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Options to achieve net-zero emissions from agriculture and land use changes in Latin America and the Caribbean

Patrice Dumas, Stefan Wirsenius, Tim Searchinger, Nadine Andrieu, Adrien Vogt-Schilb[1]

Abstract

Eleven countries in Latin America and the Caribbean have pledged to reach net-zero emissions by around 2050. Changes in the food system are key to reach these carbon neutrality goals, as agriculture and resulting land-use changes are responsible for almost half of greenhouse gas emissions in the region. We quantify the effect of supply-side (e.g., yield improvements, silvopasture, agroforestry) and demand-side (e.g., reduction of waste and losses, changing diets) options to reduce emissions and transform the land use system in a net carbon sink by 2050 while improving nutrition for the growing population. We consider both direct agriculture emissions and the pressure that food production puts on land use changes, and track separately emissions that happen in the region and emissions linked to trade. Our findings confirm that cattle plays a preponderant role, emitting nearly 60% of greenhouse gas emissions from agriculture and land-use change. Reaching a net-negative emissions food system able to balance emissions from the rest of the economy will require ambitious and sustained improvements in yields and changes in diets to moderate the increasing demand for beef, continuously decrease the share of land dedicated to agriculture, and increase instead land dedicated to carbon sequestration and biodiversity preservation.

Keywords: Agriculture, Forestry and Other Land Use; AFOLU; food; yields; diets; decarbonization; carbon neutrality.

JEL codes: Q54; Q15; Q17; Q18

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Introduction

Stabilizing climate change at 1.5°C requires reaching net-zero emissions of CO_2, and deep reductions in other greenhouse gases (GHGs) by 2050 (IPCC, 2018). Many governments and heads of state have declared their goal to achieve carbon neutrality by 2050 (CAT, 2021, NTZ

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2022) – a goal deemed to be consistent with creating net socioeconomic opportunities (World Bank, 2012, IMF, 2020).

Agriculture, land use, and land-use changes cause 21% of global GHG emissions (Lamb et al 2021), mainly in the form of carbon dioxide from deforestation and other land use changes, methane from ruminants (mostly cattle used for meat and dairy) and rice production, and nitrous oxide emissions from fertilizers. Deforestation itself is driven by meat consumption, as 77% of agricultural land globally is used for livestock - either grazing or feed production (FAOSTAT, 2022). Demand for food is expected to increase more than 50% by 2050, driven by population and income growth, leading to increased emissions if no action is taken (Searchinger et al, 2019; Tilman and Clark 2014).

Land use and dietary choices should thus play a key role in emission-reduction strategies (Searchinger et al, 2019, Svensson et al, 2021). The land system is unique in that it could become a net carbon sink through afforestation. Indeed, most scenarios reviewed by the IPCC use reforestation to balance emissions from sources deemed difficult to abate (e.g., air travel) and achieve net-zero emissions by 2050 and net-negative emissions afterwards (IPCC, 2018). Furthermore, land not used for food production can be used to conserve biodiversity.

Latin America and the Caribbean exemplify the challenges related to land use. In the region, the land and food system is responsible for just under half of GHG emissions (WRI, 2022) and employs an estimated 15% of the workforce (Saget et al., 2020). In addition, the region suffers from an acute biodiversity crisis, having lost an estimated 94% of its vertebrate population in 50 years, largely due to habitat destruction (WWF, 2020). At the same time, 11 countries from the region have already pledged to reach net-zero emissions by around 2050 (NTZ 2022), a goal that could create the equivalent of 1% of GDP in economic benefits and 15 million net new jobs by 2030 in the region (Saget et al., 2020; Vogt-Schilb, 2021).

Many options could reduce GHG emissions from agriculture (e.g., Searchinger et al 2019; Fazekas et al, 2022). For instance, changes to animal diets, breading for lower methane production, and enteric methane emission reductions using antimicrobial agents can reduce emissions from livestock, as can managing flooding time for rice paddy. Increasing nitrogen fertilization efficiency or using more nitrogen fixing legume crops can reduce N_2O emissions. Forest protections, silvopasture and agroforestry (where trees are grown on the same land used for livestock or crops), increasing yields, and reducing consumption of the most land-intensive items, including beef, can help reduce deforestation and increase forest cover instead.

Several challenges entangle the assessment of emission-reduction options. One concerns land-use change emissions. Most lifecycle analyses attribute emissions from deforestation to land uses that happen on parcels that have recently be cleared, e.g., to give room for grazing or palm grown for oil (e.g., Henders et al 2015). In contrast, recent studies have emphasized the relevance of considering the *carbon opportunity cost of land,* linked to the notion that using land for agriculture inherently sacrifices the potential to store more carbon in native vegetation (Searchinger et al, 2018).[2] Trade is a second complexity: a fraction of the GHGs generated by the food system is "embedded" in exports to other countries (e.g, Pendrill et al, 2019; Hong et al, 2020). Between one fifth and one fourth of GHG emissions from the food system in Latin America and the Caribbean have been linked to exports to the rest of the world (Saget et al, 2020, Dummet et al, 2020).

To the best of our knowledge, there is no study of options to reach net-zero food systems available for Latin America and the Caribbean that consider the two complexities described above. World-scale integrated assessment models that provide results for the region (e.g., Calvin et al. 2016, Santos Da Silva 2019) tend to focus on the role of afforestation and bioenergy, bundle supply-side options together, and seldom report the impact of dietary changes and trade. Emission reduction studies that focus on the region sometimes include diet changes (e.g., Bataille et al. 2020; Groves et al, 2020; Quiros-Tortos et al, 2021; Benavides et al, 2021, Schaldach et al. 2017), but tend to neglect agricultural options to reduce direct emissions and disregard the impact of trade.

This study quantifies options to reduce greenhouse gases emissions from food production in Latin America and the Caribbean, considering their impacts through direct production emissions, the carbon opportunity cost of land, and global trade. We study contrasting scenarios to 2050 that explore both supply and demand side changes. They include a baseline based on historical trends and three emission reduction scenarios of varying ambition, which are calibrated from the literature quantifying emission reduction options for the region. Although all the products are concerned, beef meat is particularly scrutinized, because of its importance in regional diets and as a driver of emissions. Our scenarios are meant to explore options and stimulate debates. They should not be interpreted as normative material, as they use imperfect data, and disregard any barrier to their implementation.

We use a model that focuses on Latin America and the Caribbean while describing the global agriculture and land use system, based on Searchinger et al (2019). We provide results for the region as a whole, for its two largest countries, Brazil, Mexico, and for 4 subregions, the Andes, the Caribbean, Central America, and the Southern Cone. We assess both direct emissions from agriculture production and the carbon opportunity cost of land used for food – obtained by using the intersecting a map of crops and pastures and a map of the carbon content of the natural vegetation that could grow on the same land (Searchinger, 2018).

Our results confirm that beef plays a disproportionate role in GHG emissions from agriculture in Latin America. Beef production is responsible for 57% of agriculture production emissions

[2] Both methods find that cattle is the leading cause of deforestation globally. But there are differences. For instance, palm oil and soybean are identified as important drivers in the recently-cleared-parcel approach, while the carbon-opportunity-cost approach finds that they have a similar footprint than other oils and other cereals respectively (Searchinger et al, 2018).

and 58% of land use emissions while only contributing 12% of protein (9 g per person per day) and 4% of calories intake (105 kcal per person per day) in the region.

Current development patterns have an unsustainable environmental impact. In our baseline scenario, economic growth means that the average caloric intake would increase from 2710 kcal/day to 2954 kcal/day per capita by 2050 – while beef consumption increases to 11g/day. Coupled with population growth, this would lead agriculture emissions to grow by nearly 45%, from 850 to 1,220 MtCO2e per year, and land use change emissions reach 1,340 MtCO2eq/year on average. These changes happen despite crop yields increase of 44%, pasture yields increase of 30% and livestock efficiency gains.

Reducing the footprint of beef is essential to transforming Latin America and the Caribbean into a net carbon sink. In our most ambitious supply-side scenario, direct emissions are reduced by 10% compared to the reference year, 2010, but land-use changes are reverted, absorbing 1,330 MtCO2eq/year on average. This requires transformational actions: stocking rates for beef (a measure of how many cows graze on one hectare of land) increase 75%, the nitrogen use efficiency (a measure of how much fertilizers are needed to achieve a given yield) increases 35%, and crop yields increase 72%. Three quarters of the land use change absorptions come from our assumption that silvopasture and other efficiency gains can dramatically improve pasture yields. Note that our supply side simulations assume exogenous demand. In actuality, increasing yields without protecting forests or moderating demand for land-intensive goods such as beef would likely result in more deforestation as it would increase the incentive for farmers and ranchers to expand their business.

Demand side solutions can also make the agriculture and land use sector a net carbon sink. In our most ambitious demand-side scenario, beef consumption increases in the poorest countries of the region, especially in Central America and the Caribbean, but is reduced 62 to 85% compared to historical levels among the highest consumers in the Southern Cone, and about 45% for Andean high beef consumer countries. The regional average decreases 50% while nutritional outcomes improve in all countries, direct emissions are stabilized, and land use changes are reverted to absorb the equivalent of 1,740MtCO2eq/year.

Combining supply and demand options reduces direct emission 40% compared to the reference year, to 500 MtCO2/year while the land use changes absorb 3,250 MtCO2eq/year. This is consistent with reaching net-zero emissions economies by 2050 if emissions from energy, industry, and waste, not modeled here, are cut drastically.[3] One important caveat, however, is that continued negative emissions after 2050 would require continuing to reduce the land footprint of food production to continue dedicating more land to the restauration of high-carbon ecosystems, a very challenging undertaking.

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[3] For reference, emissions in the region in 2018 where close to 4 GtCO2eq and could double by 2050 if not action is taken.

Concerning global trade, we find that food exports from Latin America and the Caribbean tend to worsen global emissions. Production from the region is about as GHG-intensive as the rest of the world when considering only direct emissions, but it tends to result in more emissions from land use changes. Indeed, high-carbon ecosystems in the region make the carbon opportunity cost of its land slightly higher than the global average.

Our analysis has many limitations. We did not quantify options to scale new technologies such as cell-based food, and we were constrained by available regional data. We did not investigate the barriers, such as lack of capacity, financing hurdles, counterproductive price signals, cultural barriers and political economy issues that could hamper the transformations we considered (e.g., Fazekas et al, 2022). Further research could focus on specific countries, make the most of interviews with country experts, and use finer data. Despite these limitations, our paper shows that reaching net-negative emission in the agriculture and land use system in Latin America and the Caribbean will require very drastic changes in both supply and demand for food, and that pasture intensification and dietary changes to reduce demand for beef the most promising options to reduce GHG emissions.

Concerning the more general task of planning for a net-zero GHG economy, our paper tempers claims that Latin America and the Caribbean can act as a natural global carbon sink and offset emissions from the rest of the world. Governments face stern tradeoffs when arbitrating the allocation of land between food production (and cattle in particular) vs. carbon sequestration and biodiversity preservation. We join many recent voices in warning that any strategy to go to net-zero emissions, at the country or corporate level, should first drastically reduce emissions from fossil fuels and industrial processes and only consider offsets through reforestation as a last resort (e.g., Fankhauser et al, 2020).

The rest of the paper is structured as follows. The next section describes the model we use. Then, we review the literature for options to reduce emissions from food production in Latin America and the Caribbean. The following section explains how we set up our numerical simulations. We then present the results of our simulations. The last sections provides a discussion and conclusion.

Model

We use a global balance model that represents the agricultural supply and demand balance in a year (Searchinger et al. 2019, Mora et al. 2020). We run it on the reference year, 2010 (calibrated from FAOSTAT), and on the year 2050. The model computes land uses, land use changes and resulting GHG emissions from domestic demand and net exports, taking yields, diets, feed required to produce livestock, and rules on trade as given. We represent explicitly six countries or subregions within Latin America and the Caribbean: Brazil, Mexico, the Andes (including Bolivia, Colombia, Ecuador, Peru and Venezuela), the Caribbean, Central America (which also includes the Guyanas), and the Southern Cone (including Argentina, Chile, Uruguay, Paraguay). We tend to refer to them as “subregions” in the text, and we tend to reserve “the region” to mean “Latin America and the Caribbean”.

Domestic demand is exogenous. It comes from direct food consumption, feed use (driven by livestock demand), processing use, for instance to produce oil, oilcrop, and oil meals[4], and nonfood demand. Food consumption is based on diets per capita (exogenously chosen in each scenario) multiplied by population (from UN projections). Nonfood demand (e.g., textiles, materials, biofuels) is exogenous and constant across scenarios (as in Searchinger et al, 2019). The input requirements and coproduction relations are all linear. Losses are also represented with linear relationships. We use different coefficients to capture supply side losses and waste and losses on the demand side. We also account for specific food losses with coefficients linking available food energy and consumed food energy (calibrated using Gustavsson et al. 2011).

Bilateral trade is not represented. Instead, all subregions import and export to a global pool for each product. Trade is represented differently for beef, dairy and small ruminant products, which are associated with grasslands and for other products. For beef, dairy and small ruminant products the production shares are modified based on efficiency change, some dairy production being kept local. The method is explained in more details with the efficiency change below. For other products, imports are determined as a share of domestic demand, based on a fixed dependency ratio calibrated on 2010 data from FAOSTAT. This results in a total quantify of global trade for each product. From there, exports are determined by assuming that the market share of each country or country groups stays constant to what is in the reference year according to FAOSTAT – except in scenarios that specify a different rule.

The production of most crops, poultry and pork simply matches demand. We also use the following item-specific rules. Beef production is computed from dairy and beef meat demand. The demand for dairy determines dairy meat co-production calibrated from Herrero et al. (2013), and then beef production adjusts to fulfill the total bovine meat demand. Vegetal oils are considered to be perfect substitutes. Production of oil crops is driven by the oilcrop meal demand, except for palm oil. Palm oil demand adjusts to match the total vegetal oil demand. We assume exogenous trends of (wild) fish capture, that we allocate to satisfy food and feed needs. If feed demand is higher than what fish capture can accommodate, the residual demand is assumed to be satisfied with oil crops in aquaculture. Aquaculture is assumed to supply any food demand that wild capture cannot accommodate. Aquaculture information from Hall et al., 2011 and Munkung et al., 2014.

Nitrogen input is based on production per crop and the nitrogen use efficiency (NUE) of each crop, calibrated at the country or country-group level from Zhang et al (2015). Synthetic nitrogen is computed based on the difference between total nitrogen input and the other

[4] *Oil meals*, also known as *oilmeals* or *oilseed meals* is the protein-rich substance that is left after oil is extracted from oily plants. They are used as feed or fertilizer.

sources of nitrogen: manure (determined livestock and coefficients from Herrero et al. 2013), biological fixation (determined using coefficients of fixation), and deposition from Zhang et al. (2015).

