How to measure the climate costs of using agricultural land?

Key questions about the carbon opportunity cost of agricultural land use and why it matters

The Overall Question: How to account for land use in estimating agricultural greenhouse gas (GHG) costs?

The conversion of forests and other ecosystems to cropland and pasture has contributed roughly one quarter to one third of the carbon that people have added to the atmosphere since 1850 (Friedlingstein et al. 2025). Ongoing conversion, driven by rising demand for food and biofuels, contributes around 10% of the emissions people add to atmosphere each year (Searchinger et al. 2023). Yet nearly all climate strategies consistent with the Paris Agreement require that land used for food production not only stop expanding but shrink to restore some forests and other natural lands and sequester carbon. Ultimately, the total global land “footprint” of agriculture determines whether cropland and pasture continue to expand into forests and other natural habitats, or whether they shrink and allow natural vegetation to regrow. At the same time, the global population is projected to rise from about 8.2 billion today toward 9.7 billion by 2050, and demand for more land-intensive foods, such as meats, is rising rapidly. Curbing agricultural land use while feeding a growing population therefore requires some combination of sustainably increasing the amount of food produced on current agricultural land and shifts to more land-efficient consumption patterns, such as reducing food waste, shifting high-meat diets toward more plant-rich diets, and using less land for industrial products.

Achieving these goals in turn requires that private companies and governments adopt policies and take actions that align with them. Many such climate policies are based on “lifecycle assessments” (LCAs), which seek to sum up all the climate costs of generating each individual product anywhere in its supply chain. Using these LCAs, consumers and large food purchasers can determine what the climate effects would be of changing which agricultural products they consume—such as beef, chicken, or tofu—and farmers, producers, and manufacturers can determine the climate effects of changing their production practices. A key question then becomes how uses of agricultural land should be factored into these LCAs or other climate accounting systems, so that they reflect the real effects on the climate and encourage more land-efficient behaviors.

Through the Coolfood Pledge, many food providers, such as contract caterers and restaurants, have committed to reduce their climate costs based on a lifecycle accounting system that incorporates the carbon opportunity cost (COC) of agricultural land use. Accounting methods that include COC are also growing in the academic and policy literature. This article explains the COC concept, how it can be used, and why it is used by Coolfood.

1. **What is the basic concept behind the carbon opportunity cost of agricultural land use?**

The carbon opportunity cost is a climate measure based on how much carbon is lost to the atmosphere from using land to generate an agricultural product. The world has a fixed amount of land, and if a hectare of land is used for one purpose, it cannot be used for another. Because cropland and pasture typically store far less carbon than forests and native savannas, their use for agricultural production carries a carbon cost. This cost can be expressed as a cost of consuming a kilogram of any crop, type of meat or milk, biofuel, or any other agricultural product.

Cropland and pasture are "fixed costs" of producing a crop or animal product, just like a factory is a fixed cost of producing cars. And just as constructing a factory emits greenhouse gases from such inputs as energy and steel, so producing cropland emits carbon from the clearing of vegetation and soils. Counting the carbon costs of producing each car requires factoring in some proportionate share of the carbon released to make factories. And counting the carbon costs of each kilogram of a crop requires counting a proportionate share of the carbon released to create cropland.

The carbon opportunity cost does exactly that.

2. **What's the difference between the carbon opportunity cost and agricultural land area (i.e., land occupation)?**

One simple way to measure the land use costs of a company's consumption is to add up the quantity of land, including cropland and pastureland, required to produce the agricultural products the company buys. This is the land area "footprint," also called "land occupation," and it is often counted and reported in hectares. The total COC is equal to the carbon lost from this land, which can be thought of as the "land carbon footprint."

From a climate standpoint, rather than simply measuring the land area in hectares, the COC more accurately measures the carbon costs of different agricultural products because the lands used for farmland differ, and different products tend to use different kinds of land. Some farm fields were formerly wet, warm, carbon-rich habitats, whose conversion causes large carbon losses. At the other extreme, some grazing lands were formerly dry habitats whose conversion caused little carbon loss. For example, oil palm has high yields and is thus relatively land-efficient, but tends to be produced in what would otherwise be carbon dense, wet tropical forests. In contrast, canola has much lower oil yields and is thus less land-efficient, but mostly uses drier, colder lands which were lower in carbon than tropical forests. For each ton of vegetable oil, canola uses much more land, but the carbon losses, and therefore COC per ton of oil, tend to be similar as those per ton of palm oil. In mathematical terms, the COC "weights" each hectare converted to farmland by its carbon density.

