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A low GHG development pathway design framework for agriculture, forestry and land use

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ABSTRACT

Agriculture, forestry and other land use (AFOLU) represent 22% of global greenhouse gas emissions. To meet the objectives of the Paris Agreement, the AFOLU sector greenhouse gases must be dramatically reduced and eventually transformed to net negative CO_2e within this century. The decarbonisation choices will have significant environmental, social and economic impacts, yet few analytical frameworks exist able to account holistically for AFOLU mitigation strategies and their sustainable development impacts in a way that combines advantages of global and national approaches to decarbonisation pathways. This paper proposes a pathway design framework for AFOLU decarbonisation strategies that can help governments set targets across four types of levers (increasing sequestration; improving the emissions efficiency of agriculture; incentivising dietary changes; and displacing fossil fuels with bioenergy) and help them navigate potential synergies and trade-offs with sustainable development objectives (notably food security, biodiversity preservation, poverty alleviation and job creation), in a way that facilitates co-construction and discussion with main stakeholders.

1. Introduction

The Paris Agreement established the global objective to hold the increase in the global average temperature "to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C" (Article 2.1). This requires reaching net-zero global energy and land-use CO_2 emissions and substantial reductions in other greenhouse gases (GHG) by 2050–2070, followed by net-negative CO_2 emissions thereafter [1,2]. The Paris Agreement highlights that these emission reductions should be implemented "in the context of sustainable development and efforts to eradicate poverty" and "in the light of different national circumstances" (Article 4.19). Long-term emission-reduction strategies (LTSs) can be used to reconcile the long-term global climate goals with medium term national development goals, and

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provide important insights for policy processes [3,4].

To achieve deep decarbonisation, the Intergovernmental Panel on Climate Change (IPCC) identified systemic transformations of the energy, industry, urban and land-use systems as necessary [5]. The land use system, also referred to as the AFOLU sector (agriculture, forestry and other land use) is responsible for 22% of global emissions [6]. The sector is unique in that it provides opportunities to decarbonize beyond mitigating emission sources, by increasing carbon sinks and replacing fossil fuel emissions with bioenergy in other sectors [7], albeit that later option requires carefully assessing trade-offs with food provision and biodiversity conservation goals. In this paper, we refer to the reduction of all GHG emissions and increases in carbon removals by land use as *decarbonizing* AFOLU. Actions to decarbonize AFOLU can benefit other sustainable development objectives, such as food security, biodiversity, land rights, jobs and poverty, but can also result in trade-offs with the same issues [5]. Given the global biodiversity and poverty crises, decarbonisation strategies for the AFOLU sector must maximise synergies and minimise trade-offs with these sustainable development objectives.

There are a number of studies and methodological frameworks that study the decarbonisation of AFOLU, including several global top-down models [8–10]. While these global models play a fundamental role in mapping out Paris-compatible decarbonisation pathways for the AFOLU sector, they represent existing land use, national circumstances, objectives and policy approaches at a relatively low resolution. Other models analyse AFOLU decarbonisation on the scale of regions or countries, and better capture national circumstances. However, these analyses generally lack the overarching global context provided by global models [3].

The Deep Decarbonisation Pathways (DDP) Initiative, which started with a project building low carbon development pathways for 16 major emerging and developed countries in the lead-up to the Paris Agreement focusing primarily on energy supply CO_2 emissions [11], has developed a method to bridge the gap between global IAMs and country-based studies on decarbonisation [3]. The DDP method describes the social, economic and technological transformation options to reach both development and emissions neutrality objectives. The pathway design starts from a description of the energy system and economic structure that could sustain these long-term goals and then works backwards to identify the medium and short-term transformations necessary for a region to evolve towards these goals. Each country has different circumstances and objectives; in order to ensure that these are taken into account in the pathways, the method emphasises a bottom-up and country-driven process [3,12].

Describing sectoral transformations (e.g. hectares of forest preserved) instead of focusing narrowly on GHG emissions is important for several reasons [3,4]. It facilitates discussing decarbonisation strategies with the sectoral ministries and private sector actors that will be physically responsible for implementing them (e.g., agriculture ministries and farmers). It also allows investigating and discussing how specific decarbonisation measures promote or hinder development objectives (e.g. preserving biodiversity). Finally, it allows for the identification of specific policy and regulatory measures to implement decarbonisation objectives (e.g., payment for ecosystem services to incentivize forest conservation).

The DDP in Latin America and the Caribbean (DDPLAC) project applied a similar method to the original DDP project to analyse low GHG development pathways constructed by national teams in Argentina, Colombia, Costa Rica, Ecuador, Mexico and Peru, combining an economy-wide analysis with sectoral deep-dives and covering most GHGs, including those associated with AFOLU. These analyses are covered in-depth in other papers in this special issue [4,13–19]. The initial AFOLU analyses were carried out with an accounting as opposed to physical driver-based framework, and experience from the project revealed the usefulness of a more comprehensive framework.