Direct production emissions are taken from Herrero et al. (2013), based on the IPCC method for nitrous oxide emissions and on FAOSTAT data for direct agricultural energy use production emissions, except for aquaculture which come from Hall et al., 2011 and Munkung et al., 2014. Methane emissions from rice are estimated by Yan et al. 2009. Input production emissions, corresponding to fertilizers mining or synthesis and pesticides synthesis come from EPA (2010). Emissions reduction options are modelled as reduction coefficients, except for rice, for which a spreadsheet model results are used (Yan et al. 2009). For aquaculture, switch of production systems can also be used.

The carbon opportunity cost of land quantifies how much carbon could be sequestered if the land used for food production was used instead for growing native vegetation (Searchinger, 2018). We assess it by intersecting a map of crop and pasture's locations and a map of natural vegetation carbon content. The map of natural vegetation carbon content is based on the potential carbon content computed by a plant model rescaled on averages per biomes found in the literature. Carbon content in crops is substracted for perennial crops.

The carbon opportunity cost corresponds to the total stock of carbon content that would accumulate, in decades, if agriculture were abandoned. To compute an equivalent emission flux, we annualize it using a 4% yearly discount rate, which corresponds to a division of the potential carbon by approximately 30 years. This computation is used for the reference year. For the scenarios to 2050, land use is determined using land use yields based on exogenous harvested yields per product and an exogenous cropping intensity coefficient per country (or group of countries). Then, the land use change patterns of 2007-2011 are used to determine the vegetation replaced by each crop and by pastures and average carbon content by biome and type of vegetation is used to determine the natural vegetation carbon content, with the same factor used to compute the annual equivalent as for the reference year.

With this method, carbon stock changes associated with land use change emissions that occur one time can be compared to and summed with fossil fuel substitution by biomass and production emissions that are repeated. The overall balance depends crucially on the discount rate considered, or, equivalently on the amortization factor.

Reviewing options to reduce emissions in Latin America and the Caribbean

This section reviews options to reduce emissions from the food system. The following section provides details on how we modelled these options in our simulations.

Supply side options

We used expert knowledge and the literature to determine a list of interesting options to reduce GHGs from agriculture and their magnitudes and assess the relevance for Latin America and the Caribbean of the options listed by Searchinger et al (2019). The main source of literature are the life cycle analysis (LCA) studies comparing agricultural practices and value chains, as well as larger scale studies of deployment/potentials of agricultural sector GHG reductions options. We reviewed all the Latin America and the Caribbean based studies analyzed in the thorough study by Poore et al. (2018). Some of the practices listed below, such as those related to increasing soil carbon or fostering silvopastures, are sometimes described under the umbrella term “regenerative agriculture”.

Livestock production can be intensified by providing more digestible feed to cattle, either more digestible grass or concentrate feed, by increasing livestock numbers or rotating livestock on pastures to match with grass growth, by adding nitrogen fixing legumes in their pastures, by removing plants that livestock cannot eat, by avoiding pasture degradation and by complementing grass intake in dry season, with hay or concentrate feed. Livestock sector comparisons of intensification levels all over Latin America and the Caribbean consistently finds that more intensive livestock rearing leads to less production emissions by unit of product and less land use (Bartl et al. 2011, Celis et al. 2013, Picasso et al. 2014, Dick et al. 2015, Mazzetto et al. 2015, Cardoso et al., 2016, Huerta et al. 2016, Pashaei Kamali et al. 2016). Silvopasture is a practice where nitrogen fixing shrubs and trees complement grass to avoid nutrient depletion and provides a more favorable microclimate. Silvopasture can significantly reduce the carbon opportunity cost of cattle, through the increase of production per unit of feed and per unit of pasture area, the decrease in input use, and the accumulation of carbon in trees (Landholm et al. 2019, Arango et al. 2020). Intensification using more concentrate feed and feedlots reduce GHGs and often increase environmental impacts other than GHG emissions, in particular toxicity (Picasso et al. 2014, Dick et al. Huerta et al. 2016), and in some cases nutrient pollution (Picasso et al. 2014).

No LCA analysis of livestock production improvement that we reviewed takes into account land use change emissions. In Searchinger et al. (2018), estimates of the impact of beef intensification options on GHG emissions from Cardoso et al. (2016) are completed with land use change emissions estimates. Searchinger et al find that, even though systems based on pasture intensification and on concentrate feed are associated with similar production emissions, land use related emissions are higher with pasture intensification, making concentrate feed a better option to reduce total GHG emissions. Emission reductions associated with removal of cattle or intensification of cattle farming depend on the local carbon opportunity cost of land and emissions from the naturally occurring fauna. Emissions reductions can be especially high in the equatorial regions where livestock replaces dense forest, but may also be low or null in regions where grassland is the natural vegetation and wild ruminants would replace cattle and emit similar amounts of methane than cattle.

Larger-scale studies of livestock intensification have assessed the consequences of pastures restoration (Strassburg et al. 2014, De Olivera Silva et al. 2018), or both pastures restoration and more concentrated feed, with concentrated feed seen as more efficient (Batista et al. 2019). The large-scale studies consider land-use change emissions in different ways, although they do not always try to leverage the possibilities of reforestation.

Changes in manure management, in particular avoiding disposal of manure in wet systems (lagoons in particular) is also proposed to reduce livestock related emissions in Latin America and the Caribbean (Celis et al. 2013, Cherubini et al. 2015).

Efficiency in nitrogen use is another option. The use of legumes as cover crops is described for sugar cane (de Oliveira-Bardonal et al. 2012) and blueberries (Cordes et al. 2016). Some studies also find different input use efficiency, showing the potential for increase in nitrogen use efficiency for fruits and nuts (Ingwersen 2012, Brito de Figueiredo et al. 2016, Cordes et al. 2016). Reducing synthetic and mineral fertilizers can help reduce nitrous oxide emissions, but care should be taken to avoid decreasing yields, which could lead to natural vegetation replacement and important land use change emissions. A study showed that smaller holder organic oranges cultivation in Brazil (less than 75 hectares) could reach almost the same yield as conventional plantation with less synthetic and mineral input, more biodiversity, and vegetation cover (Knudsen et al. 2011). In other cases, however, organic yields are often lower or much lower which means an increase in land use change emissions. Increase in yields without too much input use increase is also a way to decrease land use change emissions. Some potential to increase yields in Chile was determined for potatoes (Haverkort et al. 2014).

Increasing soil carbon is another option to reduce land use emissions proposed in the literature. Some literature on Latin America and the Caribbean suggests that no-till farming could increase soil organic carbon (Castanheira et al. 2013, Maia et al. 2013), except in the Amazon biome. However, the studies finding increase in soil organic carbon with transition to reduced or no-till farming only consider carbon change the superficial layer of land (0-30cm). When considering greater soil depth or the whole soil, most estimates of the effects of reduced tillage become small and non-significant (Luo et al. 2010, Dendooven et al. 2013, Mondal et al. 2010). There is evidence that residues retention (Dendooven et al. 2013, Raffa et al. 2015) allows to keep organic carbon in soils, but there is also evidence that in some place in Latin America and the Caribbean residues are already used for livestock (Beuchelt et al. 2015). Avoiding residues burning allow to add or keep soil organic carbon, in particular, for sugar cane (Galdos et al. 2010, de Oliveira-Bardonal et al. 2012, Garcia et al. 2016). Cover crops (Poeplau et al. 2015, Bai et al. 2019) are associated with more significant increase in soil organic carbon.

Direct energy use could also be reduced in some cases (Ingwersen 2012). For instance, reduced and no-till farming lead to reduced fuel use (Castanheira et al. 2013).

The use of bioenergy to substitute fossil fuel for energy is not such an interesting option when land-use change emissions are considered. When studies take into account that fuel crops displace the natural vegetation, they find that bioenergy causes more emissions than fossil fuels (de Souza et al. 2010, Lapola et al. 2010, Garcia et al. 2011, Searchinger et al. 2018). Use of wasted products as bioenergy can lead to net emissions reductions, an example is provided with a study on the use of discarded bananas from coffee shade trees to produce ethanol (Graefe et al. 2011).

Agroforestry is an interesting option to reduce emissions of various crops, especially cocoa (Ortiz-Rodriguez et al. 2016, Perez-Neira et al. 2016, Schroth et al. 2016) and coffee (Graefe et al. 2011, Noponen et al. 2012, van Rikxoort et al. 2014, Rahn et al. 2014). Indeed, shade trees store carbon, can have a positive effect on yield, although this depends on shade trees density, can provide with food or feed, nitrogen with legumes fixing trees and firewood substituting fossil fuels. In particular, intermediate levels of shade trees density described as commercial polyculture systems store relatively high levels of carbon with yields very similar with monocultures. Full accounting of the whole GHG balance, including carbon storage in trees, effect of fertilizers and land use change related emissions is not available in any study, which would allow to have a more precise idea on the overall balance.

Rice emissions reductions have been much less studied in Latin America and the Caribbean than in Asia, but the options are similar, with changes in flooding and in residues management (Chirinda et al. 2018). Changes in residues management are presented as changes in tillage since reductions in methane emissions following a change in tillage result from residues incorporation in the soil. A study presenting effects of residues left on soil surface versus incorporated with a very important reduction in emissions is also presented (Zschornack et al. 2011). Given that the change evaluated in this study is the same as the incorporation of residues effect associated with reduced tillage, and since these results have not been reproduced, we did not consider this option to be reliable. In the modeling and scenarios, we reused the same approach for the effect of floodings and residues management for Latin America and the Caribbean as for the rest of the world (Chirinda et al. 2018, Yan et al. 2009)[5].

Demand side options

Changing human diets globally can be an important lever for greenhouse gases emissions reductions. One option is to replace part of the livestock protein intake with protein-rich crops such as soy or beans (Searchinger et al, 2019).

Some authors have argued that global beef consumption could be reduced to the point where beef is not produced on areas with a high carbon opportunity cost, and instead relegated to low-opportunity costs areas such as savannas (Searchinger et al, 2019). In Latin America and

5 The emissions reported in Chirinda et al. 2018 comes from FAOSTAT, using a simpler method than our study. They are similar within 30% with the data used in our modelling, except for Brazil with much lower emissions in FAOSTAT (0.06 in FAOSTAT versus 0.21 tonnes CH4/ha in Yan et al. 2009)

the Caribbean, the majority of beef and dairy products come from temperate (including humid elevated plateau areas) or humid tropical areas, meaning that there is a large potential for demand substitution before all the production with high carbon intensity is replaced.

The health impact of diets is another important issue. In Latin America and the Caribbean, for instance, the prevalence of food insecurity is very high, at more than 75% (Benites-Zapata et al, 2021). But while some households suffer for insufficient protein intake, the main malnutrition issue in the region is that diets tend to be deficient in fruits, vegetables, fiber, and whole grains, and excessive in processed meats, red meats, and sugary drinks (IDB, 2019). Beef consumption is also very unequally distributed (Appendix Figure 1): Brazil and the rest of the South Cone consume 13g and 18g of beef protein per day and per person, compared to 11g in Canada and the USA, an average of 9g over the region, 6g in Europe, 4g globally, and less than 4g in the Caribbean and Central America. This suggest that there may be some room to reduce average beef consumption while improving nutrition outcomes in all countries in the region.

Within livestock products, pork and poultry are associated with lower emissions than ruminants (beef, dairy, sheep, and goats), such that substitutions from beef to other animal products can also decrease the GHG footprints of diets. Even though beef is relatively cheap to produce in Latin America and the Caribbean, other protein sources are often cheaper to produce, meaning that reducing beef intake could result in financial savings. There may be many other barriers to changing human diets, which are not considered in this study (e.g., IDB 2019, Fazekas et al, 2022).

Another lever for demand side reduction are the reduction of waste and losses, which is estimated to affect 14% of global food production just between the harvest and retail stages (FAO, 2019). Moderating the human population increase is sometimes proposed as a lever – although in Latin America and the Caribbean the population density and demographic trends are lower than in other regions of the world. We did not model different population scenarios.

Setting up emission reduction scenarios

We study contrasting scenarios to 2050 that explore both supply and demand side changes, including a baseline based on historical trends and three emission reduction scenarios of varying ambition, calibrated from the literature presented above and expert judgment. Although all the products are concerned, beef meat is particularly scrutinized, because of its importance in regional diets and as a driver of emissions. We calibrate our scenarios from the review of literature below and expert judgement. We think that all our scenarios are technically feasible, but we do not explore political or financial feasibility. Our scenarios are meant to explore options to reach long-term climate stabilization goals and stimulate debates. They should not be interpreted as normative material, as they use imperfect data, and disregard any barrier to their implementation.

The overall setup of scenarios follows Searchinger et al (2019), with a baseline based on widely used work from the FAO (Alexandratos et al., 2012). As livestock efficiency (e.g., in heads per hectare) and pasture yield change are not specified in Alexandratos et al. 2012 scenario, we make additional assumptions based on trends continuations.

We consider four supply-side emissions reduction scenarios, that we label “Reasonable production”, “Ambitious production”, “Breakthrough production”, and “Best pasture yields”. The first three scenarios include change in crop yields and livestock efficiency, in nitrogen use efficiency and technological options directly reducing GHG emissions. The “Best pasture yields” scenario simulates very ambitious stocking rate changes that reflect the impact of intensifying beef production and using silvopasture systems in Latin America and the Caribbean (but not the rest of the world), but no other supply-side improvement compared to the baseline (Strassburg et al. 2014, Landholm et al. 2019).

The supply side scenarios are simulated with a variant regarding trade. In the standard implementation, exports of each item by each country or group of country keeps up with global trade. In the variant, exports from Latin America and the Caribbean are fixed in quantities to what they were in the reference year. The imports that are not satisfied by exports from Latin America and the Caribbean are satisfied by the rest of the world using the relative shares in total trade rescaled after removing Latin America and the Caribbean. Comparing these variants provides insights on the impact of trade on global emissions, it shows whether, from a global GHG perspective, it is more efficient to produce in Latin America and the Caribbean, or in the rest of the world.

On the demand side, we model three global diets scenarios: a “Moderate beef to other animal” scenario which avoids increases in beef consumption in low beef consumer regions, and proposes some decrease in big beef consumers, such as Latin America and the Caribbean, and two more ambitious diet changes, one targeted at beef and beef consumers, “Ambitious beef to veg” and another targeted at all animal products “Ambitious animal to veg”. For each of the global diet scenario, we model a variant where diets change only in Latin America and the Caribbean (while the rest of the world continues in the baseline diet).

Supply side scenarios

Livestock yields

We start by describing how the efficiency of livestock production (for both meat and dairy) changes over time in our scenarios. In all scenarios, monogastric (mainly poultry and pork) efficiency changes are based on regional trends. For small ruminants (sheep and goats), changes in efficiency are based on the beef sector changes. The beef and dairy changes happen as follow.

