Explaining the Contributions and Findings of "Assessing the Efficiency of Changes in Land Use for Mitigating Climate Change" *Nature 564, pp 249–253 (2018)*

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Background and Summary

The conversion of forests and other native habitats to agricultural use causes the release of large quantities of carbon otherwise stored in vegetation and soils, has contributed from one quarter to one third of extra carbon in the air, and continues to be a major contributor to climate change. Quickly phasing out these carbon losses is critical because virtually all strategies for stabilizing the climate at globally agreed temperatures rely on phasing out these emissions quickly, and many strategies rely on taking carbon out of the air through large-scale reforestation or other ways of using land for "negative emissions." Yet the world is now also on a path to require greater than 50% increases in crop production by 2050, and even larger increases in meat and milk that use pasture lands. And global land area is fixed. Simultaneously using global land to maintain or store more carbon while also producing more food therefore requires greater efficiency in the use of land.

This need for efficiency means that increasing either the production of food or carbon storage on an individual hectare can generate "carbon benefits" in that they each help to mitigate climate change. A carbon benefit of producing more food on the same hectare is that it reduces the quantity of land elsewhere needed to produce food to meet the same food demand, sparing more land to grow forests or otherwise to store more carbon. Such yield gains increase the capacity of global land to store carbon, and although additional efforts may or may not be necessary to fully use that capacity to store carbon, increasing this capacity by itself is a necessary step toward meeting both climate and food needs.

Today, government officials, companies and even individuals have started to make many decisions about the uses or management of land motivated at least in part by mitigating climate change. Examples include government policies that reward the conversion of cropland or pasture to forest or to bioenergy production. Decisions about diets and efforts by food companies to reduce emissions of their suppliers also focus on reducing emissions from the use of land.

This paper offers the following conclusions and contributions about these efforts:

1. Standard methods of evaluating whether changes in land use or management mitigate climate change do not measure the effect on land's efficiency in meeting both climate and food needs. Standard methods fail to do so (a) because they do not fully count the opportunity to use land to store carbon if it is not used for food or bioenergy, which we call land's carbon storage opportunity cost, and (b) because they often factor into calculations changes resulting from changes in prices that actually occur on other land, by other people, and at other's expense.

2. Because of these limitations, decisions designed to mitigate climate change by changing what land produces or production processes can be inefficient and undermine climate mitigation.
3. As a rule, standard methods underestimate by many times the significance for climate mitigation of changes in land use or changes in consumption that alter land use.
4. To address these limitations, this paper develops a new quantitative method of measuring land use efficiency, called the Carbon Benefits Index. If management of land changes what it produces, e.g., from wheat to lentils to dairy to bioenergy or to forest, the index can measure whether the change provides a net gain, a net loss or has no effect on global efficiency based on the yields of each. The index also evaluates the net effect of altering outputs by changing inputs, such as by adding more fertilizer. We provide a "Carbon Benefits Calculator" for applying the index to individual parcels of land.
5. Consumption choices can also be more or less climate efficient, such as different diets. The Carbon Benefits Index measures their efficiency as well but segregates analysis of the efficiency of production from the efficiency of consumption.
6. By factoring in the carbon storage opportunity cost of land, we find:
    - each European's diet on average causes as many emissions as all other consumption by that person, including energy, and can be cut 70% by substituting other foods for ruminant meat and dairy,
    - producing beef with reasonably efficient grazing in Brazil has more carbon benefits than producing soybeans or sugarcane ethanol although restoring forest is better on highly sloped coastal rainforest lands,
    - reasonable forms of crop intensification generate net climate gains,
    - shifting Iowa cropland to cellulosic ethanol will likely greatly reduce global land use efficiency, consuming crop-based biofuels causes roughly three-times the emissions as gasoline or diesel, and electric cars using solar power cause roughly one eighth the emissions even factoring in the fossil energy used in today's battery manufacturing.