This paper proposes a comprehensive framework for low-GHG development pathway design for AFOLU, building on methodological insights drawn from the DDPLAC project. The framework is based on the general DDP method, and as such seeks to bridge the global insights from IAMs with the context-specific insights from bottom-up studies, while describing the physical transformation of the sector. This paper proceeds as follows. Section 2 provides an overview of the emissions in the global AFOLU sector. Section 3 reviews literature on decarbonisation in the AFOLU sector. Section 4 identifies key drivers of AFOLU transformation and the most important co-benefits and trade-offs with these drivers, and proposes a way of integrating them in an AFOLU pathway design framework. Section 5 discusses the objectives and main contributions of this pathway design framework, as well as how it addresses some key challenges identified in the literature review. Section 6 concludes and highlights questions for further research.

2. Overview of AFOLU greenhouse gas emissions

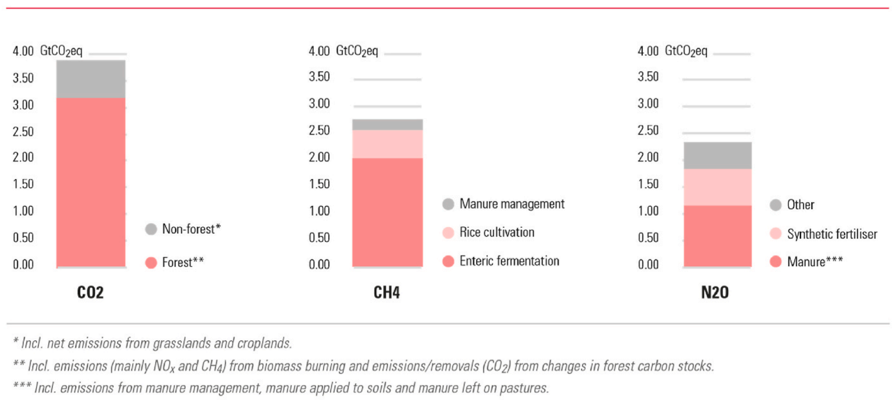
Any overview of emissions in the AFOLU sector is challenged by the significant uncertainties in sectoral emissions estimation [20,21]. Global AFOLU emissions were estimated to 9 $GtCO_2eq$/year over the period 2010–2017 by FAOSTAT, with CO_2 being the most significant gas, followed by CH_4 and subsequently by N_2O [22] (Fig. 1). For the agriculture subsector, CH_4 and N_2O emissions dominate, as most carbon fluxes (those from annual cultures) are considered neutral from one year to another. For the land use, land use change and forestry (LULUCF) sector, CO_2 is the principal gas [21]. Overall, AFOLU emissions increased by 2% between 2010 and 2017 [22].

Over the period, the agriculture subsector emitted an average 5.1 $GtCO_2eq$/year, with CH_4 emissions from ruminant enteric fermentation being the largest source. N_2O emissions from manure, including emissions from manure left on pasture, manure used as organic fertiliser and emissions from manure management, is second in importance. CH_4 emissions from rice cultivation and N_2O emissions from synthetic fertiliser application are other important emissions sources. Regarding the land use subsector (LULUCF), FAOSTAT estimates 3.9 GtCO2eq/year, with emissions from different forest activities accounting for the vast majority, including land conversions from forests to other uses (deforestation), and forest fires. Forests can both sequester and emit CO_2, depending on changes in the stock of biomass [23]. Organic soils, both peat and others, which emit CO_2 from organic matter in the soil when they are brought under (more) intensive management, are another significant source of emissions [22].

Historically, emissions from LULUCF have dominated AFOLU emissions, but recent research shows that agriculture became the major source of AFOLU emissions in 2010 [21]. This can be explained both by reduced emissions from deforestation in the 2000s, and a parallel increase in emissions from enteric fermentation and in manure and fertiliser emissions from managed soils [21,24].

3. Literature review

Although AFOLU is an important source of emissions, literature on decarbonisation tends to focus on energy production and energy-dependent systems (transport, industry, etc) while integrating non-energy emissions, including the LULUCF and broader AFOLU sector, through accounting frameworks [11]. Waisman et al. [3] describe a gap between ‘top-down’ oriented IAMs, coupling a biophysical and economic analysis of future interactions between the climate and the economy, and ‘bottom-up’ national modelling approaches to low-carbon pathways. The gap observed by Waisman et al. is largely applicable to literature that analyse AFOLU in an in-depth manner. On the one hand, certain IAMs with a detailed analysis of AFOLU decarbonisation, for example GCAM [8] and GLOBIOM [10], provide crucial insights regarding globally Paris-compatible AFOLU pathways but face challenges in their ability to represent specific country circumstances, objectives and policy approaches. On the other hand, country-oriented analyses of AFOLU pathways (e.g. Refs. [25–27]) are designed around



Source: FAOSTAT (2020)

Fig. 1. Global emissions from the AFOLU sector. Annual average 2010–2017. Source: FAOSTAT (2020)

country objectives and policies, but have so far lacked the overarching global approach of the IAMs, including consistency regarding key global boundary conditions, e.g. regarding carbon budgets, fossil fuel prices, imports and exports of key goods, and technology developments.