There are two sources for efficiency change in beef and in dairy. First, we model an autonomous over-the-board efficiency increase, corresponding to changes in herd management and animal health. For the Ambitious and Breakthrough scenarios, we added an increase of 25% on the trend efficiency, which amounts to a 4% increase of efficiency across the board (the Reasonable scenario follows the Baseline).

Second, all scenarios include a shift from livestock systems used in 2010 to more efficient systems, either with more concentrates or more digestible pasture grass, adding systems modeled as in Herrero et al (2013). Projections of production per head is converted to input-output efficiency using a panel regression on Herrero et al., (2013) and Wirsenius et al., (2010), that both give the same value for the exponential coefficient regression result. In all scenarios, the overall efficiency target increase is based on the input-output efficiency trend. Pasture yields increase based on a world scale trend. A shift to more efficient systems within each climate zone (arid, humid and temperate) is then chosen to match a target efficiency gain. The efficiency target is itself chosen to close the relative efficiency gap, with respect to the global leader region (Russia or the US), by the same amount in all countries. Table 2 in the appendix shows yields in 2010 and 2050.

Rules on grassland areas mandate that arid grassland areas stay the same in all scenarios, since arid grassland can only be used for livestock. The ratio of humid and temperate grassland areas is also kept constant considering that current ratio of humid and temperate grassland areas is representative at the region size. Trade parameters adjust such that the global repartition of production adjusts and more efficient regions gain some shares. For dairy, part of the production increase is done locally. The result of these assumptions is a relatively moderate increase in pastureland areas.

We obtain current stocking rates by downscaling livestock sector data on country reported pastures and head numbers. They are quite different among Latin America and the Caribbean subregions in the reference year. For beef, the values range from 0.3 for Mexico to 1.4 for the Caribbean. Dairy stocking rates are consistently smaller.

Table 1: Stocking rates in the reference year (2010) in tropical livestock units (TLU) per hectare, Latin America and the Caribbean subregions.

	Beef sector stocking rate	Dairy sector stocking rate
Brazil	0.98	0.68
Mexico	0.33	0.31
Andes	0.52	0.25
Caribbean	1.47	1.12
Central America and the Guianas	1.08	0.63
Southern Cone	0.41	0.28
Latin America and the Caribbean	0.62	0.43

North America is at 0.4 tropical livestock units per hectare for beef while the EU is much higher at 2.4. The differences within Latin America and the Caribbean partially corresponds to different climates, with different shares of arid, humid and temperate zones. Indeed, higher grass potential yields can be attained in equatorial or humid subtropical climates. However, climate is not the main driver of grassland use intensification, for instance land use availability, input prices and availability, distance to infrastructures and management choices play a large role. According to the literature, Strassburg et al. 2014 for Brazil or Landholm et al. 2019 for humid Columbia, stocking rates could be sustainably multiplied by 3 in these environments.

In the baseline, grass yield increase in every subregion 26% between 2010 and 2050, following the world trend – Appendix table 1 shows values in 2010. A scenario of larger increase for Latin America and the Caribbean is also set up, with a 200% increase for humid areas and 150% increase for temperate areas for the Andes and Brazil subregions, based on Strassburg et al. 2014 and Landholm et al. 2019, and a 100% increase for humid areas and a 50% increase for temperate areas for the other Latin American and Caribbean regions – with less favorable subtropical instead of equatorial climates. In humid regions, this grass yield can be interpreted as switching to silvopasture systems. Indeed, while we do not track separately the carbon stored in trees and the carbon stored in reforested areas (because we lack data to do so), our model assumes all land not used for food production is implicitly reforested. This makes it equivalent to increase grass yields and to increase the carbon captured in trees in silvopasture systems.

Crop yields
Bioenergy does not play a large role in our scenarios – given the ambiguous effect on overall GHG emissions reported in the literature. In particular, we model no bioenergy with carbon capture and storage (BECCS). The feasibility of large-scale BECCS from commercial, financial, and political economy perspectives, as well as its consistency with biodiversity, land, and water conservation goals, has been abundantly called into question (Gasser et al., 2015; Heck et al., 2018; Smith et al., 2016; Turner et al., 2018). Problems with carbon capture and storage technology include that it is not industrially and commercially demonstrated (it could leak CO_2, and/or result into prohibitive costs for users) and the availability of CO_2 storage sites is not a given.

Reduced and no-till farming, with cover crops, is already well-developed in Latin America and the Caribbean in conventional agriculture. It corresponds mainly with the use of herbicides combined with genetically modified herbicide resistant crops (Castanheira et al. 2013). We assume it is in the baseline.

In the baseline, cropland yield changes are based on Alexandratos et al. (2012). The three supply-side scenarios assume a 5% increase of cropping intensity. Baseline crop yields increase are modified with 20% more change than in the baseline in the Ambitious production variant and 50% more change in the Breakthrough production variant.

Nitrogen
The different Latin America and the Caribbean subregions have quite different nitrogen use efficiencies (NUE) today. The Southern Cone and Brazil have a NUE of 0.67 and 0.54 respectively, similar to OECD countries, Mexico 0.4 and other subregions about 0.3 (Zhang et al., 2015). The prevalence of soybeans in Southern Cone and Brazil is important in explaining higher NUE levels.

We model a 20% increase in NUE for the Reasonable production scenario, filling a gap in efficiency of 50% for Ambitious and 75% for Breakthrough. The NUE of the Southern Cone in the Breakthrough production scenario reaches 0.8, which would be quite challenging to attain. Reaching such high levels will require using advance technological options (such as coated nitrogen fertilizer) and mobilizing more intercropping of legumes and other crops, such as maize. For the subregions starting at 0.3, the NUE in the Breakthrough scenario raises above 0.5. Even though the change is important, these levels would be easier to attain thanks to overall yield increases, fractioning nitrogen doses and adding legumes in rotations.

Other technology changes
The technological supply-side options that we model focus on the following (all reductions are described relative to the baseline improvement in 2050)

- enteric emission reductions, using antimicrobial agents, with different assumptions on uptake. These options are modelled identically for Latin America and the Caribbean and the rest of the world, as antimicrobial agents are supposed to be applicable everywhere.
    - in Reasonable 7.5% of beef and 15% of dairy
    - in Ambitious 5% of small ruminants, 15% of beef and 30% of dairy
    - in Breakthrough 30% for every sector
- manure management, with: switching from wet to dry manure management systems; switching to efficient methanisation, without using agricultural products; and increase in frequency of application of manure.
    - In the Reasonable production scenario, we assume a reduction of 40% of the methane from manure that is managed in wet form, and 20% mitigation of nitrous oxide from dry pork systems and 10% mitigation of nitrous oxide from dry beef and dairy systems.
    - In the Ambitious production scenario, we assume 60%, 35% and 20 % reductions respectively.
    - In the Breakthrough production scenario, we assume 80%, 50% and 30% reductions.

- pasture range nitrogen deposition emissions, by planting grass that secrete nitrification inhibitors, in non-arid systems. We model different ambitions on penetration: none in Reasonable, 20% and 40% in Ambitious and Breakthrough. Those scenarios are particularly suitable for Latin America and the Caribbean, since grasses producing biological nitrification inhibitor are native from that region (Subbarao et al. 2012).
- rice methane emissions mitigation with share of single drawdown and multiple drawdown both set to 25%, and changes in straw management (for all the supply side scenario), and an additional 20% increase of rice yield in the Breakthrough production scenario which allows to decrease the area even more, with methane emissions being mainly related to rice flooded areas. These mitigation options with flooding and residues management are consistent with the literature on Latin America and the Caribbean. The amplitude of the effects of the changes in practices for rice mitigation could be different from the studies found for Latin America and the Caribbean, but those studies results are not convergent nor clearly explained, therefore we used the numbers from the global scenarios in Searchinger et al (2019).

We also model changes on direct GHG emissions from energy use in the Ambitious and Breakthrough production scenarios, concerning both direct agriculture energy use and inputs production. Those scenarios correspond to both increased efficiency and change in energy source, switching to carbon-free electricity. We follow Searchinger et al (2019) and model

- in Ambitious, -37% for nitrogen synthesis and direct agriculture energy use, -50% for aquatic products energy use and for other inputs production
- in Breakthrough, -75% for all the inputs production and aquatic products energy use and -62.5% for direct agriculture energy use

The manure reduction scenarios, nitrogen use efficiency and direct energy use scenarios are consistent with evidence from the literature surveyed in the previous section but go beyond increased efficiency described in the literature.

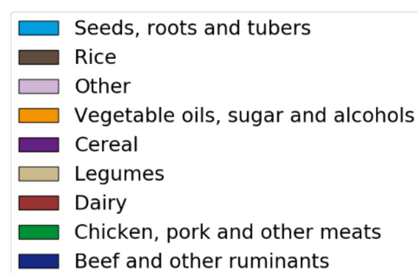
Changes in demand side, diets, and waste

There are not many scenarios for demand-side emission reduction options focused on Latin America and the Caribbean. Here, we developed demand-side scenarios based on global scenarios from Searchinger et al, 2019, with a focus on modelling beef consumption reduction and comparing the effects of reducing different types of livestock products.

The baseline diet change follows the FAO scenarios (Alexandratos et al., 2012), with the additional assumption that every country gets a minimum of 3000 kcal/cap/day of available food energy by 2050 in all scenarios. This additional assumption does not concern our modelling of Latin America and the Caribbean directly because in the FAO baseline all the subregions or countries in the region pass this threshold. The FAO scenario proposes important increases in overall consumption, and in particular for beef: more than 50% for Mexico and the Carribean, 35% for the Andes, Central America and the Guianas region, and 14% for Brazil where consumption is already very high compared to the rest of the world, and 5% for the Southern cone.

In the “Moderate beef to other animal” diet, the baseline change in meat (measured in total energy available) is conserved, but some beef is substituted by monogastric meat (pork and poultry). The changes are computed at the FAO region size and proportionately spread on countries. Latin America and the Caribbean is a region in the FAO regional aggregation. For subregions with low beef consumption (less than 60 kcal/pers/day) an increase of 50% maximum of beef is modelled, with a 60 kcal/pers/day ceiling. For regions with high beef consumption, consumption is decreased using either the trend continuation (for the US and EU) or a trend similar to the US decrease for other regions (including Latin America and the Caribbean). In addition, a 10% reduction of waste and losses is applied.

The diet evaluated in the “Ambitious beef to veg” scenario focuses on modeling the impact of beef consumption. In this scenario, 30% of global beef consumption in the baseline scenario is replaced by a mix of pulses (e.g., lentils, beans, and peas) and soybean, using an energy equivalent, starting by the countries where beef consumption is the highest. Some Latin America and the Caribbean countries reduce their beef consumption drastically, for instance Argentina and Uruguay cut 85%, Brazil, Paraguay, Ecuador, Bolivia and Chile between 60 and 65%. As a comparison, the US and EU countries cut about 40%. Barbados, Bahamas and Bermuda islands also cut between 58 and 80%. Conversely, many countries such as Nicaragua, El Salvador, Jamaica or Guyana are still below the threshold and therefore do not to cut their demand at all, compared to the baseline. Most other countries in Latin America and the Caribbean are in between and do not cut much of their consumption in this scenario.



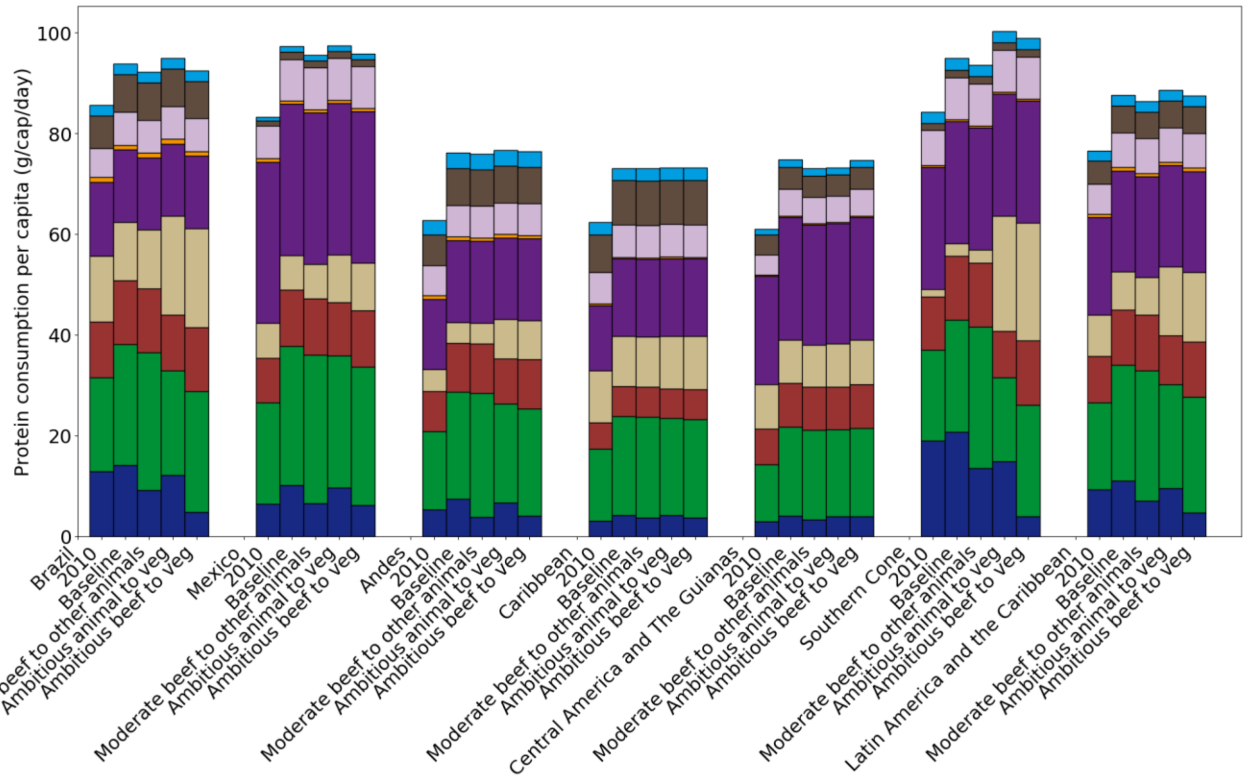


Figure 1: Diets by region and scenario, in proteins

In the “Ambitious animal to veg” scenario, the same decrease in total animal products energy consumption is kept as in the “Ambitious beef to veg” scenario to have a comparable diet, but the change is spread on all the animal products, including dairy, keeping the relative share among animal products as in the reference year. In both Ambitious scenarios, a 25% reduction in wastes and losses is applied.

The resulting future diets as well as the reference year (2010) are shown in Figure 1. Consumption of fruits and vegetables is included under “Others” and does not vary across scenarios. The Appendix shows the diets in terms of available and consumed energy (showing the effect of waste reduction).

Results

Supply side scenarios

Livestock efficiency and crop yields

We first consider the impact of our modelling choices on aggregate food production statistics.