Why is land use efficiency for climate purposes hard to measure and how does the Carbon Benefits Index calculate this efficiency?

Our paper defines the efficiency of land for greenhouse gas mitigation, which we call land's "carbon efficiency," as the efficiency of each hectare in contributing toward the total capacity of global land to reduce atmospheric greenhouse gas levels while meeting the same food demand. This capacity can increase by storing more carbon or by reducing emissions from the agriculture production process, often in the form of methane or nitrous oxide.

This efficiency is hard to measure because land produces very different outputs, not just apples and oranges, but also carbon storage in forest or bioenergy that substitutes for fossil fuels. If land is producing wheat, increasing the yield of that wheat is obviously an increase in efficiency for climate purposes, as is increasing the carbon stored in an existing forest. But how do we know when a hectare shifts from producing wheat to forest if that achieves a net gain, a net loss or just shifts equivalent levels of output from one form to another?

Intuitively, in a world that needs both wheat and forest, if a hectare is good at producing wheat and bad at producing forest, then wheat is likely to be the more efficient use and vice versa. But how do we measure these changes? The benefits of forest can be measured in carbon storage and the benefits of biofuels can be measured in displaced fossil fuels, but the carbon in wheat or soybeans is consumed. How valuable, therefore, is a kilogram of wheat versus a kilogram of soybeans or a kilogram of carbon storage in forest?

Changing land management to boost yields of the same output, such as more corn, can also have trade-offs. For example, a crop farmer could achieve a net gain in maize yield by adding more nitrogen fertilizer, but this change leads to more greenhouse gas emissions. A dairy farmer could increase milk yields by giving the cows more concentrate feeds, but the production of crop concentrates involves higher greenhouse gas emissions -- although consumption by cattle may lead to lower methane emissions intensity. We call these emissions "production emissions." Management of soils could also change in ways that alter their carbon storage. When factoring in changes in all aspects – output yields, production emissions, and soil carbon – how should we calculate net gains or losses in climate effects?

The Carbon Benefits Index solves this problem by counting the benefit of each type of output that is consumed, such as crops or meat or milk, by the global greenhouse gas emissions that its production on one hectare avoids from others. If a hectare is producing one ton of wheat, that ton does not have to be produced elsewhere for the world to provide the same quantity of wheat, freeing up more land to store carbon. The index bases this cost on the average greenhouse gas cost of producing each food, e.g., wheat, globally. The assumption is that if one hectare did not produce a ton of some food, that food would be produced elsewhere at the global average rate of loss of carbon from vegetation and soils to produce a ton of that food and at the global average rate of production emissions.

One advantage of using the global average cost is that it measures the comparative advantage of using a hectare for different purposes, e.g., one crop or another, or forest. If land produces wheat with less loss of carbon and lower production emissions, that difference will be reflected in the benefits counted for that hectare. The use that has the greatest comparative advantage – the use of a particular hectare that is most efficient relative to the global average -- will have the greatest benefits. Even if two uses of land are more inefficient than the global average, the less inefficient use will have more benefits. As a result, changes in the use or management of a hectare that increase carbon benefits on that hectare increase the efficiency of global land uses compared to the present global average.

Why the index calculates changes in the efficiency both of production and consumption, e.g., changes in diets, but segregates the two efficiencies.

The index measures the efficiency of changes in the management or use of individual hectares based on the assumption that the same amount of each food will continue to be consumed and produced globally. If the food is not produced in one place, it must therefore be produced somewhere else. This assumption does not imply that existing consumption levels are ideal. Instead, the index uses this assumption so that it can separately calculate the efficiency of production changes and consumption changes. It segregates these efficiencies for both policy and conceptual reasons.