Apart from literature coupling a biophysical and economic analysis, another body of research focuses exclusively on biophysical dimensions. Without economic constraints, this work is better able to represent agricultural and land use realities (such as agronomic constraints). Nonetheless, research adopting a global geographical scope, e.g. Ref. [9], faces similar challenges to capturing national policy settings as IAMs, while regional- or country-oriented work, e.g. Refs. [28,29] often omit key global boundary conditions.

Little research exists that bridges the gap between globally and nationally oriented work. One example is work carried out by the FABLE Consortium, which seeks to capture national conditions and policy contexts and global boundary conditions in its pathway work. Their method starts from bottom-up country-oriented analyses, which are then aggregated to ensure coherence at the global level [30]. While this approach bridges the gaps between global pathways and country-specific bottom-up modelling, the framework not able to represent the diversity of possible strategies to redesign agricultural production systems (beyond input or resource efficiency or substitution, for instance through more complex crop rotation or crop association schemes, more complex agricultural landscapes or the synergies between crop- and livestock production). This limits the variety of pathways that teams from different national contexts can conceive with the tool.

Another example of work that seeks to bridge the gap between national and global analyses is the recently concluded DDPLAC project. This project included national research teams from Ecuador, Peru, Colombia, Mexico, and Argentina, who used quantitative national models to build scenarios looking at country GHG emissions and other national development priorities to 2050. A key objective of the project was to develop modelling capacity where it did not previously exist, and many teams did not have operational models at the start of the project. The scenarios built through these models were then articulated within a common reporting framework defined for the project, in order to ensure that results were comparable across countries [13] and to enable dialogue on key assumptions across different national contexts [3]. The framework's starting point is national pathways, and global coherence among different national scenarios and global Paris-compatibility is not ensured via quantitative 'hard' equilibria and constraints, but rather assessed narratively.

At its onset, the DDPLAC project focused on energy-related emissions. However, since AFOLU emissions constitute a large share of the region's GHG emissions, an AFOLU component was added to the project. As it was added late in the process, the sector was analysed with an emission accounting approach, focusing on tracking the evolution of emissions, agricultural production and land use until 2050, as opposed to the driver-focused method outlined in Waisman et al. [3] (a table illustrating the reporting framework used for AFOLU in DDPLAC can be found in table 3 in annex A). Nonetheless, certain countries chose to work with models providing significant insight into the AFOLU sector, depending on their national objectives. For instance, the Colombian team worked with GCAM since exploring the energy-AFOLU-water nexus was a key priority [13], while the Ecuadorian team's interest in bioenergy with carbon capture and storage (BECCS) and deforestation led them to work with a model with a geographically explicit and detailed land use representation [15] (please see Refs. [13–19] for a more comprehensive discussion on the different models used by the different country research teams). Nonetheless, many research teams reported difficulty in working with AFOLU, e.g. Refs. [16,31].

AFOLU pathway results in DDPLAC show that all six countries project declining AFOLU emissions from 2015 to 2050, and Costa Rica and Mexico show net negative emissions from the sector by 2050. Agricultural emissions increase in Argentina, Colombia, Ecuador and Peru, while they decrease in Costa Rica and Mexico. The reporting framework enables some insights into the underlying sectoral transformations. Forests, both new (afforestation) and old (forestland remaining forestland) are the key driver of AFOLU emission reductions – and forest surface increases in most countries. Indeed, increasing afforestation and slowing deforestation are key national objectives in multiple participating countries [14–17]. Increases in agricultural production explain the difficulty to reduce agricultural emissions. In general, pathways increase either livestock density or crop yields, and the land use for grazing decreases while that for crops increases. The reporting framework did not enable a detailed analysis of the *drivers* of transformation in the pathways, meaning that questions around the drivers of the reduction in deforestation and increases in crop yields or animal density are not addressed. A more thorough analysis of pathway results for AFOLU is available in Annex A.

To resolve the key issues discussed here, a new framework to design AFOLU pathways is needed which rests on 'bottom-up' principles to be able to accommodate national objectives and policy approaches, while enabling a discussion around key global boundary conditions and assumptions. To analyse the physical transformation of the sector and increase policy relevance, the framework must be oriented toward the drivers of AFOLU transformation.