Here is what happens to livestock intensification in our baseline. Globally, following the trends for beef and dairy efficiency leads to an efficiency gap closing of 75% for beef and 65% for dairy. The switching of systems for livestock intensification in Latin America and the Caribbean in the baseline depends on the subregion.

Mexico is quite special, as, for beef, the humid and temperate systems have much higher efficiencies than arid systems. Therefore, the efficiency gap target in the baseline can be attained by increasing production in humid and temperate systems, with no need for systems switching (this however increases land use change emissions). Conversely, for dairy, switching to systems using more concentrates is needed.

Other subregions require less systems switching to reach their efficiency gap closing target. The shares switched are not so important for beef, about 12-15%, except in the Caribbean (25%), and more important for dairy, about 40% except for the Southern Cone and Brazil (15-20%). Most of the system switch are towards more grains in the ruminant intake, but there are also switching to more digestible grass, mostly in some humid systems.

In the Southern Cone and Mexico, the overall consequences of those changes bring the overall feed requirements for beef (measured as feed dry matter over beef production), to EU/US efficiency levels. In Central America and the Guianas, Andes, and Brazil, feed requirements for beef drop from twice what they are in the US and EU to about 45% more. The Caribbean starts from higher feed requirements and still lags behind by 2050 in the baseline. For dairy, the results are similar, except that the Caribbean is similar to Central America and the Guianas, Andes and Brazil. This lever can be pushed more for some Latin America and the Caribbean subregions but following the world-scale trends with the increase of feedlot finishing and increased pasture digestibility could already bring up most of what is needed. This could still be challenging, as it implies preventing extensive and relatively inefficient livestock rearing typically present in the frontiers in Latin America and the Caribbean (e.g., in Brazil, Andes, and Chacos).

Manure management scenarios translate, for the whole Latin America and the Caribbean, to -11%, -21% and -28% of manure management emissions in the Reasonable, Ambition and Breakthrough scenarios, respectively, compared to the baseline. In the Breakthrough production scenario, this leads to unchanged manure management emissions in 2050 compared to the reference year (2010). Similar numbers for the subregions are obtained, with +/- 4% in the Breakthrough production scenario depending on the livestock rearing structure of the region.

To report the effect of yield improvements, we compare land use in 2050 the different scenarios to what it would be if the reference year production was obtained from yields in the 2050. (This allows to disentangle the impact of a changing basket of crops produced). In the baseline, the overall yield increase obtained this way ranges from 37% (Southern Cone) to 52% (Caribbean and Central America and the Guianas). In the Ambitious scenario, overall yields increase between 50% and 70%, and in the Breakthrough production variant from 60% to 87%.

Emissions in Latin American and Caribbean

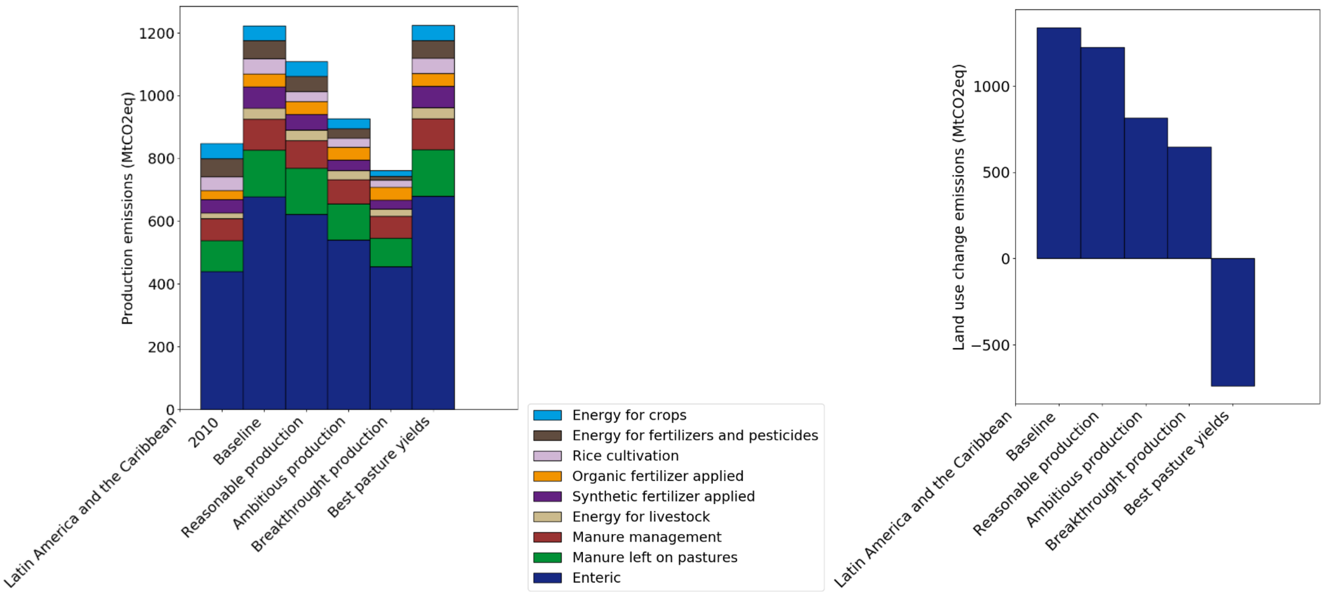


Figure 2: Production and land use emissions in supply side scenarios

We now turn to the impact of supply-side options on emissions (Figure 2 – see appendix for subregion results). In these scenarios, production in the region is driven by baseline diet changes, both in the region and globally through exports. In the Breakthrough scenario, emissions are reduced 33% from the baseline, but only 10% compared to the reference year due to demand increase. Since there isn't much additional efficiency built in the Breakthrough production scenario, mostly technological options to reduce production emissions, the land use emissions are not reduced much compared to the baseline. The increase of pasture yields in the "Best pasture yields" scenario has an important effect on land use change emissions, leading to an important reforestation.[6] The Appendix shows results per subregion. Brazil dominates emission reductions, because of its size and the importance of beef in Brazil.

The impact of trade on emissions

Emissions measured in Latin America and the Caribbean only reflect partially the consequences of supply-side emissions. Indeed, exports increase emissions from the region, but decrease the need for production elsewhere. The overall consequences of exports depend on the how regional emissions intensities compare to global ones. To quantify this issue, we assess emissions in Latin America and the Caribbean and globally across

[6] Notice that our scenarios are based on exogenous demand assumptions. In actuality, improving beef yields without protecting forests and/or moderating domestic and international beef demand could lead to cheaper beef production, more domestic beef demand, more beef exports, expanded beef production, and increased deforestation.

scenarios. We also consider scenarios where exports from the region fixed at the reference year level (labeled RefX in the figure).

Figure 3 compares direct emissions when measured at the global and regional level, and when exports are fixed (to low 2010 values) versus endogenous (at higher 2050 values). It shows that increasing exports from Latin America and the Caribbean does not have a significant impact on global direct emissions. Only considering emissions in Latin America and the Caribbean, one could incorrectly conclude that decreasing exports allowed reducing production emissions by about 30%. But food not imported from the region must be produced elsewhere, meaning that emissions elsewhere will offset and, it turns out, even cancel that gain. Indeed, regional food producers are about as GHG-intensive as the rest of the world exporters.

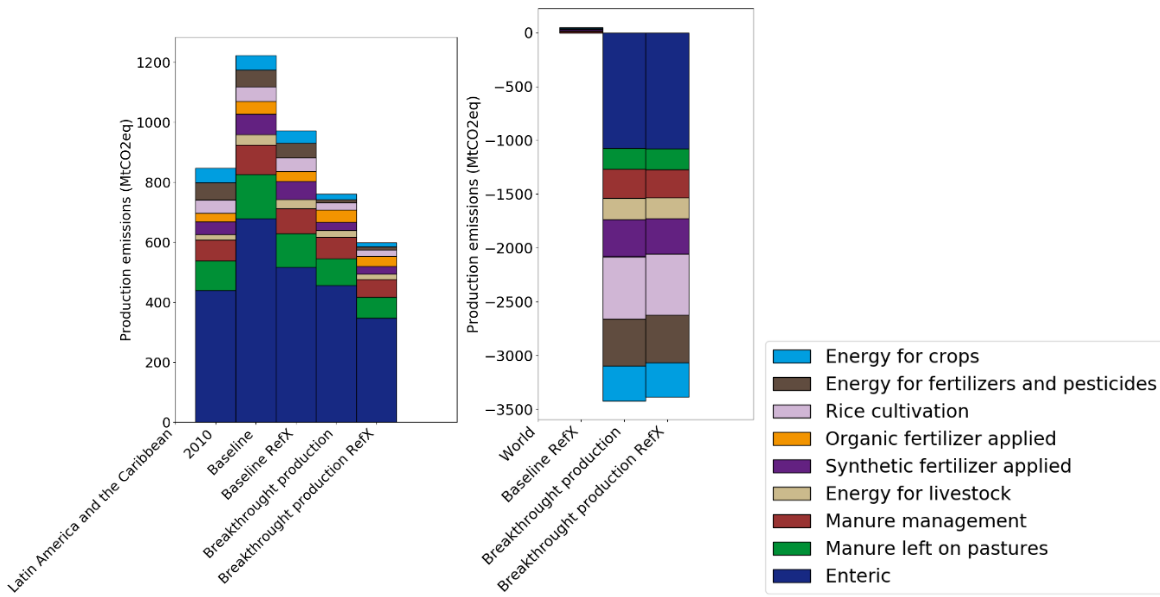
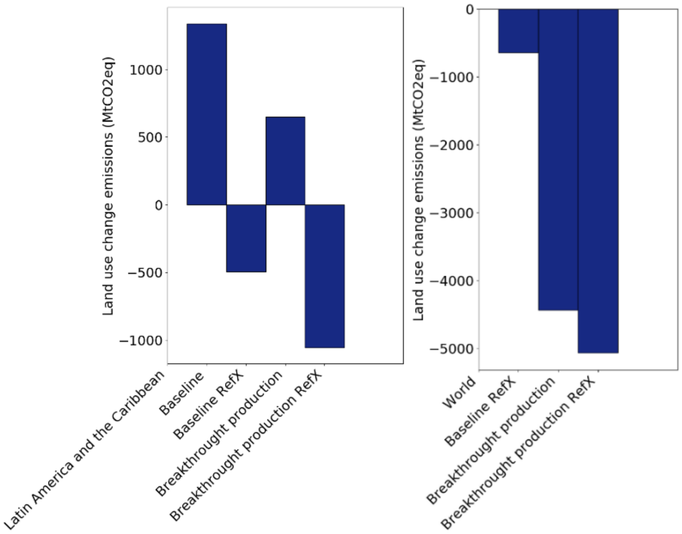


Figure 3: Production emissions in Latin America and the Caribbean and difference of world-scale production emissions with the baseline, with and without fixed exports

Considering emissions related to land use change, however, shows the value of decreasing exports from the region. Figure 4 shows that moving from the high endogenous exports to the lower reference export would save about 1.5 $GtCO_2$ in the region, and about 0.6 $GtCO_2$ globally after accounting for the need to produce elsewhere. This shows that Latin America and the Caribbean hosts high-carbon ecosystem, and that there is an opportunity cost in using land in the region to produce food, compared to land available elsewhere.

Figure 4: Land use change emissions in Latin America and the Caribbean and difference of world-scale land use change emissions with the baseline, with and without fixed exports



Demand side scenarios

The comparison of demand scenarios show that beef is a more relevant target than animal products (Figure 5 – see appendix for subregion results). Indeed, the ambitious scenario targeting beef leads to more than twice more direct emissions reduction than the scenario that reduces all animal products. A moderate shift from beef to other animal products reduces production emissions more than an ambitious reduction of all animal products. The pattern is even stronger for land use emissions a moderate reduction target on beef reverts deforestation, while an ambitious reduction of all animal products does not.

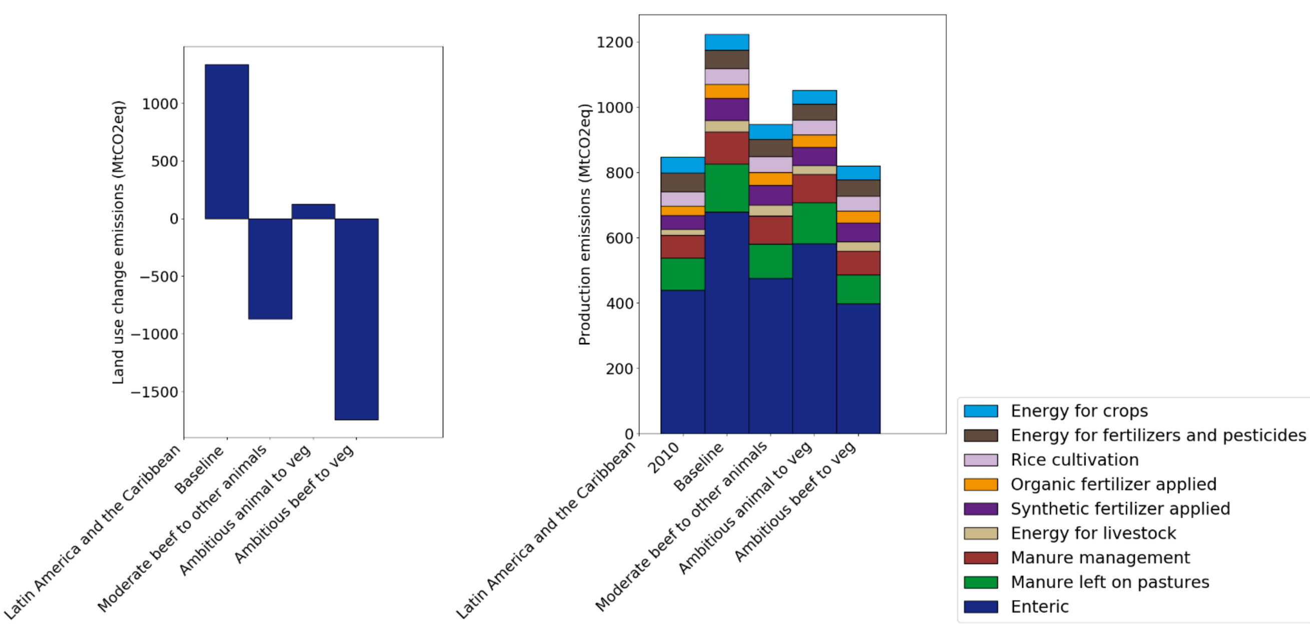


Figure 5: Production and land use emissions by diet scenario

Comparing supply and demand scenarios shows that demand-only and supply-only scenarios produce emission reduction of the same magnitude and can achieve more in term of land use change emissions reductions than direct emissions. Pasture yield increase, as we saw previously, also leads to important decrease in land use related emissions.

