wholesale consumers. Research has not yet systematically examined such effects, although some evidence from studies of other types of environmental labelling[29,42,85] and of corporate social responsibility indexes suggests that labelling can be effective in shifting corporate behaviour even when consumer effects are modest[86,87]. Indeed, some types of environmental disclosures at the corporate level can have an effect on stock prices, and thus provide a powerful incentive[40].

One possible influence pathway involves making producers or intermediaries more aware of GHG-intensive inputs (that is, fossil fuel energy and fertilizers) that are being managed inefficiently. Thus, the mere assessment of GHG emissions from a product may draw attention to potential cost savings from reducing inefficiencies in product life cycles. Although many businesses have adopted carbon accounting, tracking indirect GHG emissions from the full life cycle of their products has lagged and remains a challenge to organizational carbon accounting[88,89]. A study of 63 large Brazilian companies found that the implementation of an environmental management system was significantly related to reductions in GHG emissions, which suggests that tracking and analysing resource use can lead to emission reductions[90]. In addition, Li et al.[91] found that for the top 100 listed companies (2008–2012) in China, environmental management systems were positively correlated with corporate green innovation. Research remains scarce on whether the implementation of carbon information systems in particular leads to similar improvements in GHG emissions.

Labelling may also induce some producers to reduce emissions to score well in labelling systems and gain reputational benefits. Evidence shows that corporate reputation affects profits[92,93]. Lee et al.[94] report that supply-chain managers identified 'risk of brand damage' as the primary motivation to measure and address supply-chain social and environmental impacts. Although research is lacking, a reasonable hypothesis is that reputational risk might drive product innovation and GHG-intensity reduction. Darnall and Aragón-Correa[42] suggest that reputational risk drove firms to reduce trans fats in food before nutrition labelling was required. Similarly, corporations in the United States reduced their toxic chemical releases when they were first required to publicly disclose emissions through the Toxic Release Inventory, even though such reductions were not legally mandated[95].

Carbon accounting in support of labelling systems can also increase corporate motivations to require GHG emissions data and reductions from suppliers. Drawing on the experiences of the Carbon Trust labelling efforts, van der Ven et al.[96] identified benefits from carbon labelling that arise from scaling (for example, the widespread global uptake of carbon assessment methodologies) and entrenchment (for example, identification of efficiencies in corporate supply chains). Carbon labelling and supply-chain contracting can thus be mutually reinforcing. Supply-chain contracting requirements can increase the ability of corporate buyers to obtain emissions information from suppliers. In turn, the information gathered from supply chains to support carbon labelling systems can bolster the motivations and ability of corporate buyers to press their suppliers to reduce their carbon footprints.

Carbon labelling may signal what will be required under future regulations and how future regulations will affect product lines. For instance, in the United States, the Energy Star certification is usually set to identify the top 25% of energy-performing products, but it is expected that many current Energy Star standards will become future mandatory minimum standards for all products[97]. A label that discloses high GHG emissions may indicate a corporation's vulnerability if governments adopt climate regulations, carbon taxes or border adjustments or if corporate buyers include carbon requirements in supply-chain contracts. The information generated by labels may also facilitate the adoption of these types of public and private climate governance requirements, signal the likelihood of future requirements and lay the groundwork for meeting the requirements.

Overall, carbon labelling systems provide data that can help corporations meet the growing demand for attention to environmental, social and governance (ESG) goals. Moreover, the public nature of labelling systems allows corporations to signal their movement towards achieving these goals. We thus expect substantial synergies between labelling, pressure for supply-chain and other scope 3 emissions reductions, environmental, social and governance pressure from investors, and other processes that encourage a broader consideration of life-cycle GHG emissions in corporate decision making.

## Challenges and paths forward

The most fundamental challenges to the wider use of carbon labelling arise from an incomplete understanding of labelling systems, competing objectives for these systems and the tendency to look for panaceas. The focus of research on retail consumers suggests that public and private entities that create labelling systems may assume that they are only valuable if they affect retail consumer behaviour, even when the effects on corporate and government behaviour may be equally or more important. Public and private policymakers might presume trade-offs between labelling and other policy initiatives, but there might be synergies[98–101]. Labelling systems generate information about product-specific GHG emissions that can be used by corporations and governments to support supply-chain requirements and by governments to develop climate mitigation measures, such as border adjustments[102].

The competing objectives of the producers and distributors of products create other challenges. Many corporations' profits are greatest for products with the largest carbon footprints, so these actors may be resistant to labelling. For example, the profits from a vehicle sale may be larger for fuel-intensive rather than fuel-efficient vehicles[103]. Such motives may also prompt industry efforts to weaken labelling systems by making it too easy for products to look environmentally friendly or by allowing for exceptions and evasion of accountability through offshoring production or other means. The interplay between governments, corporations and non-governmental organizations is complex. In their study of environmental labelling, Darnall et al.[28] found that independently sponsored environmental labels have the strongest rules, whereas privately sponsored labels have the weakest. Bullock[26] demonstrated that the private sector can be more powerful than the public sector in the standard setting of labels. Some suggested that the dynamics of labelling are driven by competition across sectors[104], first movers[105] or the scope of what is encompassed in labelling[85,106].

Carbon labelling can be easily overlooked by public and private policymakers who do not account for the difficulties of adopting and implementing other climate mitigation initiatives or who seek panaceas. Although labelling systems can reduce GHG emissions and complement other climate initiatives, they are certainly not sufficient to achieve emissions reduction targets on their own. However, labelling may be more feasible because it may be seen as less restrictive or as allowing more time to push product life cycles towards reduced emissions. Labelling can also be implemented by the private sector when governments lack the political support to adopt regulatory measures, and it can have effects that transcend national boundaries even without international agreements. The barriers to labelling may thus be weaker than the barriers to direct government product regulation or carbon pricing. Labelling may also facilitate later government adoption of these approaches. In evaluating mitigation initiatives, it is important to recognize that a somewhat effective label will have greater impact than a stronger policy that is not adopted or adopted at a much later date. The desire for mitigation panaceas should not block real progress in reducing emissions.