Furthermore, capturing the AFOLU transformations co-benefits and trade-offs with key sustainable development objectives, such as no hunger (SDG 2), life on land (SDG 14), and jobs and poverty (SDG 1 and 8), is a broad challenge in the literature. Food security is taken into account by previous work, although frequently through the simplified lens of food availability which sidesteps complex issues of food *accessibility* [9], while biodiversity is often reduced to biodiversity on natural lands, leaving agricultural biodiversity out [32]. A DDP framework for AFOLU pathway design must be able to integrate an analysis of co-benefits and trade-offs on key sustainable development issues, in addition to being driver-oriented and bridging the gap between country- and global decarbonisation pathways.

4. From an accounting-based to a driver-oriented approach to AFOLU decarbonisation

Based on our experience with designing AFOLU pathways in DDPLAC, this section proposes an AFOLU pathway design framework oriented towards the drivers of transformation.

4.1. AFOLU key drivers and areas of co-benefit/trade-off

4.1.1. Drivers of transformation

Literature on AFOLU decarbonisation proposes many different individual mitigation options. Building towards a driver-oriented pathway design framework, we have synthesised individual mitigation options from the literature into four categories of decarbonisation drivers. The categorisation has been inspired by the compilation of drivers in the IPCC's Special Report on Climate Change and Land use (SRCCL) [6] and previous work on the transformation of AFOLU by Aubert et al. [33]. The literature and modelling work focuses on emissions mitigation in the AFOLU sector tends to emphasise drivers linked to land use [34]. While reducing deforestation and increasing afforestation have been dominant topics in the past, with agricultural emissions surpassing those of land use according to some estimations (see section 2), more emphasis is needed for drivers for reducing agricultural emissions [21].

4.1.1.1. Land use and land use change to maximise carbon sequestration. Until bioenergy or direct air capture with carbon capture and storage (BECCS or DACCS) or enhanced weathering are mastered, AFOLU is the only sector capable of bulk negative emissions [34]. All pathways compatible with a 1.5 °C trajectory in IPCC's report on the impacts and pathways associated with 1.5 °C global warming (SR15) rely on land-based carbon dioxide removal (CDR), including afforestation and BECCS, which underscores the fundamental importance of land-based negative emissions for achieving the Paris goals. To generate the negative emissions necessary in a majority of scenarios compatible with 1.5 °C (50–150 $GtCO_2$), more than 1% of the earth's land surface (1.7 million km^2) must change land use to support CDR technologies [34]. This recourse to CDR have been critiqued for overestimating their potential for negative emissions [35]; and, in the case of BECCS, for risking transgressions of several planetary boundaries (freshwater use, biosphere integrity and biogeochemical flows) [36]; and for being costly [37]. Maintaining existing carbon sinks is another way of maximising carbon sequestration in AFOLU, principally through reducing degradation and loss of forests and peatlands [6]. Both forests and peatlands stock immense quantities of carbon globally [38–40], and are important sources of CO_2 emissions (1.4 GtCO2/year for 1990–2010 and 1 GtCO2 in 2010 respectively) [21,36].

4.1.1.2. Bioenergy for fossil carbon substitution. Bioenergy can replace fossil fuels [1], and is generally accounted for as a low emission fuel, with high variability depending on the supply process [41]) since GHG gases emitted during the combustion of biomass are sequestered again as harvested biomass grows back [21]. The emissions generated from the harvest and combustion of biomass for bioenergy are then re-sequestered on a time-scale depending on the cultures used. Bioenergy production, with or without carbon capture and storage (CCS), is used as a driver of decarbonisation in many of the scenarios achieving 1.5 °C temperature increase in the SR15 report. These scenarios rely on 40–310 EJ/year from biofuels [34], which depend on significant land use change at a rhythm considered unrealistic by some authors [42]. Furthermore, the status of bioenergy as a low-carbon fuel has been challenged, for instance Searchinger et al. [43], demonstrate that lifecycle cost analyses tend to underestimate the impact of bioenergy on emissions because they neglect the opportunity cost of dedicating land for fuel instead of food or reforestation.

4.1.1.3. Reducing the emissions intensity of agricultural production. Agricultural emissions constitute more than half of AFOLU emissions, and although generally identified as a 'hard-to-abate' sector, there are numerous options to reduce the emissions intensity of agricultural production. For instance, N_2O emissions from managed soils can be mitigated by reducing excessive nitrogen fertiliser application [44]. Research suggests that more than half of the nitrogen applied to managed soils is lost to the environment, and thus not taken up by plants [45]. Another example involves reducing CH_4 emissions from enteric fermentation through modifications of the diets of cattle. Recent research indicates that emissions reductions of up to 30% are possible if chemicals are added to cattle feed [46], and other research shows emissions per cattle can be reduced by 24% by reducing the share of lipids and nitrates in diets [47].