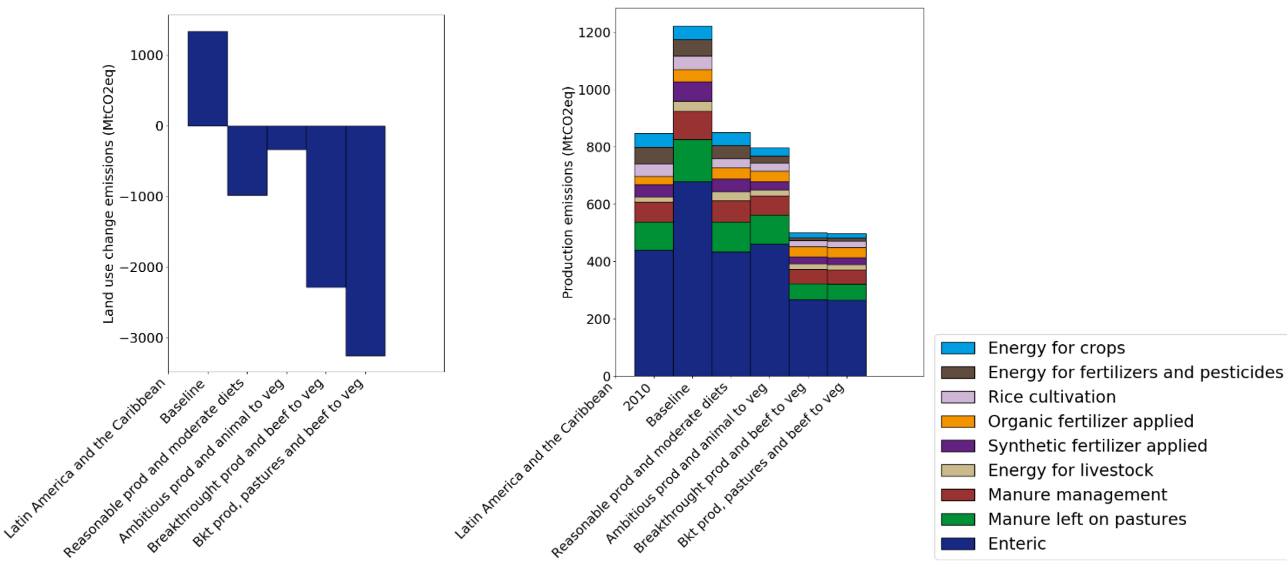


Figure 6: Production and land use emissions in combined supply- and demand-size scenarios

The combination of demand and production process changes reduce production emissions, by roughly 60% less than in the 2050 baseline and 40% less that in the 2010 reference year (Figure 6 – see appendix for country results). The combination also frees land to allow natural vegetation to regrow.

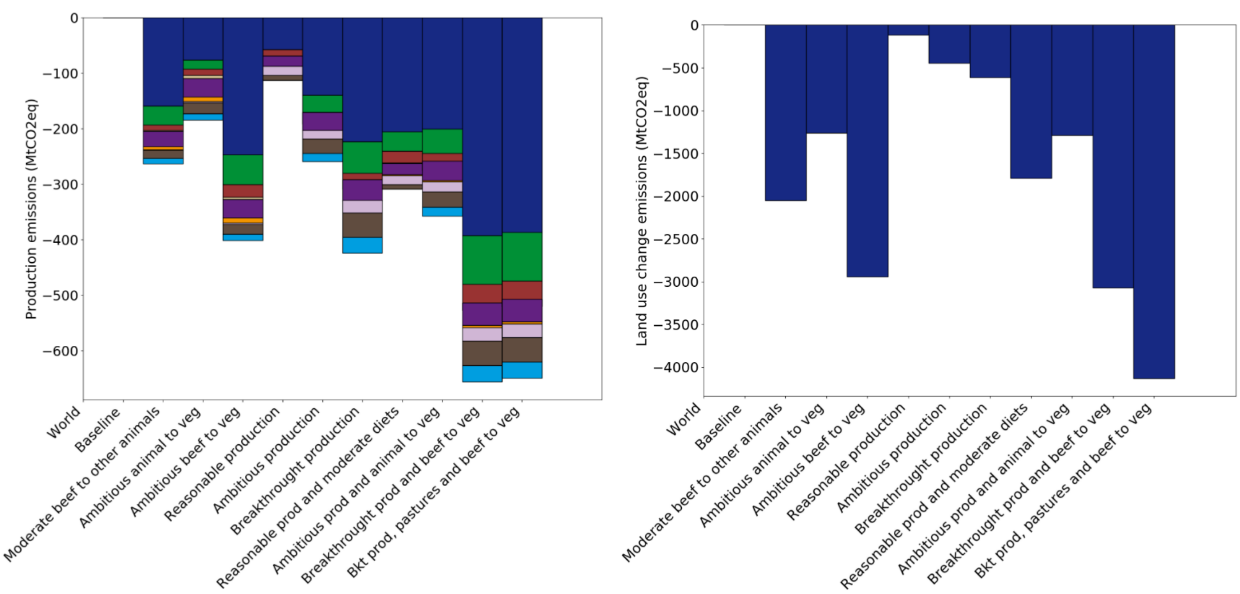


Figure 7*: Impact of Latin American and the Caribbean supply and demand scenarios on global emissions when the rest of the world stays on its baseline (difference with baseline emissions)*

Figure 7 shows the impact of Latin America and the Caribbean diets and supply-side scenarios on global emissions, assuming the rest of the world stays on the baseline – see appendix for subregion results. Isolating the effect of changes in Latin America and the Caribbean region on global reductions for the combinations of demand and production emissions reductions show similar reductions to those obtained in scenarios where the rest of the world is also changing and the changes in emissions are only evaluated in the Latin America and the Caribbean region.

Discussion and conclusion

Our results indicate that both demand and supply side options need to be mobilized to make the food system consistent with net-zero emissions. Even in the most ambitious scenarios, production emissions are still far from zero. Residual emissions from agriculture, and livestock especially, are unavoidable. To offset emissions, regrowing natural vegetation is essential. This in turn requires reducing demand, especially for beef, and increasing yields, especially pasture yields.

On the demand side, reducing average beef consumption can make regional diets less unequal. Today, the region hosts the countries with the highest beef consumption per capita in the world, as well as countries with very low consumption levels.

Reducing production emissions requires a comprehensive approach, with important margins of improvements for nitrogen use, rice emissions and direct energy use. But the reduction of beef related emissions will dominate absolute levels of emissions reductions. Enteric methane emissions and nitrous oxide emissions on pastures are key levers to reduce direct emissions. Efficiency improvements can play a role but selecting feed to modify the microbial rumen and manure left on pasture are the main levers to reduce methane and nitrous oxide emissions.

If Latin America and the Caribbean countries keep up with increases in efficiency with the rest of the world, exports can replace other country productions, or decrease, without much consequences for direct production emissions. The region however is home to high-carbon ecosystems, suggesting that exports from the region may result in net deforestation at the global scale.

Our work has limitations. One is that we faced various challenges related to data availability. Large scale data about agricultural practices were not easily available for all the countries in Latin America and the Caribbean. In particular, GHG data for intensive diversified agroecology-based farming are missing, except for cocoa and coffee agroforestry, for which data is available, albeit not in a single study. Pasture yield increases are particularly relevant for Latin America and the Caribbean, but we could only find one study at the country level to put numbers on it. The use of livestock in some countries to launder drug dealing money may introduce biases, but we do not believe that this impacts our conclusions.

Another limitation is that while farmers may have different capacities to implement supply-side changes when they produce for their own consumption, for local markets and for international markets, we did not find data that allowed to model them separately. Farmers type and size may be two different things: cocoa and coffee farmers described in LCA analyses are often smallholders who produce for international markets.

Land use strategies described in our scenarios would also have impacts on dimensions or indicators that we have not considered. For instance, dietary changes could have distributional impacts within countries. While we found in a preliminary analysis, not shown here, that the share of animal products and the share of beef in food-related expenditures in Argentina is roughly constant across income classes, more research is needed on this topic. Further, both demand and supply-side changes could have impacts on rural employment and revenues, which we have not considered (see also Saget et al, 2020).

Overall, our scenarios are consistent with a land sparing strategy to reduce as much as possible GHG emissions and store carbon in natural vegetation, in an ambitious yet feasible way. Continued negative emissions from land use change after 2050 would require continuing to reduce the land footprint of food production.

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References

Arango, J., Ruden, A., Martinez-Baron, D., Loboguerrero, A. M., Berndt, A., Chacón, M., Torres, C. F., Oyhantcabal, W., Gomez, C. A., Ricci, P., Ku-Vera, J., Burkart, S., Moorby, J. M., and Chirinda, N. (2020). Ambition meets reality: Achieving GHG emission reduction targets in the livestock sector of Latin America. Frontiers in Sustainable Food Systems, 4:65.

Alexandratos, Nikos, and Jelle Bruinsma. "World agriculture towards 2030/2050: the 2012 revision." (2012).

Bai, X., Huang, Y., Ren, W., Coyne, M., Jacinthe, P.-A., Tao, B., Hui, D., Yang, J., and Matocha, C. (2019). Responses of soil carbon sequestration to climate-smart agriculture practices: A meta-analysis. Global Change Biology, 25(8):2591–2606.

Bartl, K., Gómez, C. A., and Nemecek, T. (2011). Life cycle assessment of milk produced in two smallholder dairy systems in the highlands and the coast of Peru. Journal of Cleaner Production, 19(13):1494–1505.

Bataille, C., Waisman, H., Briand, Y., Svensson, J., Vogt-Schilb, A., Jaramillo, M., Delgado, R., Arguello, R., Clarke, L., Wild, T., Lallana, F., Bravo, G., Nadal, G., Le Treut, G., Godinez, G., Quiros-Tortos, J., Pereira, E., Howells, M., Buira, D., Tovilla, J., Farbes, J., Ryan, J., De La Torre Ugarte, D., Collado, M., Requejo, F., Gomez, X., Soria, R., Villamar, D., Rochedo, P., and Imperio, M. (2020). Net-zero deep decarbonization pathways in Latin America: Challenges and opportunities. Energy Strategy Reviews, 30:100510.

Batista, E., Soares-Filho, B., Barbosa, F., Merry, F., Davis, J., van der Hoff, R., and Rajão, R. G. (2019). Large-scale pasture restoration may not be the best option to reduce greenhouse gas emissions in Brazil. Environmental Research Letters, 14(12):125009.

Benavides, Carlos, L. Cifuentes, Manuel Diaz, Horacio Gilabert, Luis Gonzales, Diego Gonzalez, David Groves, et al. “Options to Achieve Carbon Neutrality in Chile: An Assessment Under Uncertainty.” Inter-American Development Bank, August 20, 2021.

Beuchelt, T. D., Camacho Villa, C. T., Göhring, L., Hernández Rodríguez, V. M., Hellin, J., Sonder, K., and Erenstein, O. (2015). Social and income trade-offs of conservation agriculture practices on crop residue use in Mexico's central highlands. Agricultural Systems, 134:61–75. Biomass use trade-offs in cereal cropping systems:Lessons and implications from the developing world.

Brito de Figueirêdo, M. C., Potting, J., Lopes Serrano, L. A., Bezerra, M. A., da Silva Barros, V., Gondim, R. S., and Nemecek, T. (2016). Environmental assessment of tropical perennial crops: the case of the brazilian cashew. Journal of Cleaner Production, 112:131–140.

Calvin, K. V., Beach, R., Gurgel, A., Labriet, M., and Loboguerrero Rodriguez, A. M. (2016). Agriculture, forestry, and other land-use emissions in latin america. Energy Economics, 56:615–624.

Cardoso, A. S., Berndt, A., Leytem, A., Alves, B. J., das N.O. de Carvalho, I., de Barros Soares, L. H., Urquiaga, S., and Boddey, R. M. (2016). Impact of the intensification of beef production in Brazil on greenhouse gas emissions and land use. Agricultural Systems, 143:86–96.

Castanheira, É. G. and Freire, F. (2013). Greenhouse gas assessment of soybean production: implications of land use change and different cultivation systems. Journal of Cleaner Production, 54:49–60.

CAT, 2021. Climate target updates slow as science ramps up need for action. Climate Action Tracker.

Celis, J. E., Sandoval, N., and Wells, G. (2013). Carbon footprint estimation resulting from beef cattle at the Central irrigated valley, Bio-Bio region, Chile. Annals of Agrarian Science, 11(1).

Cherubini, E., Zanghelini, G. M., Alvarenga, R. A. F., Franco, D., and Soares, S. R. (2015). Life cycle assessment of swine production in Brazil: a comparison of four manure management systems. Journal of Cleaner Production, 87:68–77.

Chirinda, N., Arenas, L., Katto, M., Loaiza, S., Correa, F., Isthitani, M., Loboguerrero, A. M., Martínez-Barón, D., Graterol, E., Jaramillo, S., Torres, C. F., Arango, M., Guzmán, M., Avila, I., Hube, S., Kurtz, D. B., Zorrilla, G., Terra, J., Irisarri, P., Tarlera, S., LaHue, G., Scivittaro, W. B., Noguera, A., and Bayer, C. (2018). Sustainable and low greenhouse gas emitting rice production in Latin America and the Caribbean: A review on the transition from ideality to reality. Sustainability, 10(3). article number 671.

Cordes, H., Iriarte, A., and Villalobos, P. (2016). Evaluating the carbon footprint of Chilean organic blueberry production. The International Journal of Life Cycle Assessment, 21:281–292. doi:10.1007/s11367-016-1034-8.

de Oliveira Bordonal, R., de Figueiredo, E. B., and La Scala Jr, N. (2012). Greenhouse gas balance due to the conversion of sugarcane areas from burned to green harvest, considering other conservationist management practices. GCB Bioenergy, 4(6):846–858.

De Oliveira Silva, R., Barioni, L. G., Queiroz Pellegrino, G., and Moran, D. (2018). The role of agricultural intensification in brazil's nationally determined contribution on emissions mitigation. Agricultural Systems, 161:102–112.

de Souza, S. P., Pacca, S., de Ávila, M. T., and Borges, J. L. B. (2010). Greenhouse gas emissions and energy balance of palm oil biofuel. Renewable Energy, 35(11):2552–2561.

Dendooven, L., Patiño-Zúñiga, L., Verhulst, N., K, K. B., García-Gaytán, A., Luna-Guido, M., and Govaerts, B. (2013). Greenhouse gas emissions from nontilled, permanent raised, and conventionally tilled beds in the central highlands of Mexico. In Kang, M. and SS, S. B., editors, Combating climate change, an agricultural perspective. CRC Press, Leiden, Netherlands.

Dick, M., Abreu da Silva, M., and Dewes, H. (2015). Life cycle assessment of beef cattle production in two typical grassland systems of southern Brazil. Journal of Cleaner Production, 96:426–434. Integrating Cleaner Production into Sustainability Strategies. doi:10.1016/j.jclepro.2014.01.080.