Policy reasons first. Even if consumption of a good is inefficient, trying to reduce its global consumption by reducing production on a single hectare is likely to be both ineffective and inequitable. For example, producing beef causes far more greenhouse gas emissions than producing lentils both from loss of carbon storage on land and in the production process. Hence, shifting global consumption from beef to lentils would help mitigate climate change. But if one farmer took one hectare of beef out of production, the vast majority of that beef would be replaced by other farmers, so consumption would change little. Other farmers might replace the beef by clearing more land or by shifting from other foods to beef, which might even cause much of the reduced consumption to occur in more efficient foods. In addition, each farmer's production decisions affect consumption of the rich and poor alike by affecting prices paid by both. In fact, the poor are affected by price increases more than the rich because they are less able to absorb higher prices. As a result, if it were desirable to alter consumption through prices, the most effective and equitable ways of doing so would not be by trying to change what some individual hectares produce but by using policies targeted at consumption, e.g., retail taxes that increase beef prices, particularly in wealthier countries, or taxes on high carbon goods matched with subsidies for lower carbon foods.

Conceptually, trying to reduce global consumption by changing one hectare also confuses both the source of the greenhouse gas benefit and who pays for it. If reducing beef production on one hectare does reduce food consumption and therefore land use demands, the source of benefit is the reduced consumption not the changed production of the hectare removed from beef production, which may or may not shift to a more efficient use. To illustrate this point, the reduced consumption of beef by global consumers would still occur even if the landowner removing agricultural land from beef production left the land bare and produced nothing at all because that would have the same effect on beef consumption. In addition, the people who pay for this reduced consumption are the consumers of food globally, who pay more for food or consume less, not the landowner or those who purchase the alternative outputs of that specific land use change, e.g., forest or bioenergy.

By segregating production and consumption decisions, the carbon benefits index avoids attributing greenhouse gas reductions to producers for changes in consumption that are achieved by others and at others' expense and simultaneously avoids attributing to those who change their consumption the effects of changes in the efficiency of production also achieved by others and at others' expense.

What are the standard climate methods for evaluating land management and consumption decisions and why don't they measure efficiency?

Policymakers and researchers primarily use one of two basic methods to evaluate land use management and changes. Both methods tend to greatly underestimate the real costs of using land because they do not count what we call the carbon storage opportunity cost, which is the carbon that could be stored if the land were not required for food production or used to produce bioenergy.

Lifecycle Analyses: One method belongs under the broad category of lifecycle analyses (LCAs). LCAs attempt to add up all the greenhouse gas emissions in a production system, for example, all the emissions in producing beef. They can evaluate global consumption or just consumption from food from a particular farm or region. LCAs are typically used to evaluate the greenhouse gas costs of consumption, e.g., the greenhouse gas costs of consuming a kilogram of beef. But the same basic approach is used to evaluate the emissions from a particular farm or even a country's overall production system.

A challenge for LCAs is how to evaluate the greenhouse gas costs of using land to produce food instead of allowing that land to be used for carbon storage. In most cases, the LCAs will count land use requirements in hectares only. Although those who perform LCAs generally understand that this land use has greenhouse gas implications, the LCA's own calculation of emissions ignores this effect. Some LCAs will attribute greenhouse gas costs only if they result from the new, direct clearing of land. As a result, these calculators treat production on all land previously cleared – the vast majority of the world's agricultural land – as having no carbon storage opportunity cost.

A now common approach counts emissions from land use for a particular crop or animal product only if the area devoted to that particular crop or product has recently expanded in a particular country and that country's overall agricultural area is also expanding. The resulting greenhouse gas emissions from the loss of forest or other habitats are then averaged over that country's entire production of the crop or animal product. Again, because this approach counts no greenhouse gas emissions for all land cleared in previous years for agriculture, this method assigns no greenhouse gas cost for the use of the overwhelming majority of agricultural land.

This approach derives from confusion about two separate questions: What are the new carbon costs of clearing agricultural land each year – which depend on a country's changes in production and yields of all foods -- and what are the incremental effects of each kilogram of demand for a food. To analyze the effects consuming one ton of a food, what we should care about are those incremental effects. Just as LCAs count the greenhouse gas costs of each kilogram of fertilizer used or each animal to produce a food, so should they count the costs of each hectare devoted to that food.