3. Why assign a COC to agricultural land that was cleared in the past?

Whoever uses existing farmland contributes to the total demand for farmland and therefore the total agricultural footprint. That is true even if their own crops or meat or milk come from long-existing cropland. The same is true of the land carbon footprint, measured by COC. It is the total demand for farmland that determines whether farmland expands, releasing carbon, or contracts, sequestering carbon. Each use of a hectare carries the cost of requiring another hectare.

This is consistent with basic economic principles as housing illustrates. Although most housing has long existed with its construction costs paid off, an older house still has value, so buying or renting it is not free. Why? Because using that land and living in that house avoids the cost of building a new house. In an expanding housing market, adjusting for quality, the cost of a house is precisely equal to the cost of building or renting a new house because someone would pay that much to avoid paying for a new house. Similarly, buying or renting farmland has a cost to farmers. Just like housing, adjusted for quality (including location factors), this purchase price or rent equals the cost of constructing or renting new farmland. This land use cost is incorporated into the cost of crops and meat.

Carbon costs are no different. In a world with expanding cropland, the carbon cost of using existing cropland and pasture, or of the crops, meat or milk they produce, is the carbon that would be lost to replace the cropland and produce these agricultural products on new farmland.

Treating existing housing or existing cropland as free would cause large problems because people would lack any incentive to use them efficiently. Similarly, treating existing cropland as “carbon free" would eliminate the climate incentive to use it efficiently and therefore to minimize the overall carbon losses from agriculture.

4. How is the carbon opportunity cost of agricultural land use calculated?

For crops, the calculation starts with a recreated map of the carbon stocks of native vegetation and soils across the world (e.g., the carbon stored in natural forests and wetlands). The method then overlays a map of where each crop is produced. Using wheat as an example, this allows a calculation of the carbon lost on the specific hectares used to produce wheat. Dividing the total carbon lost on all wheat-producing lands by the total production of wheat results in the tons of carbon lost per metric ton of each crop produced. This quantity of carbon lost is converted to carbon dioxide, and to annualize this number, for reasons discussed below, this number is divided by a number of years, such as 20 or 30.

This calculation describes the “carbon loss method,” which is most appropriate today, because agricultural land continues to expand. Each person’s or organization’s consumption contributes equally to that expansion. This method assumes that the next additional ton of crop will require the same amount of carbon loss from native vegetation and soils as was lost to produce an average ton of that crop. (This is similar to traditional LCA accounting for agricultural production emissions, which assumes that purchasing a ton of a crop will emit the same amount of GHGs as were emitted to produce an average ton of that crop.)

Equation for calculation carbon opportunity cost per tonne of product:

$$\frac{\left(Native\ carbon\ stock\ \left[\frac{tC}{ha}\right] - Agricultural\ carbon\ stock\ \left[\frac{tC}{ha}\right]\right) * \left(\frac{44}{12}\right)}{Yield\ (tonnes\ of\ product/ha/year)}$$

5. **How does the carbon opportunity cost differ from other land use metrics like direct land use change emissions?**

LCAs often assign emissions for land use change only for those products generated on *recently cleared* land (e.g., the previous 20 years). If the precise location of a product is known and was recently cleared, the emissions from land clearing are counted as direct land use change (dLUC); if the source of products can only be traced to a wider area, such as a country, the emissions are known as statistical land use change (sLUC). These metrics focus on ***where*** recent agricultural expansion occurs.

Yet dLUC and sLUC emissions do not assign emissions based on ***how much*** agricultural land is used. For example, if a livestock producer in Europe uses soybeans that happen to have been produced on recently cleared land, such as in the Brazilian Amazon, the resulting meat or milk is counted as having high carbon costs using a dLUC or sLUC approach. However, if the soybeans come from the U.S., where the land clearing for cropland happened many decades ago, the dLUC or sLUC approach assigns no carbon cost for the land use. That is true even if the producer is inefficient and uses twice the number of soybeans for the same milk or meat. As a result, increasing use of long-ago cleared agricultural land is assigned no climate cost and decreasing it is assigned no climate benefit. The dLUC/sLUC approach effectively makes the use of agricultural land cleared more than 20 years ago "free" from a climate perspective. It is the equivalent of treating existing houses as free.