Dummett, Cassie, et al. Illicit harvest, complicit goods. The State of Illegal Deforestation for Agriculture. Report Forest Trends, 2021.

EPA. EPA lifecycle analysis of greenhouse gas emissions from renewable fuels. EPA-420-F-10-006, 2010.

Fankhauser, S., Smith, S. M., Allen, M., Axelsson, K., Hale, T., Hepburn, C., Kendall, J. M., Khosla, R., Lezaun, J., Mitchell-Larson, E., Obersteiner, M., Rajamani, L., Rickaby, R., Seddon, N., & Wetzer, T. (2022). The meaning of net zero and how to get it right. Nature Climate Change, 12(1), 15–21. https://doi.org/10.1038/s41558-021-01245-w

FAO. The Future of Food and Agriculture—Alternative Pathways to 2050. Food and Agriculture Organization of the United Nations Rome, 2018.

FAO. The State of Food and Agriculture: Moving Forward on Food Loos and Waste Reduction. Food and Agriculture Organization of the United Nations Rome, 2019.

FAOSTAT, 2021: FAOSTAT. https://www.fao.org/faostat/en/#data/GT.

Fazekas, A., Bataille, C., Vogt-Schilb, A., 2022. Achieving Net-Zero Prosperity: How Governments Can Unlock 15 Essential Transformations. Inter-American Development Bank.

Galdos, M. V., Cerri, C. C., Lal, R., Bernoux, M., Feigl, B., and Cerri, C. E. P. (2010). Net greenhouse gas fluxes in Brazilian ethanol production systems. GCB Bioenergy, 2(1):37–44.

García, C. A., Fuentes, A., Hennecke, A., Riegelhaupt, E., Manzini, F., and Masera, O. (2011). Life-cycle greenhouse gas emissions and energy balances of sugarcane ethanol production in Mexico. Applied Energy, 88(6):2088–2097.

García, C. A., García-Treviño, E. S., Aguilar-Rivera, N., and Armendáriz, C. (2016). Carbon footprint of sugar production in Mexico. Journal of Cleaner Production, 112:2632–2641.

Gasser, T., Guivarch, C., Tachiiri, K., Jones, C.D., Ciais, P. (2015). Negative emissions physically needed to keep global warming below 2 °C. Nature Communications 6, 7958.

Graefe, S., Dufour, D., Giraldo, A., Muñoz, L. A., Mora, P., Solís, H., Garcés, H., and Gonzalez, A. (2011). Energy and carbon footprints of ethanol production using banana and cooking banana discard: A case study from Costa Rica and Ecuador. Biomass and Bioenergy, 35(7):2640–2649.

Groves, David G., James Syme, Edmundo Molina-Perez, Carlos Calvo, Luis Víctor-Gallardo, Guido Godinez-Zamora, Jairo Quirós-Tortós, et al. The Benefits and Costs Of Decarbonizing Costa Rica's Economy: Informing the Implementation of Costa Rica's National Decarbonization Plan under Uncertainty. Inter-American Development Bank, 2020.

Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R., and Meybeck, A. (2011). Global food losses and food waste. Extent, causes and prevention. Technical report, FAO.

Hall, S. J., Delaporte, A., Phillips, M. J., Beveridge, M., and O'Keefe, M. (2011). Blue frontiers: Managing the environmental costs of aquaculture. Technical report, The WorldFish Center, Penang, Malaysia.

Haverkort, A. J., Sandaña, P., and Kalazich, J. (2014). Yield gaps and ecological footprints of potato production systems in Chile. Potato Research, 57:13–31.

Heck, V., Gerten, D., Lucht, W., Popp, A. (2018). Biomass-based negative emissions difficult to reconcile with planetary boundaries. Nature Climate Change 8, 151–155.

Henders, S., Persson, U.M., Kastner, T., 2015. Trading forests: land-use change and carbon emissions embodied in production and exports of forest-risk commodities. Environ. Res. Lett. 10, 125012.

Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M. C., Thornton, P. K., Blümmel, M., Weiss, F., Grace, D., and Obersteiner, M. (2013). Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proceedings of the National Academy of Sciences.

Hong, C., Zhao, H., Qin, Y., Burney, J.A., Pongratz, J., Hartung, K., Liu, Y., Moore, F.C., Jackson, R.B., Zhang, Q. and Davis, S.J., 2022. Land-use emissions embodied in international trade. Science, 376(6593), pp.597-603.

Huerta, A. R., Güereca, L. P., and de la Salud Rubio Lozano, M. (2016). Environmental impact of beef production in Mexico through life cycle assessment. Resources, Conservation and Recycling, 109:44–53.

IDB, 2019. Agriculture Sector Framework Document. Inter-American Development Bank

IDB, DDPLAC (2019). Getting to Net-Zero Emissions: Lessons from Latin America and the Caribbean. Inter-American Development Bank and Deep Decarbonization Pathways for Latin America and the Caribbean.

IMF. "Greening the Recovery." Special Series on Fiscal Policies to Respond to COVID-19. International Monetary Fund, 2020.

IPCC (2018). Summary for Policymakers, in: Global Warming of 1.5°C: An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. Cambridge, United Kingdom and New York, NY, USA.

Ingwersen, W. W. (2012). Life cycle assessment of fresh pineapple from Costa Rica. Journal of Cleaner Production, 35:152–163.

Knudsen, M. T., Fonseca de Almeida, G., Langer, V., Santiago de Abreu, L., and Halberg, N. (2011). Environmental assessment of organic juice imported to Denmark: a case study on oranges (Citrus sinensis) from Brazil. Organic Agriculture, 1:167.

Lamb, W., T. Wiedmann, J. Pongratz, and Etc., 2021: A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. Environmental Research Letters,.

Landholm, D. M., Pradhan, P., Wegmann, P., Sánchez, M. A. R., Salazar, J. C. S., and Kropp, J. P. (2019). Reducing deforestation and improving livestock productivity: greenhouse gas mitigation potential of silvopastoral systems in Caquetá. Environmental Research Letters, 14(11):114007.

Lapola, D. M., Schaldach, R., Alcamo, J., Bondeau, A., Koch, J., Koelking, C., and Priess, J. A. (2010). Indirect land-use changes can overcome carbon savings from biofuels in Brazil. Proceedings of the National Academy of Sciences, 107(8):3388–3393.

Luo, Z., Wang, E., and Sun, O. J. (2010). Can no-tillage stimulate carbon sequestration in agricultural soils? a meta-analysis of paired experiments. Agriculture, Ecosystems & Environment, 139(1):224–231.

Maia, S. M. F., Carvalho, J. L. N., Cerri, C. E. P., Lal, R., Bernoux, M., Galdos, M. V., and Cerri, C. C. (2013). Contrasting approaches for estimating soil carbon changes in amazon and cerrado biomes. Soil and Tillage Research, 133:75–84.

Mazzetto, A., Feigl, B., Schils, R., Cerri, C., and Cerri, C. (2015). Improved pasture and herd management to reduce greenhouse gas emissions from a brazilian beef production system. Livestock Science, 175:101–112.

Mondal, S., Chakraborty, D., Bandyopadhyay, K., Aggarwal, P., and Rana, D. S. (2020). A global analysis of the impact of zero-tillage on soil physical condition, organic carbon content, and plant root response. Land Degradation & Development, 31(5):557–567.

Mora, O., Le Mouël, C., de Lattre-Gasquet, M., Donnars, C., Dumas, P., Réchauchère, O., Brunelle, T., Manceron, S., Marajo-Petitzon, E., Moreau, C., Barzman, M., Forslund, A., and Marty, P. (2020). Exploring the future of land use and food security: A new set of global scenarios. PLOS ONE, 15(7):1–29.

Mungkung, R., Phillips, M., Castine, S., Beveridge, M., Chaiyawannakarn, N., Nawapakpilai, S., and Waite, R. (2014). Exploratory analysis of resource demand and the environmental footprint of future aquaculture development using life cycle assessment. White Paper 2014-31, WorldFish, Penang, Malaysia.

NTZ, 2022. Net Zero Tracker. https://zerotracker.net/ Accessed February 2022

Noponen, M. R., Edwards-Jones, G., Haggar, J. P., Soto, G., Attarzadeh, N., and Healey, J. R. (2012). Greenhouse gas emissions in coffee grown with differing input levels under conventional and organic management. Agriculture, Ecosystems & Environment, 151:6–15.

Ortiz-Rodríguez, O. O., Villamizar-Gallardo, R. A., Naranjo-Merino, C. A., García-Caceres, R. G., and Castañeda-galvís, M. T. (2016). Carbon footprint of the colombian cocoa production. Engenharia Agrícola, 36(2).

Pashaei Kamali, F., van der Linden, A., Meuwissen, M. P., Malafaia, G. C., Oude Lansink, A. G., and de Boer, I. J. (2016). Environmental and economic performance of beef farming systems with different feeding strategies in southern brazil. Agricultural Systems, 146:70–79.

Pendrill, F., Persson, U.M., Godar, J., Kastner, T., Moran, D., Schmidt, S., Wood, R., 2019. Agricultural and forestry trade drives large share of tropical deforestation emissions. Global Environmental Change 56, 1–10.

Pérez Neira, D. (2016). Energy sustainability of Ecuadorian cacao export and its contribution to climate change. a case study through product life cycle assessment. Journal of Cleaner Production, 112:2560–2568.

Picasso, V. D., Modernel, P. D., Becoña, G., Salvo, L., Gutiérrez, L., and Astigarraga, L. (2014). Sustainability of meat production beyond carbon footprint: a synthesis of case studies from grazing systems in uruguay. Meat Science, 98(3):346–354. doi:10.1016/j.meatsci.2014.07.005.

Poeplau, C. and Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops – a meta-analysis. Agriculture, Ecosystems & Environment, 200:33–41.

Poore, J. and Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. Science, 360(6392):987–992.

Quiros-Tortos, Jairo, Godinez-Samora, Guido, Daniel De La Torre Ugarte, Carlos Heros, Juan Lazo Lazo, Elias Ruiz, Berioska Quispe, et al. “Costos y Beneficios de La Carbono-Neutralidad En El Perú: Una Evaluación Robusta.” Inter-American Development Bank and 2050 Pathways Platform, 2021.

Raffa, D. W., Bogdanski, A., and Tittonell, P. (2015). How does crop residue removal affect soil organic carbon and yield? a hierarchical analysis of management and environmental factors. Biomass and Bioenergy, 81:345–355. doi:10.1016/j.biombioe.2015.07.022.

Rahn, E., Läderach, P., Baca, M., Cressy, C., Schroth, G., Malin, D., van Rikxoort, H., and Shriver, J. (2014). Climate change adaptation, mitigation and livelihood benefits in coffee production: where are the synergies? Mitigation and Adaptation Strategies for Global Change, 19:1119–1137.

Saget, C., Vogt-Schilb, A., Luu, T. (2020). Jobs in a net-zero emissions future in Latin America and the Caribbean. Inter-American Development Bank and Internacional Labour Organization.

Santos Da Silva, S. R., Miralles-Wilhelm, F., Muñoz-Castillo, R., Clarke, L. E., Braun, C. J., Delgado, A., Edmonds, J. A., Hejazi, M., Horing, J., Horowitz, R., Kyle, P., Link, R., Patel, P., Turner, S., and McJeon, H. C. (2019). The Paris pledges and the energy-water-land nexus in Latin America: Exploring implications of greenhouse gas emission reductions. PLOS ONE, 14(4):1–26. doi:10.1371/journal.pone.0215013.

Schaldach, R., Göpel, J., and Klingler, M. (2017). The role of future land-use change in southern Amazonia to reach the aims of Brazil's national climate plan. Erdkunde, 71(3):213–230.

Schroth, G., Jeusset, A., Gomes, A. d. S., Florence, C. T., Coelho, N. A. P., Faria, D., and Läderach, P. (2016). Climate friendliness of cocoa agroforests is compatible with productivity increase. Mitigation and Adaptation Strategies for Global Change, 21:67–80.

Searchinger, T., Waite, R., Hanson, C., Ranganathan, J., and Dumas, P. (2019). Creating a sustainable food future. World resources report, World Ressources Institute.

Searchinger, T. D., Wirsenius, S., Beringer, T., and Dumas, P. (2018). Assessing the efficiency of changes in land use for mitigating climate change. Nature, 564:249–253.

Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., van Vuuren, D.P., Rogelj, J., Ciais, P., Milne, J., Canadell, J.G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J.R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., Yongsung, C. (2016). Biophysical and economic limits to negative CO2 emissions. Nature Clim. Change 6, 42–50.

Strassburg, B. B., Latawiec, A. E., Barioni, L. G., Nobre, C. A., da Silva, V. P., Valentim, J. F., Vianna, M., and Assad, E. D. (2014). When enough should be enough:

Improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. Global Environmental Change, 28:84–97.

Subbarao, G. V., Sahrawat, K. L., Nakahara, K., Rao, I. M., Ishitani, M., Hash, C. T., Kishii, M., Bonnett, D. G., Berry, W. L., and Lata, J. C. (2012). A paradigm shift towards low-nitrifying production systems: the role of biological nitrification inhibition (BNI). Annals of Botany, 112(2):297–316.

Svensson, Johannes, Henri Waisman, Adrien Vogt-Schilb, Chris Bataille, Pierre-Marie Aubert, Marcela Jaramilo-Gil, Jam Angulo-Paniagua, et al. “A Low GHG Development Pathway Design Framework for Agriculture, Forestry and Land Use.” Energy Strategy Reviews 37 (September 1, 2021): 100683.

Turner, P.A., Field, C.B., Lobell, D.B., Sanchez, D.L., Mach, K.J. (2018). Unprecedented rates of land-use transformation in modelled climate change mitigation pathways. Nature Sustainability 1, 240–245.

van Rikxoort, H., Schroth, G., Läderach, P., and Rodríguez-Sánchez, B. (2014). Carbon footprints and carbon stocks reveal climate-friendly coffee production. Agronomy for Sustainable Development, 34:887–897.

Vogt-Schilb, Adrien. “Stronger Sustainable Growth.” In Opportunities for Stronger and Sustainable Postpandemic Growth, edited by Cavallo, Eduardo and Andrew Powell. Inter American Development Bank, 2021.

Vosti, S., Msangi, S., Lima, E., Quiroga, R., Batka, M., and Zanocco, C. (2011). Agricultural greenhouse gas emissions in Latin America and the Caribbean. current situation, future trends and one policy experiment. Inter-American Development Bank Infrastructure and Environment Discussion Paper IDB-DP-167.

Wirsenius, S., Azar, C., and Berndes, G. (2010). How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? Agricultural Systems, 103(9):621–638.

Yan, X., Akiyama, H., Yagi, K., and Akimoto, H. (2009). Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 intergovernmental panel on climate change guidelines. Global Biogeochemical Cycles, 23(2):GB2002.