The main reason some LCAs follow this approach is they wish to attribute all the greenhouse gas costs of previous land clearing to the past. They do so because each year the world counts as additional emissions only the emissions that result from new land clearing. But the continued use of land for food comes with the opportunity cost of not letting that land revert to forest or other native vegetation. And in a world that continues to expand agricultural land, a reduction in a food's consumption by any one person would reduce the net expansion of agricultural land. For this reason, a method is needed that counts the amount of land expansion due just to the incremental consumption of a food.

Economic Land Use Models: The second basic method for estimating the greenhouse gas implications of a land use change is to use a linked global economic, land use model. Although these models greatly differ from each other, they all basically work as follows. A hectare of land now producing food, for example, is changed to forest or bioenergy production. The model estimates the greenhouse gas reductions that occur from the growth of the forest or from the displacement of fossil fuels by the bioenergy on that hectare. This first step therefore generates what we would call a carbon benefit. However, the model then estimates effects of market interactions on carbon stored elsewhere. The loss of one food's production causes prices for that food to increase; as a result, some consumers reduce their consumption of food or switch to other foods, and some farmers increase their production. The models attempt to estimate the land use change that results from this increase in production, and the loss of carbon storage, and then deduct these costs from the direct gain. These deductions are called "leakage" or emissions from "indirect land use change."

If accurate, these models could have many uses, but they do not truly measure the changes in each hectare's land use efficiency, i.e., that hectare's contribution to the global capacity of land to store carbon and minimize emissions while meeting the same food demands. One reason is that they do not segregate the effects on the efficiency of production from the effects of efficiency of consumption. In some economic models, a large effect of diverting cropland to forest or bioenergy is reduced global consumption of food, i.e., much of the food is not replaced because of higher prices, which reduces the amount of new agricultural land required to replace the food. As discussed above, this climate "benefit" results from changes in consumption, not changes in the efficiency of the hectare taken out of production. The change in food consumption would occur not only if the hectare taken out of food production were used to produce forest, bioenergy or any other non-food crop, but also if it were left bare and produced nothing at all.

These models may also estimate that the increased prices caused by taking one hectare out of production cause other farmers to produce more food on existing agricultural land by using more inputs, such as fertilizer, labor or irrigation. Although that change does contribute to the global efficiency of land, this efficiency gain occurs on other land, by other farmers, and at the expense of global consumers, who pay more for food. This benefit in the form of yield gains on other lands therefore also has nothing to do with the efficiency of the hectare deliberately removed from food production and would again occur if this hectare were left bare and produced nothing at all.

To appreciate these distinctions, imagine a possible economic analysis of a strange climate policy that requires that all driving use luxury, gas-guzzling SUVs. Obviously, the greenhouse gas emissions for each kilometer driven would increase. Driving itself would become less carbon efficient. But the model might estimate that the cost of driving would rise so high that many people would stay home. It might also estimate that others would switch to mass transit and might even estimate that governments or private businesses would invest more to improve that mass transit, further increasing use of mass transit. None of these changes would alter the fact that driving a large SUV is less climate-efficient than driving a smaller vehicle.

The distinction matters because, to the extent governments wish to use higher prices to reduce transportation overall and to increase mass transit, governments can still do so without also forcing people to drive inefficient cars. For example, governments can and do impose taxes on gasoline and diesel, and subsidize mass transit, and do so while also establishing requirements for higher not lower fuel economy standards in vehicles. The combination achieves greater overall greenhouse gas reductions because it results in less driving, more mass transit, and more efficient driving also.

For the same reason, governments can achieve greater greenhouse gas mitigation through the combined uses of land by requiring more not less efficient land uses and then using other policies if they wish to alter consumption or increase yields on other lands. For example, they can tax high carbon foods and subsidize low carbon foods, and they can subsidize investments and practices that increase yields. To follow such an approach, however, policymakers need to know which changes in land use are more efficient by themselves (without regard to these effects on consumption or production efforts by others). That is the question the Carbon Benefits Index addresses.