6. **Why does using COC help better inform decision making around land use and production and consumption of agricultural products?**

The COC reflects the carbon cost of decisions that increase or decrease the use of agricultural land. Measurements using COC recognize the costs of increasing agricultural land use and the benefits of decreasing it, e.g., by reducing food loss and waste, reducing meat consumption in high-meat diets, or increasing agricultural output per hectare.

The COC metric therefore addresses the issues that dLUC and sLUC metrics miss. The dLUC and sLUC metrics recognize no climate costs to increasing consumption of land-intensive products such as beef or increasing waste so long as the agricultural products come from land cleared more than 20 years ago. Conversely, in a traditional carbon accounting system without COC, reducing food loss and waste or shifting diets will generally lead to a reduction in agricultural production emissions (e.g., reduced methane or nitrous oxide), but the important double-benefit of also reducing land use will go uncounted and unincentivized. Failing to account for COC can even cause perverse incentives. For example, a practice that reduces agricultural production emissions even a little, but increases land use a lot – such as grazing the same number of cattle on far more land in a way that slightly reduces fertilizer emissions – would appear to be a net benefit for the climate, when in reality the climate costs of the additional land use are greater than the benefits of modestly reduced fertilizer emissions.

If companies or individuals want to use carbon accounting to accurately inform to mitigate or minimize total carbon in the atmosphere, costs and benefits of using more or less agricultural land must be factored in.

7. Why is COC annualized over 20 or 30 years?

When natural ecosystems are converted to agriculture, the losses of plant and soil carbon occur quickly, but then the land is typically used for many years. When evaluating the COC of an agricultural product, these carbon losses should be distributed (i.e., divided) over several years of production to estimate an annual COC value.

How many years is a question of policy. Climate strategies require that the world quickly reduce emissions. It therefore makes sense to focus on the effects of changes in consumption or production on carbon over a limited number of years into the future, such as 20 or 30 years. Dividing the average carbon lost to produce each ton of crop by 30 years results in effect assigns the carbon loss to 30 years of production.

This calculation makes it possible to evaluate the effect of changes in the demand for crops on atmospheric carbon 30 years after any change. For example, if people increase demand for biofuels, which reduce fossil emissions, but that require another hectare of agricultural land, this calculation indicates how much overall emissions to the atmosphere would change after 30 years of biofuel use. The choice of 20 or 30 years reflects the decisions policymakers have made when confronting the question of over what period to judge the effect of biofuels on atmospheric carbon. A similar result can be achieved using more formal economic tools using discount rates to reflect the added value of mitigating emissions earlier rather than later (Searchinger et al. 2018).

8. What is the relationship between carbon opportunity cost and annual emissions from new land use change?

When countries report their annual emissions, they only report emissions from recent (e.g., prior 20 years) land use change and assign no emissions to the ongoing use of existing agricultural land. In effect, the emissions from the past conversion of existing agricultural lands are assigned to the past. How then does the carbon opportunity cost metric relate to new land use change?

The answer is that changes in COC measure the contribution of changes in consumption and yields to the portion of new land use change caused by net agricultural expansion. For example, if the world increases its demand for agricultural products by 1% per year (as measured by total carbon opportunity cost) and farmers do not improve yields, agricultural land will expand by 1% and release an amount of carbon from trees, shrubs and soils equal to 1% of the total carbon released in the past to create the world's existing farmland.

If, however, the world's farmers could also increase their yields by 1% per year, agricultural land will not expand and avoid these emissions. (Mathematically, the world would consume1% more products, but because of higher yields, the carbon opportunity cost of agricultural would products decrease by 1%, and the total carbon opportunity cost of world agriculture would remain the same.) Similarly, even if yields did not grow by 1%, the world could avoid emissions from land use change if people and companies also reduced their food losses by an amount equal to the 1%. In either event, the result would be no net agricultural expansion and no emissions from net land use change.

In short, although the total carbon opportunity cost of world agriculture reflects the cost of past land use changes, changes in carbon opportunity cost equal new emissions from land use change. The main value of calculating the carbon opportunity cost is focusing on the change.

This math not only works collectively but at the company and even the individual level. Every company or individual can avoid contributing to emissions from net expansion of agricultural land by becoming more land-efficient, for example, by modifying diets or reducing food waste. Changes in carbon opportunity cost measure this company or individual contribution. The metric can therefore be used to set and track company, individual or even national targets for consumption or yields to avoid contributing to net land use change.