4.1.1.4. Diets and food waste. Changes in dietary preferences away from emission intensive products, notably animal products, could drive emission reductions [48,49] and is identified as an important driver in the SR15 [5]. This applies more to industrialised and emerging economies, where emission intensive food products constitute a more important share of the diet than in developing countries. Reducing food waste is another important driver of AFOLU decarbonisation [5]. An estimated 30% of all food produced is wasted post harvest [50]. In developing countries, the losses take place during transport and storage, while in industrialised countries they occur in households at the final consumer [50].

4.1.2. Synergies and trade-offs with other sustainability objectives

Decarbonising AFOLU will impact multiple sustainable development objectives (SDG's), either through synergies or trade-offs. Following a review of the IPCC's recent report on climate change and land use (SRCCL) [6], IPBES 2019 Assessment of biodiversity [51], and the SR15 and the Paris Agreement's recognition that mitigation must take place in the context of poverty eradication efforts, we have shortlisted food availability and security, biodiversity and poverty reduction (SDGs 2, 15 and 1) as the most important SDG's.

4.1.2.1. Food availability and security. Emission mitigation actions that reduce the amount of food available for human consumption – at a local, regional and global level - risk negative effects on food availability [40]. Mitigation actions that are intensive in land use run this risk, such as afforestation and bioenergy production. Increases in the food productivity, improvements in agricultural land management [6], and dietary shifts away from animal products all have co-benefits with food availability by increasing the amount of food available for human consumption (dietary shifts do this by reducing land use for feed production [49,52] and the share of grains and legumes used as feed instead of food for humans [53]). In many developing countries, where animal products constitute a low share of the diet [54], further reductions may come with costs to human nutrition and health.

4.1.2.2. Biodiversity. Both natural lands and agricultural landscapes harbour a rich biodiversity [55–58]. Activities in AFOLU affect both [59], and the effect depends on the decarbonisation pathway pursued

Table 1
Elements included in the DDP AFOLU storyline.

Elements in the storyline (including discussion of their importance and how they are informed)	Driver of transformation & sustainable development objective
Macro-elements	
Total population and population distribution. • The **population size** informs overall domestic demand for food and for land for settlements. • The **rural/urban distribution** of the **population** provides insight into the share of the labour force that is available for agriculture; an important factor in the agricultural transformation.	**Diets**; **food security**; **agricultural jobs and poverty;** and **land use.**
GDP per capita. • Explains changes in the **overall demand for food** in contexts where poverty limits the overall calorie intake. • Explains **composition of diets**. GDP per capita has a positive correlation with meat consumption, up to GDP per capita incomes of 35–53 000 USD (at 2005 constant prices), whereafter per capita meat consumption stagnates or decreases as per capita income grows further [69].	**Diets;** and **food security**.
International trade and foreign demand. Exports and imports of agriculture and forestry products are a component of overall demand, and the storyline tracks the key assumptions made on foreign demand and domestic imports.	General impact on the production mix and indirect impact on a broad range of drivers and SDGs.
Crop and livestock production. The storyline analyses the following dimensions: • **Crop and animal productivity** and what methods and technologies (e.g. nitrogen application, animal feed) are used to ensure this productivity. This provides crucial information on the land use and **environmental** impacts of agriculture. • Practices that enable **carbon storage on agricultural lands** (e.g. silviopasture, agroforestry and practices increasing the soil carbon content). The way these practices are integrated in agricultural production **informs** opportunities for carbon sequestration, but also provides important information regarding agricultural biodiversity. • **Systems of production**. Given the intricate ways in which agricultural practices are inter-linked (for instance, the capacity to use animal manure as a fertiliser on managed soils depend on the proximity of animal production to crop production), the storyline looks at these questions through the **prism** of *systems of production*, such as conventional agriculture, organic agriculture.	Crop and livestock production have a broad impact on the sector, notably on the **emissions intensity of agricultural production**, the land use available for **carbon sinks** and **bioenergy production**, **biodiversity**, and **food security**.
Forests and peatlands. The storyline explores the drivers of losses and gains of forest- and peatland. Globally important drivers that are explicitly covered in the storyline include the conversion of forests and peatlands to agricultural commodity production [38,70–73], with beef, soy, and palm oil being key commodities [74]; wood harvesting (commercial exploitation or firewood harvesting) [72,73], and natural disturbances [73]. Land tenure and improved forest monitoring are identified as levers to reduce deforestation [75,76].	**Increased carbon sinks through land use**; **biodiversity**.
Bioenergy demand and production. • The storyline analyses the evolution of **demand for bioenergy** from other sectors and countries. • The **production of biomass** is and its land use is analysed, particularly by exploring whether biomass comes **from** dedicated crops and forestry plantations (as opposed to residues and co-products).	**Bioenergy; land use for carbon sinks; biodiversity.**
Food prices and the share of income spent on food. The storyline analyses the share of household income spent on food, as well as the evolution of food prices. A combined analysis of these two elements provide insight into the choices that consumers can make with regards to their food purchases and their diets, and a household's access to food.	**Diets; food security**; **agricultural production**.
Consumer habits and preferences regarding food consumption. Culture and consumer habits and preferences are an important driver of dietary change and for food waste, and social norms will play an important role in future dietary changes [77]. This part of the storyline describes how these preferences evolve, especially with regards to the consumption of animal products and food waste.	**Diets; food security**; **agricultural production**.