WRI, 2022. Climate Watch Historical Country Greenhouse Gas Emissions Data (1990-2018). World Resources Institute.

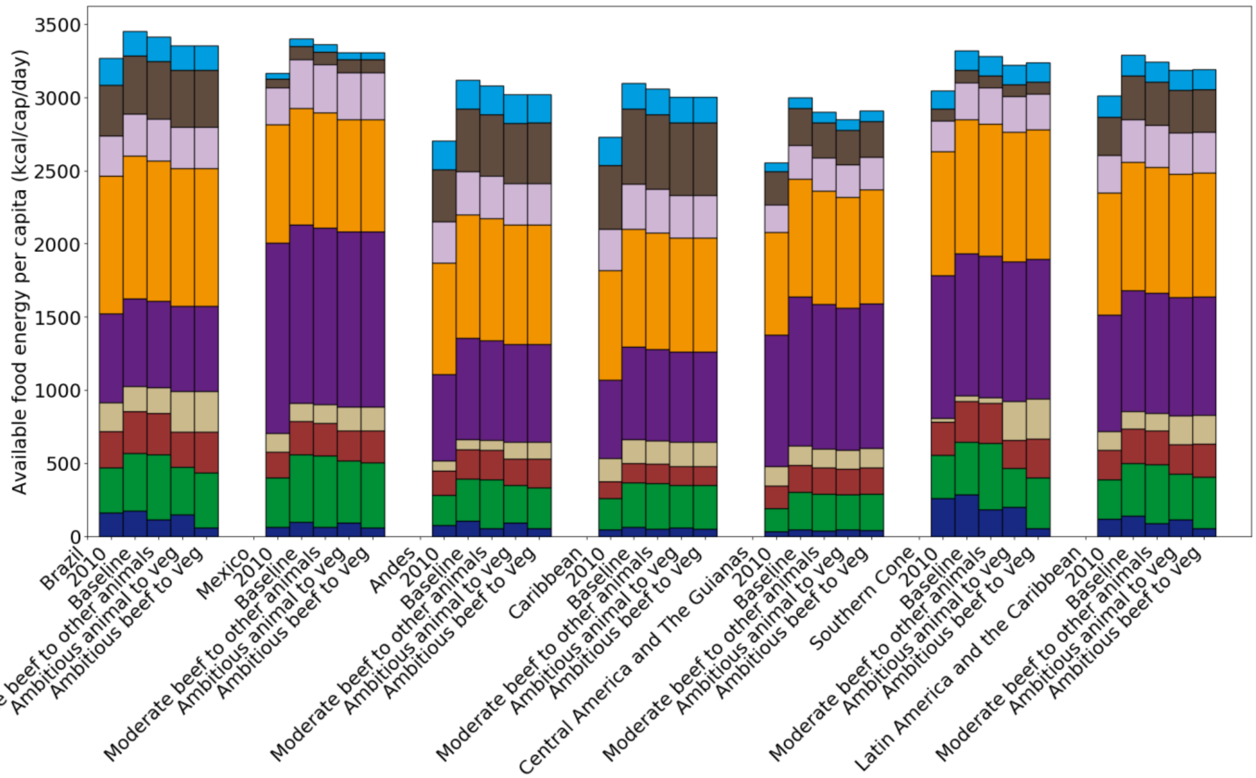
World Bank. Inclusive Green Growth : The Pathway to Sustainable Development. Washington, D.C.: World Bank, 2012.

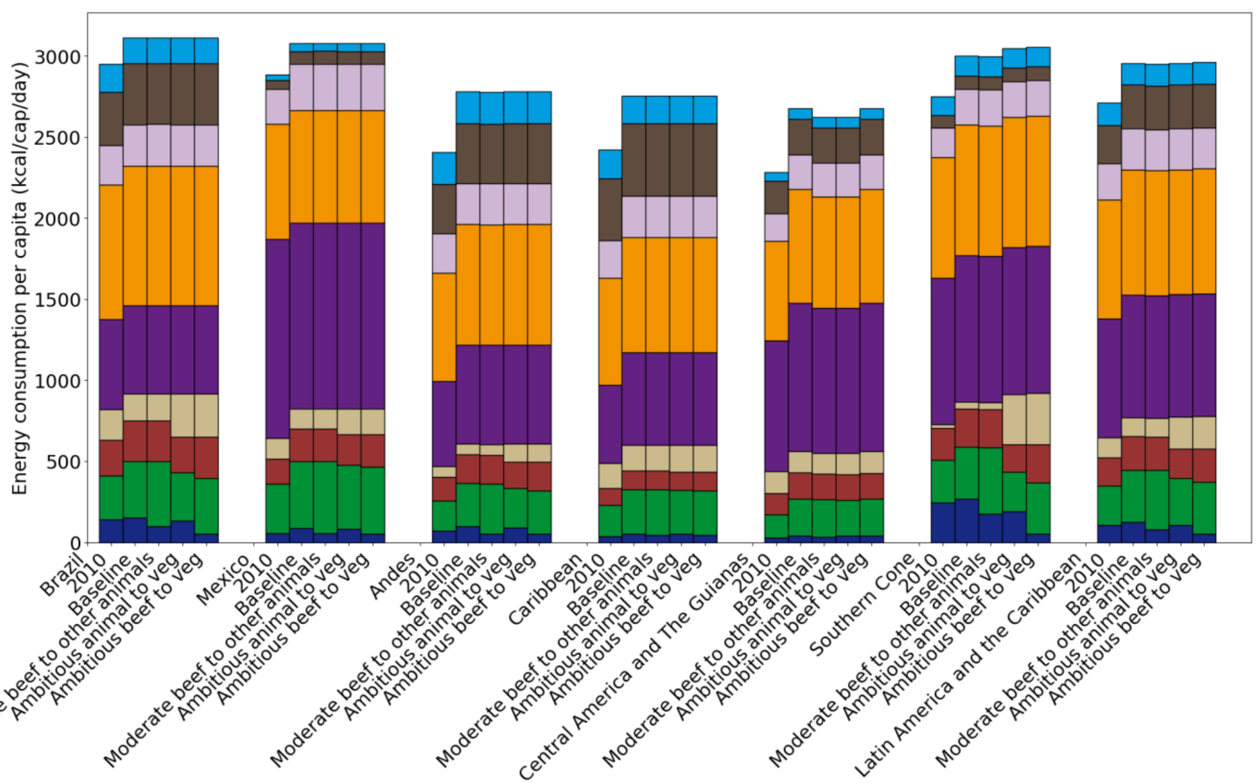
WWF, 2020. Living Planet Report 2020 - Bending the curve of biodiversity loss. World Wide Fund, Gland, Switzerland.

Zhang, X., Davidson, E. A., Mauzerall, D. L., Searchinger, T. D., Dumas, P., and Shen, Y. (2015). Managing nitrogen for sustainable development. Nature, 528:51–59.

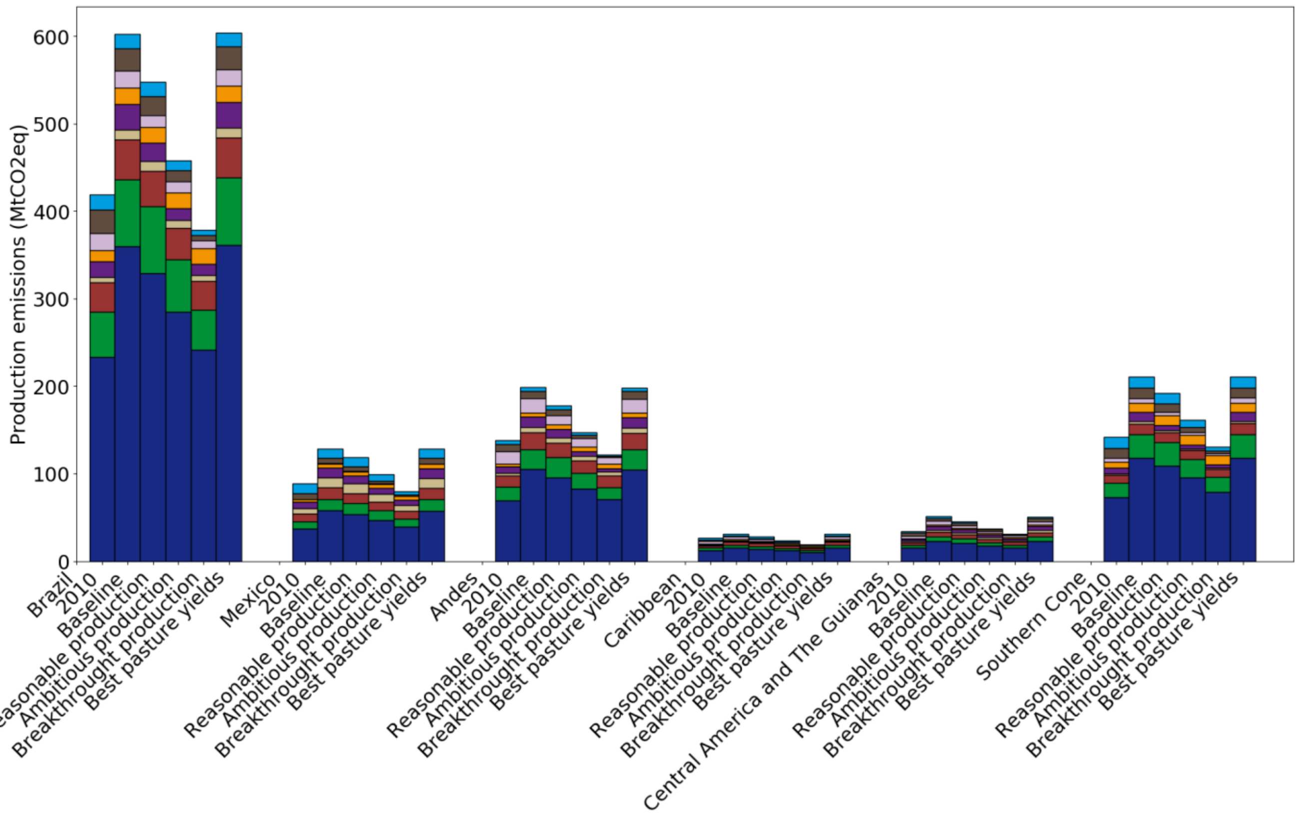
Zschornack, T., Bayer, C., Zanatta, J. A., Vieira, F. C. B., and Anghinoni, I. (2011). Mitigation of methane and nitrous oxide emissions from flood-irrigated rice by no incorporation of winter crop residues into the soil. Revista Brasileira de Ciência do Solo, 35(2).

Appendix

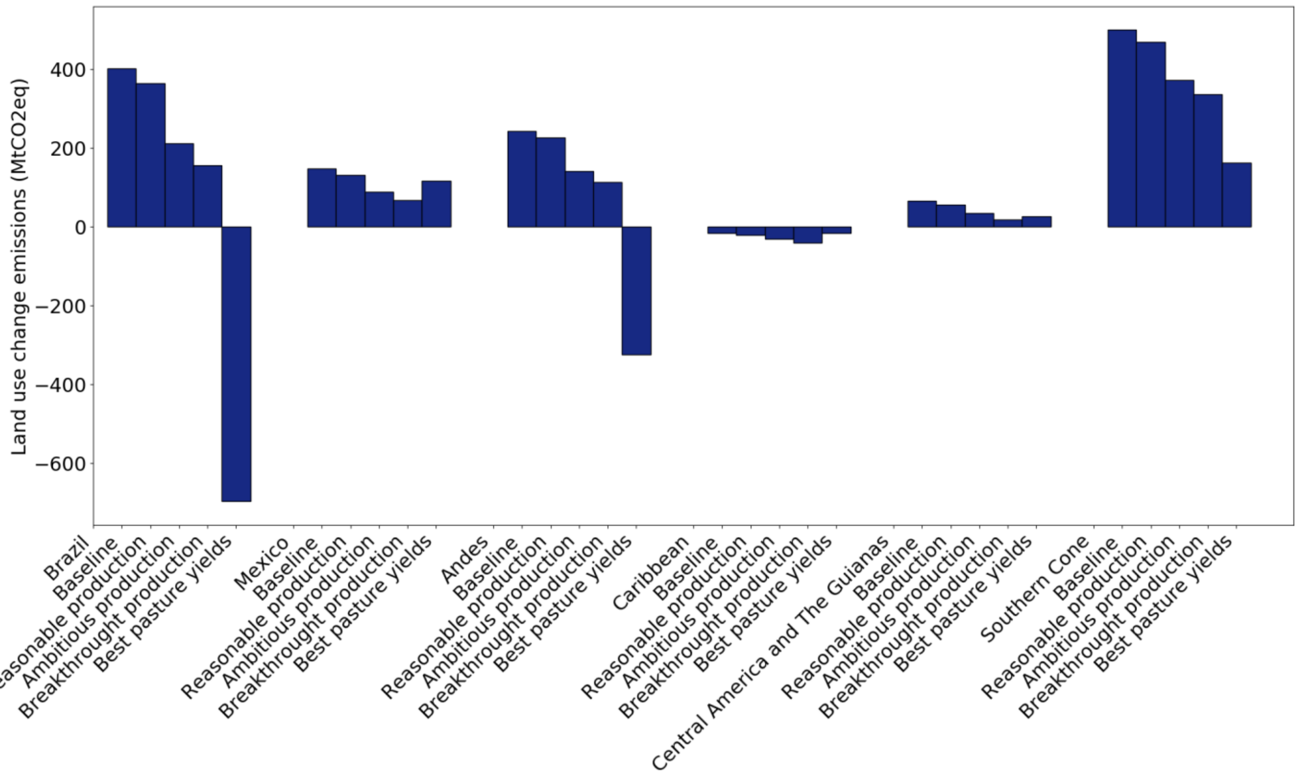

Available food energy per capita (kcal/cap/day)
0
500
1000
1500
2000
2500
3000
3500
Brazil
2010
Baseline
Moderate beef to other animals
Ambitious animal to veg
Ambitious beef to veg
Mexico
2010
Baseline
Moderate beef to other animals
Ambitious animal to veg
Ambitious beef to veg
Andes
2010
Baseline
Moderate beef to other animals
Ambitious animal to veg
Ambitious beef to veg
Caribbean
2010
Baseline
Moderate beef to other animals
Ambitious animal to veg
Ambitious beef to veg
Central America and The Guianas
2010
Baseline
Moderate beef to other animals
Ambitious animal to veg
Ambitious beef to veg
Southern Cone
2010
Baseline
Moderate beef to other animals
Ambitious animal to veg
Ambitious beef to veg
Latin America and the Caribbean
2010
Baseline
Moderate beef to other animals
Ambitious animal to veg
Ambitious beef to veg