9. **Would there still be a carbon opportunity cost of land use if cropland starts shrinking instead of expanding?**

Even if global cropland area were shrinking, each hectare used would still have a carbon cost because the alternative would be allowing a hectare to reestablish natural vegetation. The carbon cost of increasing demand for crops would then be the foregone carbon sequestration. This is sometimes called the "carbon gain method." It can be measured by the quantity of carbon that could be sequestered over a 20- or 30-year period. This might be a preferable method to the "carbon loss method" if the world managed to decrease agricultural land.

10. **What are the advantages of using COC rather than using economic models to calculate indirect land use change?**

The COC metric is based on a simple identity: If someone consumes more crops that on average use 1 hectare of land, the world will increase agricultural land by 1 hectare unless someone else uses less. The COC metric assigns the average carbon losses for that 1 hectare in and of itself. This is true even if increased crop prices from increased demand cause some other people to "use" less land.

By contrast, economic models often used to estimate indirect land use change for biofuels try to estimate and factor reduced land use by others triggered by price changes. For example, if crops or cropland are diverted to biofuels, some economic models estimate higher crop prices will cause people around the world to consume less food. As a result, displacing one hectare for biofuels will lead to less than a full hectare of new cropland and therefore fewer indirect land use change emissions (Searchinger et al. 2015; Hertel et al. 2010). Uncertainties in economics result in a vast variety of indirect land use change estimates (and some models are more rigorous than others), but the conceptual difference is that the COC metric isolates the effects of increased or decreased land use by themselves while indirect land use change factors in avoided land use by others.

This focus on land use costs by themselves, rather than reduced land use by others, reflects standard accounting approaches. For example, some economic models estimate that when any person burns an additional gallon of gasoline, the extremely small increase this causes in the global price of oil is still large enough to lead the billions of other users of oil around the world to collectively consume one quarter of a gallon less (Hill et al. 2016). As a result, total gasoline consumption only goes up by ¾ of a gallon. But burning a gallon of gasoline physically releases a gallon's worth of emissions, not ¾ of a gallon), and standard carbon accounting methods assign that full gallon of emissions. Indeed, moving in the other direction, if gasoline emissions were calculated using economic models, when people reduce their use of gasoline by one gallon, they would still be assigned emissions for ¼ of that gallon because lower prices would induce others around the world to consume that much more.

Focusing on the carbon costs of each actor separately makes sense for many reasons:

- Just as the carbon costs of gasoline result from the quantity of gasoline used, so the loss of carbon in natural lands results from the quantity of land used. It makes little logical sense to treat those who use gasoline or land as using less than they do because price effects lead others to use less.
- If others consume less gasoline or land, they should receive the credit, particularly as they bear the economic cost in reduced use of gasoline or food. Not only is this equitable but this what allows for a proper cost/benefit analysis.
- Using economic models likely leads to double counting. Both the person using more gasoline or land counts the reduction in gasoline or land by others, and those who do the reducing count the same reductions. By contrast, the global COC of each person adds up to the total carbon lost to produce the agricultural products.

In addition, the changes in COCs add up to the emissions from agricultural expansion or reduction caused by increased or decreased consumption.

- Reductions by others depend not just on higher prices but many other factors. For example, if governments adjust gasoline taxes or food assistance, or if incomes grow for other reasons, the reductions might not occur. Under this kind of accounting, the emissions assigned to a gallon of gasoline or a kind of food would constantly change.
- This is not how "costs" typically work. For example, the cost of crops incorporates the cost of using croplands, such as the rent, regardless of whether others consume fewer crops.

Although carbon costs are not typically calculated using economic feedbacks, reliable economic models are still valuable for policy analysis. For example, policymakers should want to know if diverting crops and cropland to biofuels reduces food consumption, especially by people with low incomes. But that is a separate function.

11. **How does incorporating carbon opportunity cost in GHG reporting provide new opportunities to reduce emissions?**

Properly used, the carbon opportunity cost metric provides companies with new opportunities to reduce their emissions. Adding carbon opportunity cost to agricultural production emissions increases total climate costs several-fold, which may seem discouraging, but the baseline carbon opportunity cost should be viewed as a separate number. What matters is the change over time. Companies calculating the carbon opportunity cost of their agricultural land use can reduce their total emissions either by reducing waste, shifting their consumption to less land-intensive products, or by increasing the output per hectare. There are at least two ways to set such targets.