[60]. Agricultural expansion is a key driver of biodiversity losses on natural lands globally, while intensive agricultural production practices, such as water withdrawals, chemical inputs, high animal densities, and monocultures, harm biodiversity and ecosystem regulation services on agricultural lands [59]. Systems of agricultural production that limit abovementioned practices (such as agroecology and low-density animal rearing) could improve biodiversity on agricultural lands [55,61], whereas mitigation options that spare existing or regenerate natural lands, such as reforestation, can have synergies with biodiversity on natural lands [62].

4.1.2.3. Poverty and jobs. The agriculture sector is the largest employer worldwide, and the largest sector in many economies [63]. Furthermore, the incidence of poverty is high among agricultural workers, as many of the world's poor work as smallholder subsistence farmers outside of the formal sector [64]. Some research show that decarbonisation, as compared to business-*as*-usual scenarios, could have positive employment impacts in agriculture in LAC [65]. Furthermore, different decarbonisation pathways are likely to have different impacts on agricultural jobs: organic farming is shown to be more labour intensive than conventional farming in Europe [66], and there are vast differences in labour intensity between mechanised and non-mechanised agricultural production [67]. Nonetheless, the employment- and poverty impacts of specific AFOLU decarbonisation pathways are still poorly understood, and require further research.

4.2. A concrete description of the DDP AFOLU pathway design framework

Following the identification of key drivers of transformation and

Table 2
Indicators included in the DDP AFOLU dashboard.

Category	Indicators
Greenhouse gas emissions	In order to facilitate an analysis of the physical transformation of AFOLU, the dashboard uses IPCC's activity-based emissions categories. - Emissions from forestland loss, forestland gains and from land remaining forestland ($MtCO_2$/year) - Net emissions from grasslands ($MtCO_2$/year) - Net emissions from croplands ($MtCO_2$/year) - Emissions from peatlands ($MtCO_2$/year) - Emissions from enteric fermentation ($MtCO_2eq$/year) - Manure management ($MtCO_2eq$/year), accounting for N_2O and CH_4 emissions in separate categories - Fertiliser application, differentiated according to organic and synthetic fertilisers ($MtCO_2eq$/year)
Consumption of AFOLU products	
Diets	The dashboard tracks the daily per capita calorie intake (kcal/cap/day) of different food product categories, taken from FAOSTAT. These include dairy products, ruminant meat, other meat, rice, other cereals, roots and tubers, oil crops, sugar crops, legumes, and fruits and vegetables.
Food waste and losses	- Post-harvest food losses (losses during storage, transport and retail) (Mt/year) - Food waste at the final consumer (Mt/year).
International trade	Trade in net flows (exports – imports) according to the same product categories as for diets, plus wood products (tons/year).
Animal production	- Total animal production, including both milk and meat (in kcal/year and tons/year). - Evolution of animal herds of cattle, sheep and goats, pigs, and poultry (animal heads). - Evolution of animal milk (l/head/year) and meat productivity (carcass weight at slaughter) for the same species (milk only for the first two categories). - Animal density (livestock in LU/hectare of agricultural land)
Crop production	- Total crop production (in kcal/year and tons/year). - Crop yields (ton/ha/year) for key crops, including sugar cane, soy, maize, rice, wheat, bananas, oil palm, coffee, cotton. The crops selected reflect globally important crops for trade, GHG emissions, and calorie intake. - Cropping intensity (harvests per year). - Application of synthetic and organic fertiliser (ton/ha/year).
Land use	The evolution of land use in hectares of land use categories used in the IPCC emissions inventory for AFOLU, including cropland; grassland, including separate categories for natural grassland and grassland for grazing; forestland, including separate categories for natural and plantation forests; wetland; settled land; and other land.
Biogenic sink and forestry	- Annual loss of natural forest (ha/year) - Forest density (ton biomass dry matter/ha) - Sequestration rate (ton biomass dry matter/ha/year) - Timber and non-timber forest products harvested (ton/year) For the last three indicators, the dashboard distinguishes between natural and plantation forests due to their different carbon and biodiversity dynamics. Regarding the former, plantation forests are sometimes considered to sequester at a faster rate [23], while natural forests have a higher carbon density [78]. Regarding the latter, natural forests support a richer biodiversity [79].
Bioenergy production	- Land use for bioenergy production (ha) - Total bioenergy produced (EJ/year) - Share of bioenergy produced by dedicated energy-crops and forest plantations (% of EJ/year)
Biodiversity	The dashboard analyses both biodiversity on natural and agricultural lands. - Pesticide application (kg/ha) - Surface of natural lands, including forests, wetlands and natural grasslands (ha) - Protected lands (ha)
Food security	- Share of population in undernourishment.