Greater emphasis is needed on interactions between labelling and other mitigation initiatives. Valid and credible quantification, whether or not included on labels, can support efforts to combat greenwashing[107] as it provides a metric to evaluate companies' climate claims. It can also inform corporations' efforts to use procurement policies to reduce suppliers' GHG emissions[108,109] and make it easier for suppliers to demonstrate compliance with such policies. Detailed quantification requires disclosure of information that allows comparisons across product categories by sophisticated consumers and facilitates the development of supply-chain requirements. Such quantification may be limited by a lack of data or access to proprietary data. However, although the data used to develop labels should be accurate enough to support informed choices, it need not always be precise. The trade-off between accuracy at a higher cost and imprecision at a lower cost needs to be assessed based on how the accuracy, precision and cost trade-offs influence the actions of consumers, producers and other supply-chain actors. Data development and label design efforts should also prioritize products with GHG-intensive supply chains[51].

As a substantial portion of GHG emissions are embedded in international trade, border adjustments are under active discussion in many countries, in the EU, for which a border-adjustment scheme was recently adopted by the European Commission[110,111]. The information generated for carbon labelling may facilitate the development, implementation and defence of border adjustments[112]. For instance, an economy-wide labelling system could produce information that would permit a more accurate assessment of product-related GHG emissions for purposes of expanding border adjustments from energy-intensive sectors to other sectors. A labelling system that is tied to an eventual border adjustment scheme could also improve the chances that the latter would be found to be non-discriminatory by the World Trade Organization[102].

Challenges for labelling systems arise in meeting data needs, developing protocols to convert data into labels, creating effective and trustworthy procedures to develop labelling rules, and designing and modifying labels. Effort is required to keep the processes used to develop labelling systems balanced between public and private interests[113]. To make labelling systems widely credible and effective, decision processes should ideally engage the full range of interested and affected parties, public and private[114], across product life cycles from material extractors to final consumers and waste disposers. In practice, however, a search for full engagement can impede incremental improvements on the available information and can delay the implementation of carbon labelling systems, so a balance between engagement and practicality is needed. The procedures required to make rules should consider the fact that deliberations about complex technical issues tend to favour actors that have the resources for a sustained involvement in the label development process. Still, credible labelling systems need to account for the concerns of retail consumers, small producers, intermediaries and other actors who might be adversely affected by labels. Given these challenges and the urgent need for action, we conclude that labelling systems should be developed and modified incrementally through a learning process in which each round of implementation is viewed as an experiment that can inform future improvements via social learning[115]. Ongoing programmes, such as PAS 2050[116], can serve as natural experiments that will allow an understanding of how labelling influences the actions of consumers, producers and other supply-chain actors.

In 2011, Vandenbergh et al.[2] argued that it was time to try carbon labelling. That is happening: private- and government-implemented carbon and energy labelling systems have served as quiet but important components of climate mitigation strategies over the past decade. The importance of these labelling systems has only increased with the urgency of the climate threat and the difficulty to mobilize adequate governmental responses.

Vandenbergh et al.[2] also argued for a shift in the research emphasis from retail consumer behaviour to corporate behaviour. This shift has not happened. Over the past decade, except for research on buildings, labelling studies focused almost exclusively on consumer behaviour. As noted, most of these studies are limited by the difficulty of studying actual consumer behaviour. Nevertheless, a large body of research now suggests that labels have some of the desired effects on retail consumers, identifies some effective label attributes, provides increasing support for the efficacy of ordinal (for example, traffic light) labels and supports a conclusion that the effects of labels depend on context.

Available research on corporate behaviour, which includes responses to carbon labelling and other environmental disclosures, suggests the potential for substantial impacts[26] from carbon labelling and the need to prioritize corporate responsiveness in future work. The effects of carbon labelling systems depend on more than retail consumer-facing labels. They rest on GHG emissions data, which can inform choices by organizational suppliers and consumers, as well as choices by retail consumers, and can support other public and private mitigation measures, such as carbon taxes, border adjustments and supply-chain contracting requirements. Although the motivations for corporations and other organizations to develop and respond to carbon labels have only received limited attention, the available research suggests that the information generated and disclosed in the labelling process may enable organizations to identify inefficiencies or induce them to reduce the carbon footprints of their products because of brand or reputational concerns. Quantitative emissions data may be of great value for these purposes, but more needs to be known about corporations' responses to labelling and about the types of labels that may induce corporations to change the products offered to retail consumers, even if consumer responsiveness is limited.

Available research suggests that a prudent near-term strategy is for carbon labelling systems to focus on the most promising products, not all products, and to use labels that include both ordinal and quantitative information. Adding quantitative information to a label can often be done without undermining the simplicity and clarity of the ordinal rating (see Fig. 1, ordinal + quantitative), and labels with these two features may increase the chance of driving organizational as well as consumer behaviour while the research gap on organizational behaviour is being filled. Useful insights may be drawn from comparative analyses that look at carbon labelling across products and across countries and from research on other forms of labelling, such as social justice or health labelling.

In short, the case made a decade ago by Vandenbergh et al.[2] to expand carbon labelling is even stronger today as the risks that arise from climate change and the barriers to comprehensive governmental action have become clearer. Carbon labelling is not a panacea, but the search for panaceas should not distract from interim initiatives that can reduce emissions promptly and complement more comprehensive climate mitigation measures as they become feasible.

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## Author contributions
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## Competing interests
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## Additional information

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