How do our results differ from other approaches?

As discussed, one of the principal limitations of other approaches is that they do not count, or they undercount the opportunity cost in the form of foregone carbon storage when land is used to produce food or bioenergy. Yet, these same analyses do fully count the benefits of alternative uses, such as the carbon stored in regrowing forests or the displacement of fossil fuels. By counting the benefits of these changes in land use while not counting or undercounting the carbon opportunity costs, these methods therefore overstate the benefits of the changes of agricultural land to forest or to bioenergy. For the same reason, LCAs and economic models also tend to greatly underestimate the benefits of any change in consumption that reduces the demand for land or any change in production that increases the yields of land.

Pasture: Pasture globally occupies roughly twice as much land area as cropland, yet land use analyses often treat pasture as of limited value. Converting pasture to forests, crops or biofuel production is therefore typically viewed as beneficial. That may be because the inefficiency of beef and sheep and goat meat production generally results in low production of calories or protein per hectare. Yet, regardless of these inefficiencies, people demand them, and merely shifting one hectare from their production does not necessarily reduce this consumption but mainly shifts it elsewhere.

We examined Brazilian grazing land in the Cerrado and Atlantic Coastal rainforest, which are often considered inefficient, but which others have divided into five levels of grazing efficiency. We find that producing beef even at the second lowest efficiency level provides comparable benefits to producing sugarcane ethanol, which means that shifting to sugarcane ethanol would not generate net gains. We also find that producing beef at the third level of efficiency provides more benefits than both ethanol and producing soybeans at average Brazilian yields. Only on the steep slopes of the Atlantic Coastal rainforest, which are hard to intensify, would reforestation produce greater benefits because intensification of grazing is infeasible.

Bioenergy and solar-electric cars: Most biofuel policies are motivated in part by the expectation of greenhouse gas reductions. We evaluate biofuels in two ways. First, we compare the benefits per hectare of producing ethanol from maize with those of a standard maize/soybean rotation in Iowa. The rotation produces roughly 2.5 times the carbon benefits of maize ethanol. In fact, the by-products of ethanol production, which are used for feed, actually generate around 80% of the benefits of the maize production for ethanol. The maize-soybean rotation also produces almost twice the benefits that cellulosic ethanol might produce in the future based on highly optimistic assumptions.

We also evaluate the greenhouse gas emissions of using biofuels. With the benefits index method, the land use carbon cost is equal to the average loss of carbon attributable to production of an amount of the crop globally, used for the biofuel, e.g., the amount of maize after accounting for biofuel by-products. Using this method, the carbon costs of biodiesel from different possible vegetable oils are all roughly around three-times the carbon dioxide emissions of using diesel. For ethanol from maize and wheat, the costs are more than two-times the carbon dioxide emissions of gasoline. This analysis also finds that the land use carbon cost of using maize using the carbon benefits index is roughly ten-times the estimate adopted by California using its particular economic model.

Finally, we estimate that electric cars powered by solar energy generate one eighth the emissions of gasoline or diesel, primarily through the fossil energy used to produce batteries.

Diets: Many studies have found benefits in reducing the consumption of meat and dairy in western diets, and particularly in reducing the consumption of beef. Yet, as our discussion of lifecycle analyses explains, these studies tend to attribute little or no emissions costs to the land requirements. Using our index, we find that the total greenhouse gas costs of beef and dairy globally are 3-4 times those found by the Food and Agriculture Organization.

We also find that western diets overall have much higher greenhouse gas costs than conventionally estimated. For example, a northern European diet has emissions from diets according to our method that are similar to the typical estimates of emissions from a European's total consumption of all products, including consumption of energy. In fact, such diets factoring in land use have 20 times the emissions associated with the worst diet analyzed in a prominent paper in Nature from a few years ago. Because shifting consumption of ruminant meat and dairy to other foods would reduce emissions by 70%, we find that diet shifts can reduce absolute emissions far more than typically estimated.