In one approach, used by the Coolfood initiative, companies and other major food providers work to reduce food-related emissions by a percentage of their total carbon costs (i.e., agricultural supply chain emissions plus carbon opportunity cost). The collective goal is a 25% reduction in total carbon costs by 2030 (with a companion goal to reduce carbon costs per plate by 38% by 2030). Companies in this initiative have reduced their emissions intensity by 11% through 2024 by shifting from consumption of meat—especially beef—and toward plant-based foods. On the producing side, companies could do the same by sustainably increasing their output per hectare. For example, it is well established that farmers in Brazil can triple average beef output per hectare through better grazing practices, even without using feedlots (Strassburg et al. 2014), and doing so would reduce their carbon opportunity cost per kilogram of beef by two-thirds.

Another option is for companies to set science-based targets to improve their land use efficiency. For example, if increases in global food consumption will increase land use by 1% per year (as measured by carbon opportunity cost), then companies might set targets to sustainably increase the yields of their suppliers by 1% per year. Doing so would avoid contributing to global land use change. Increases greater than 1% per year (i.e., reductions in carbon opportunity cost intensity by greater than 1% per year) could then be netted against emissions for target setting purposes.

12. How can a company calculate the carbon opportunity cost of its agricultural land use?

Carbon opportunity cost of land use can be calculated using global, regional, or national factors. A global factor is probably more suitable for globally traded commodities, because evidence has shown that increased demand anywhere in the world is likely to transmit prices everywhere and therefore spur a global land use response (Roberts and Schlenker 2013). Regional or national factors may be more appropriate for agricultural commodities with less global trade. Updated COC estimates have global, regional, and some national carbon opportunity cost factors that companies can choose to use.

Coolfood has published a calculator that companies or individuals can use. It currently includes global COC factors and is being updated to include regional and some national factors.

13. Do all emissions from land use change result from increased consumption of agricultural products and if not, what is the added value of calculating direct or statistical land use change emissions in addition to calculating COC?

Not all emissions from land use change result from net agricultural expansion and the increased demand for agricultural products. Gross deforestation and other land use changes also occur because the location of some agricultural land is shifting from one place to another. This refers not to traditional slash and burn ("swidden") agriculture, but rather the shifting of agricultural production from higher-income countries to lower-income countries in the tropics, and also shifting of agricultural production from one part of a country to another, typically from drier, hillier land to flatter, wetter, and more carbon-rich land (Potapov et al. 2021) (Aide et al. 2013). This shift largely reflects changes in where it is most economical to produce food, reflecting changes in technologies and patterns of development. This shifting causes serious carbon costs even if abandoned lands reforest, because new conversion causes rapid carbon loss while reforestation sequesters carbon more slowly.

Metrics that address direct or statistical land use change emissions can help to account for the emissions that occur from this shifting of agricultural land. By contrast, the COC metric accounts for the emissions that result from increasing the total demand for agricultural land.

14. Is the carbon opportunity cost metric well-established in the scientific literature?

The carbon opportunity cost metric has been used in the scientific literature since the late 2000s, and COC estimates have been calculated for all major crops and livestock products and for multiple geographic scales. Different researchers have called this metric by different names, with some using the carbon loss or carbon gain method, but the concept is similar across these studies. A sample of studies is listed below.

Article	Name of metric	Geographic scale and product coverage
Stehfest et al. (2009)	Cost of natural vegetation; recovery of natural vegetation	Global; crops, livestock products
Nguyen et al. (2010)	Opportunity cost of land use	EU; livestock products, alternative production systems
West et al. (2010)	Carbon-crop tradeoff index (tons of carbon lost per ton of crop)	Global; crops
Schmidinger and Stehfest (2012)	Land use change related to additional production; “missed potential carbon sink” of land occupation	Brazil and several EU countries; livestock products
Balmford et al. (2018)	GHG opportunity costs of land farmed	Asian paddy rice, European wheat, Latin American beef, and European dairy
Searchinger et al. (2018)	Carbon opportunity cost	Global; crops, livestock products, bioenergy feedstocks
Smith et al. (2019)	Carbon opportunity cost	United Kingdom; crops, livestock products, alternative production systems
Hayek et al. (2021)	Carbon opportunity cost	Global; livestock products
Yang and Tan (2021)	Land carbon loss	Global; crops, livestock products, and wood products
Alcock et al. (2022)	Land use carbon cost	Global; vegetable oils
Yang et al. (2022)	Carbon opportunity cost	30 provinces in China; crops, livestock products
Blaustein-Rejto et al. (2023)	Carbon opportunity cost	Global; multiple beef production systems
Yang et al. (2024)	Land carbon loss	31 provinces in China; 26 different crops and livestock products

Note: not exhaustive.

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