sustainable development issues to be covered by an AFOLU pathway design framework, we translated this into a *storyline* and a *dashboard* component, building on the general pathway design framework proposed in Waisman et al. [3] and the translation of the same into a pathway design framework for personal transport [68].

4.2.1. DDP AFOLU storyline: analysing the underlying drivers of transformation

The DDP pathway design framework for AFOLU developed the *storyline* method component, with the objective to qualitatively or semi-quantitatively describe the underlying drivers of transformation in AFOLU and the impacts on key sustainable development issues identified in section 5.1 of this paper. The storyline is structured according to the underlying drivers that impact the issues discussed in section 4.1. For instance, the storylines do not analyse a pathway's impact on biodiversity and what role biodiversity plays in a pathway through open-ended questions, but by identifying factors that impact biodiversity, such as the demand for land use change from bioenergy production and carbon sinks, forest management practices, and agricultural production practices. Table 1 provides an overview of elements included in the storyline with a discussion of how they inform the levers of transformation and sustainable development objectives identified in section 4.1 of this article (the links between the storyline elements and the drivers and issues from section 4.1 are not exhaustively demonstrated).

4.2.2. DDP AFOLU dashboard: cross-pathway comparisons and pathway design iterations

The dashboard synthetically represents the pathways outlined in the storylines in a way that is easily comparable across pathways and countries. Concretely, the dashboard consists of a set of quantitative indicators that informs the same drivers and sustainable development issues as the storyline, focusing on the evolution of straight-forward quantifiable and comparable indicators rather than on their underlying drivers. An example of these differences is the way the two method components analyse land use changes. The dashboard maps the evolution of land use change according to different land use categories, while the storyline analyses the drivers of these land use changes, including the agricultural production systems and their land intensity, food demand and diets, forests and bioenergy. It is important to note that the dashboard itself provides insights to explain the land use changes that it displays, since it tracks dietary changes, agricultural productivity, etc. However, the quantitative format of the dashboard mean that these links are not made explicit. The dashboard leaves out certain dynamics included in the storylines in the interest of providing a synthetic analysis. An example is the systems of agricultural production, which the storyline treats under the element *agricultural production*. Table 2 describes the indicators of the dashboard.

4.2.3. The DDP AFOLU supporting tool

The storyline and dashboard take into account the full list of drivers and sustainable development issues discussed in section 4.1, with a few exceptions (discussed below). The wide diversity of information required to inform this broad range of issues mean that no single model will be sufficient: a combination of mathematical models and other tools will be necessary [11]. The DDP AFOLU pathway design framework proposes a supporting tool to help the method's users in two ways. First, the tool is designed to enable the collation of information from different models into one pathway while ensuring that this pathway is internally consistent. Second, the tool facilitates complementing parts of the storyline and the dashboard that the user cannot inform through an existing model, by proposing key variables on which assumptions can be made and aggregating these into coherent results.

The supporting tool that has been developed to perform these tasks is not a mathematical model, in the sense that it does not optimise according to predefined principles. It is rather a biomass equilibrium calculator, that breaks down the consumption and production of AFOLU products, the associated land-use, and the biomass dynamics of forests. Based on this, it calculates the emissions generated based on the IPCC guidelines for accounting for AFOLU emissions. The AFOLU sector has numerous internal biophysical equilibrium, and to ensure internal consistency of pathways, the calculator enables users to verify that key equilibriums are respected, including biomass production and consumption and land use. At the same time, the tool includes a relatively rich description of the physical transformation of the sector, in order to enable users to choose the mitigation actions that are domestically relevant. The objective to integrating a detailed analysis of the physical transformation and key biophysical equilibriums have been balanced with the goal of avoiding a technically complicated tool. The tool represents a first attempt at helping users of the method to inform the full range of issues covered by the storyline and the dashboard in a consistent manner, and remains a work in progress. It is described in further detail in Annex B. The excel document can be accessed online (please see Annex B for information on access and further description).

5. Objectives and contributions of the DDP AFOLU pathway design framework

5.1. Key contributions of the DDP AFOLU pathway design framework

This section discusses some of the methodological choices made for the development of the DDP AFOLU pathway design framework, and the objectives of the method.