How does the debate about how much yield gains spare land, or how much more demand increases agricultural land use, relate to the Carbon Benefits Index? Put another way, what are the implications of assuming that a crop or animal product would be replaced at its global average carbon cost?

Researchers debate how much increasing yields, or reducing consumption, actually avoids clearing of forest and other lands with native vegetation and their carbon. Some studies have doubted land sparing because increasing yields in one country is often associated with increases in agricultural expansion in that country. We agree with others that this association misses the distinction between local and global land sparing. Countries that increase yields often in doing so reduce the costs of producing each ton of crop. As a result, they often gain global market share and can expand their production. But doing so still saves land elsewhere.

Yet there is a debate among researchers regarding the extent to which yield increases spare lands even globally or the extent to which loss of agricultural lands, e.g., to bioenergy, leads to additional land clearing. In some models, a major result of yield gains is that people consume more, or alternatively, if land is converted to bioenergy, that people consume less, and so do not clear as much alternative land. In some models, when land goes out of production, other farmers compensate for much of the loss by increasing their yields on existing land. Modelers make different assumptions that lead to different results of what types of lands will be converted next and how much carbon will they lose for each ton of crop they produce.

How does the carbon benefits index relate to this debate?

First, although this debate has important implications for many actions, the Carbon Benefits Index provides an alternative means of judging the climate benefits of land use change regardless of which side of this debate is more correct. In effect, what the economists are debating is the following: when one person changes consumption, or one land use manager changes outputs or yield, how much do the resulting effects on price alter consumption or production by others? As in the SUV example, the debate is about changes in efficiency of consumption or production by others, not changes in the efficiency of the productivity of a particular hectare or in the consumption patterns of a particular individual. Unlike the carbon benefits index, these models do not segregate production and consumption efficiencies. Yet even if these price effects were strong, they could still be achieved through other mechanisms and in more targeted ways. Meanwhile, there are always benefits or harm caused by gains or losses in efficiency of a particular hectare or of a particular diet because these efficiencies alter the capacity to store carbon while meeting any specified level of food demand, and that is independently valuable even if it needed to be combined with other policies to fully realize the potential carbon storage gain. To achieve present climate goals, which require stabilizing carbon storage and then increasing it, increasing this capacity to store carbon is critical, and the carbon benefits index provides a more meaningful way of measuring such consequences.

Second, the carbon benefits index provides a useful tool for evaluating these economic predictions because it establishes a benchmark. For example, if the maize that is devoted to ethanol were replaced with the same loss of carbon from vegetation and soils as the global average for maize, the cost in greenhouse gas emissions attributable to land use costs would be roughly 10 times that estimated by the model used by the state of California. There are economic and biophysical reasons the result could be higher or lower than this carbon benefits estimate, as discussed in the paragraph above, but this benchmark can help to examine whether models have an adequate evidentiary basis for the alternative justification.

As the paper also discusses, these global economic land use models must simulate an enormous range of responses to any one change in management or consumption, representing the reactions of consumers around the world, their switching from one food to another, and the reactions of farmers and even governments throughout the world. Only a small number of the estimated reactions have been estimated using proper economic methods, and even they often disagree. We believe models should have a substantial burden of proof to justify results that differ greatly from the global average.

To assist these analyses, the Carbon Benefits Calculator allows a user to change the carbon opportunity costs of a food item to analyze what the implications of a land use change would be if the land use cost of replacing it were higher or lower than the global average.

Some important assumptions, details and caveats

A few important assumptions, details and caveats deserve emphasis.