Energy consumption per capita (kcal/cap/day)
0
500
1000
1500
2000
2500
3000
Brazil
2010
Baseline
Moderate beef to other animals
Ambitious animal to veg
Ambitious beef to veg
Mexico
2010
Baseline
Moderate beef to other animals
Ambitious animal to veg
Ambitious beef to veg
Andes
2010
Baseline
Moderate beef to other animals
Ambitious animal to veg
Ambitious beef to veg
Caribbean
2010
Baseline
Moderate beef to other animals
Ambitious animal to veg
Ambitious beef to veg
Central America and The Guianas
2010
Baseline
Moderate beef to other animals
Ambitious animal to veg
Ambitious beef to veg
Southern Cone
2010
Baseline
Moderate beef to other animals
Ambitious animal to veg
Ambitious beef to veg
Latin America and the Caribbean
2010
Baseline
Moderate beef to other animals
Ambitious animal to veg
Ambitious beef to veg

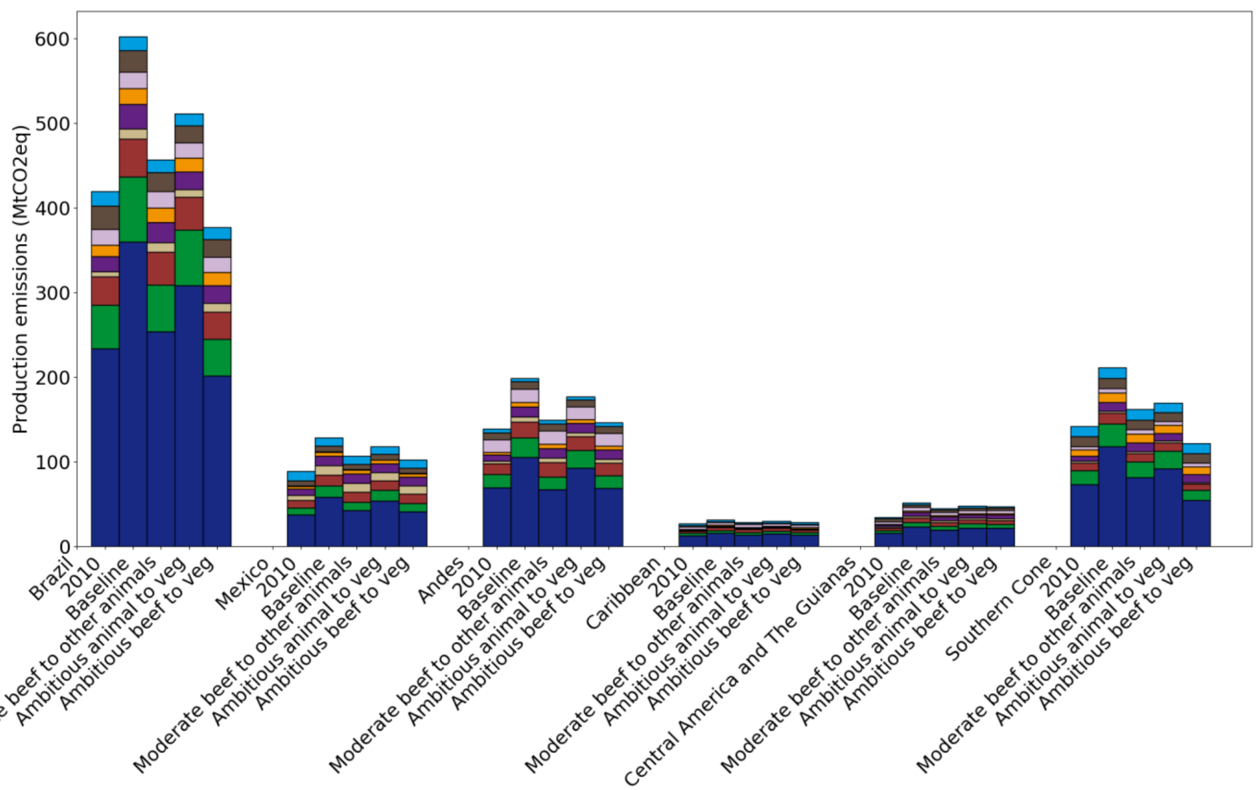
Appendix figure 1: Diets by region and scenario, in available (top) and consumed (bottom) energy



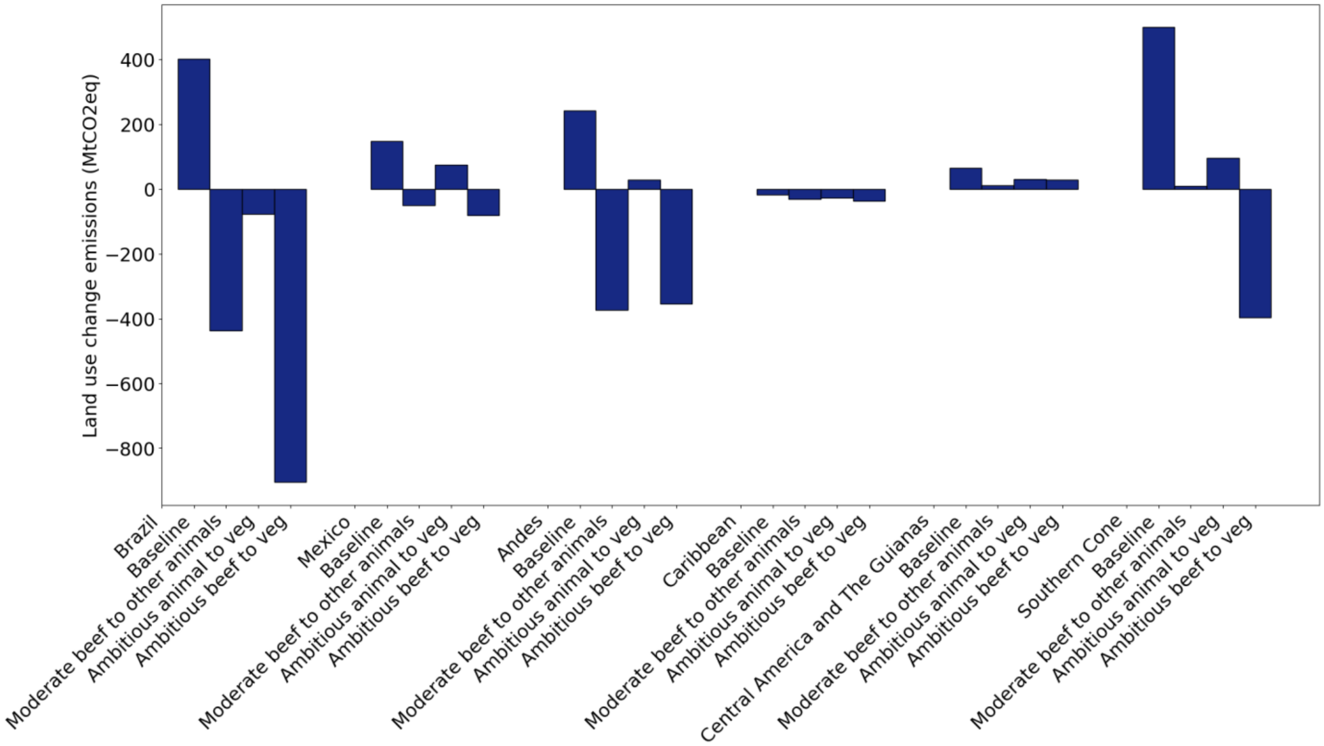
Appendix figure 2: Production emissions in supply side scenarios, by subregions



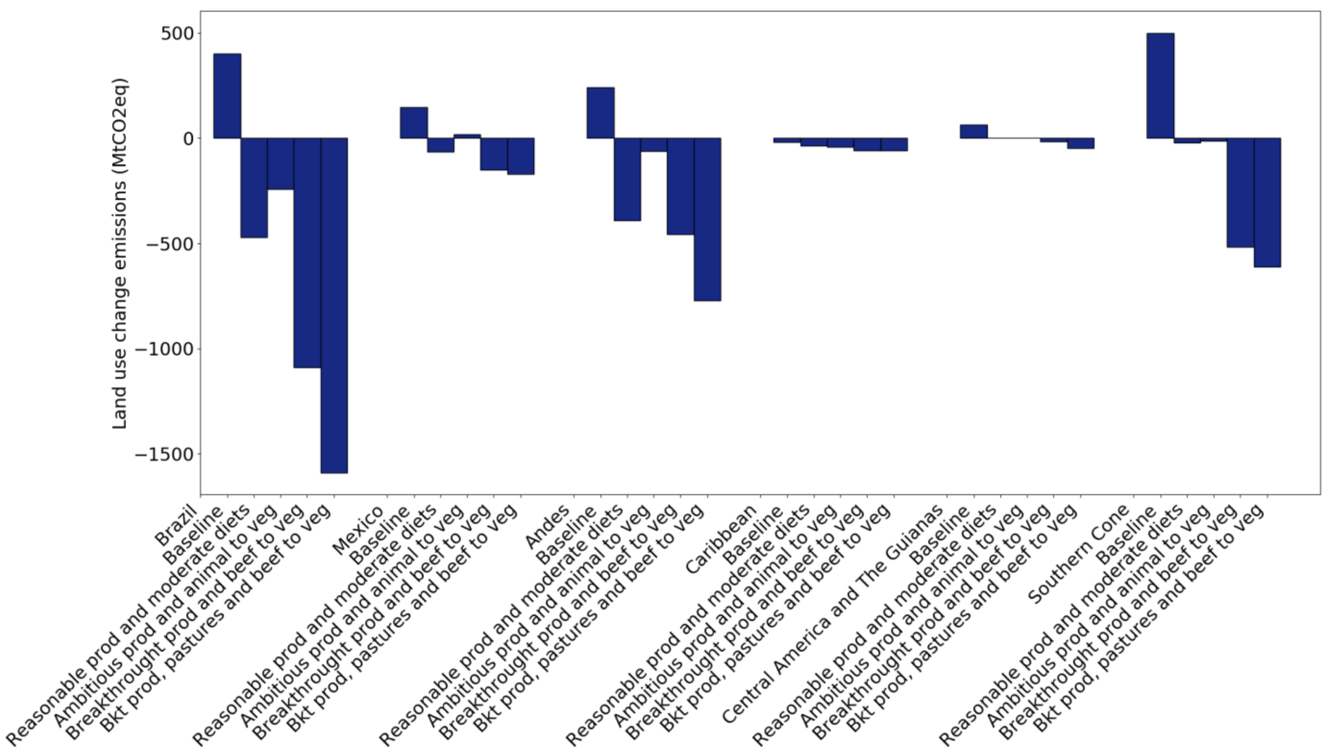
Appendix figure 3: Land use change emissions in supply-side scenarios, by subregion



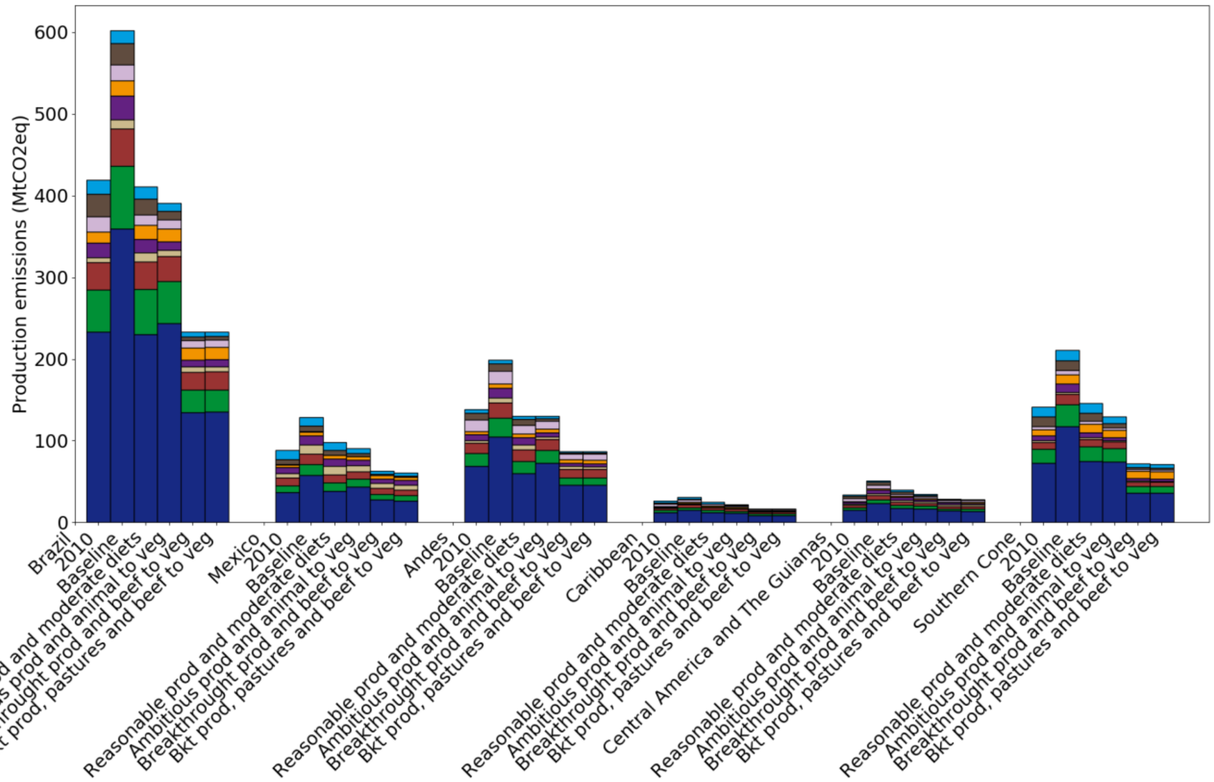
Appendix figure 4: Production emissions by diet scenario, by subregion



Appendix figure 5: Land use change emissions by diet scenario by subregion



Appendix figure 6: Land use change emissions, combined production and diet scenarios by subregion



Appendix figure 7: Production emissions, combined production, and diet scenarios

Brazil	1.85
Mexico	0.52
Andes	0.52
Caribbean	1.64
Central America and The Guianas	1.21
Southern Cone	0.47
Latin America and the Caribbean	0.95

Appendix table 1: Pasture yields in the reference year (2010) in tones of dry matter/hectare

	Beef (2010)	**Beef (2050)**	**Dairy (2010)**	**Dairy (2050)**
Brazil	38.5	30.7	2.63	1.92
Mexico	28.1	22.8	0.88	0.81
Andes	37.2	29.8	2.87	2.07
Caribbean	65.7	50	3.18	2.27
Central America and The Guianas	42.9	33.7	2.72	1.98

Southern Cone	27.5	22.8	1.04	0.9
Latin America and the Caribbean	35.3	28.3	2.12	1.62

Appendix table 2: Feed requirement coefficient, computed as total input feed dry matter divided by main product production quantity in tons of fresh matter (bovine meat for beef and raw milk for dairy), in tons of dry matter/tons, in the base year and in baseline projections.