Time: The loss of carbon from converting a forest to cropland occurs mostly quickly while the resulting production of cropland, as well as the emissions from the annual production process, can occur indefinitely. Any method of evaluating the greenhouse gas consequences of land use change must therefore find a way to fold into one calculation this one-time loss and how it should be allocated to the annual production of food. For some present biofuel policy purposes, Europe calculates both the carbon loss and the production over 20 years, and the U.S. does the same over 30 years. This means that the emissions from converting agricultural land are amortized over all the biofuels produced over 20 or 30 years. But there are different plausible ways of doing the calculation.

The decision about how to account for time is a broader question of climate policy, not particular to land use. The more emissions that occur in the short-term, e.g., over decades, the more damage there will be in that time. More warming early also causes effects on glacial melt and ocean acidification that even later cuts in emissions would not undo. The longer mitigation is delayed, the greater the chance of crossing various tipping points. The normal estimates of the economic cost of money also value short-term mitigation more. The need for vast mitigation over the next thirty years is also implicit in the Paris climate accords, which sets targets for holding down climate change that require steep emissions reductions within that period. The importance of early emissions is also implicit in the focus on mitigating methane, which is a powerful greenhouse gas but which, if emitted today, will be largely absent in 2050.

Our index uses a discount rate approach to value the costs of emissions and the benefits of food production over time, and that also factors in estimates of the rate at which different land use changes lead to losses or gains in gain carbon storage. In our central analysis, we use 4% for a variety of reasons, including that doing so roughly matches US biofuel policy. Others could argue for a different approach.

Yet we find that even using a 2% discount rate, the results of our example analyses do not change. The reason seems to be that assigning any reasonable carbon storage opportunity cost to land has large consequences, and dramatically changes the approach of other methods that do not do so.

Biodiversity: The carbon benefits index only measures land use efficiency for greenhouse gas mitigation; it does not evaluate effects on biodiversity or other ecosystem values.

Generally, preserving carbon-rich habitats, such as forests, wetlands, and many woody savannas, tends to benefit biodiversity, but there are also examples where doing so would not. For example, establishing plantation forests on native savannas would store more carbon but harm biodiversity. The value of land for biodiversity, however, depends on its broader landscape and so cannot be evaluated by an index such as ours. Biodiversity and other ecosystem effects of land use choices must be separately analyzed.

Carbon benefits index versus global optimization modeling: One type of analysis that bears some resemblance to our index is global, carbon optimization modeling. Given assumptions or estimates about the global food needs, about the carbon content of every hectare in the world and about its likely yields, a modeler can estimate what the most efficient locations of global agriculture would be, i.e., the locations that will meet food demands and store the most carbon. These models can have valuable uses, but for a variety of reasons, they cannot truly help you determine what to do with any particular hectare of land. A main reason is that they have to assign a yield and a carbon cost to every hectare in the area analyzed, which can encompass the whole world, and the information is neither precise enough to make sound decisions about individual hectares, nor can doing so recognize the wide variety of different management that can be used to produce the same crop. What this type of model can do is be suggestive of what might be a good use in a general location.

Another big difference between this type of optimization model and the carbon benefits index is that the index only uses global data to estimate average carbon costs of producing each food: the average amount of carbon loss and the average emissions from the production process for that food. This type of information can be estimated in ways that allow the likely many inaccurate understandings at the global level about individual hectares to average each other out. When the index is applied to a particular hectare, the user must supply information that then is knowable about its particular conditions and management. By contrast, global optimization models try to pinpoint precise hectares to use using data at the global level. For any particular hectare, there is a good chance that the model may be inaccurate.

What if the world were able to stop expanding agricultural land? Even if the world were to stop expanding agricultural land, land used for food production would still have an opportunity cost in foregone carbon storage. In that case, the benefit of more land-efficient food production or consumption would be the capacity to take more land out of food production and grow forests. The Carbon Benefits Index includes a variation for these circumstances, which calculates potential carbon storage benefits based on the quantity of carbon that could be stored on average through forest regrowth using the amount of land productivity on average used to produce each food. For most foods, using a 4% discount rate, the carbon opportunity cost is similar using either of our two calculation methods.