The AFOLU reporting framework used in DDPLAC focussed on quantitative indicators, without a systematic approach to the narratives underlying the pathways. Pathway narratives enable an analysis of the drivers of transformation, and the identification of actionable policy levers. Hence, the *storyline* component of the DDP AFOLU method has been developed to propose a systematic approach to pathway narratives around the underlying drivers of the AFOLU transformation, such as the role of forest monitoring and land tenure in driving reductions of deforestation.

Furthermore, the accounting framework to AFOLU pathways in DDPLAC did not enable a detailed analysis of the physical transformation of the sector (e.g. detailed mitigation options and a systematic reporting of disaggregated activity-based emissions sources). The lack of adequate detail on the physical transformation of fundamental drivers is a wider problem among decarbonisation pathways [3,80,81]. Nonetheless, unpacking the transformation associated to the emissions pathways is important, not least for the policy relevance of the analysis. The dashboard provides this detail by integrating the evolution of emissions and key indicators regarding the consumption and production of AFOLU products.

A key contribution of the DDP AFOLU pathway design framework is its comprehensive approach to the sector, integrating the drivers and most sustainable development issues covered in section 4.1. This comprehensive approach is important: actions on one of the levers predicates the range of possible actions on others, in particular through land use, and analysing and discussing levers of decarbonisation in isolation obscures these systemic aspects of the AFOLU sector. Furthermore, the way in which they are combined, and in particular the relative importance given to each of them in an overall decarbonisation strategy, has effects on the trade-offs and synergies with other sustainable development objectives, not least those discussed above.

These points merit further elaboration, and the debate around the *land sparing* and *land sharing* strategies illustrate well the systemic dimensions of AFOLU. In a *land-sparing* approach [82], the priority is to set aside land to increase the carbon sink, produce bioenergy and preserve biodiversity on natural lands [83]. This is achieved through agricultural intensification [82], and dietary shifts away from land intensive products such as meat and dairy products. The dietary shifts are likely to reduce CH_4 emissions from livestock. At the same time, the intensification of agricultural production is likely to be associated with practices that increase agricultural emissions through increased fertiliser application to soils, and are harmful to biodiversity [84], such as pesticide application and landscape simplification. In *land-sharing* strategies [28,29], a key objective is to preserve agricultural biodiversity through agroecological solutions to agronomic challenges [28,85], which limits potential for further yield increases. Dietary shifts away from animal products has positive impacts on the quantity of food available for human consumption. However, ruminant animals are needed to maintain biodiversity-rich grasslands, and hence emissions reductions from dietary changes are more modest than in the former strategy. Following more moderate dietary shifts and productivity increases, this strategy cannot free up as much land for forests as a land-sparing strategy, limiting benefits for carbon sequestration and natural biodiversity conservation.

These two examples illustrate well the importance of comprehensively analyzing the transformation of AFOLU. However, informing the full set of issues covered in the storyline and dashboard is challenging. Teams in DDPLAC found informing the full range of issues in the less comprehensive reporting template used in the project (see Table 1 in Annex A) challenging, without further assistance. Hence, the supporting tool, capable of helping teams inform the vast majority of storyline elements and dashboard indicators in a way that is internally consistent, provides crucial assistance for users of the DDP AFOLU pathway design framework.

The first version of the DDP AFOLU supporting tool developed for this paper integrates an analysis of all drivers discussed in 4.1, but integrates an analysis of the co-benefit/trade-off issues to a lesser extent. Food security is treated primarily through the prism of food availability, while questions around the access to food are not addressed. Biodiversity is primarily treated indirectly, by an analysis of key agricultural practices and land-use changes that are proven to impact biodiversity. Poverty and jobs are completely omitted from the first version of the tool. Improving the analysis of these co-benefit/trade-off issues is a key objective for the further development of the tool.

One of the key objectives of the DDP AFOLU pathway design framework is to develop a shared language among researchers and stakeholders and enable co-construction of pathways among researchers and stakeholders. The storyline, formulated in a non-technical language and exploring actionable policy levers in AFOLU, is an important building block of this shared language between researchers and stakeholders. The dashboard contributes to cross-country dialogues and knowledge sharing among researchers through by enabling cross-country comparisons of pathways and their assumptions. Furthermore, together, the dashboard and the storyline contribute to an iterative approach to pathway development. The quantitative representation of key indicators of the pathway in the dashboard help stakeholders and sectoral experts to check the consistency with policy objectives and of the feasibility of the transformations as defined in the storyline [68]. This iterative approach therefore contributes to engendering dialogue with stakeholders around the pathways, which is important for stakeholder buy-in and policy impact.

Crucially, the framework proposed does not seek to replace existing models, but rather to be used as a complement to them by enabling an iterative process in which modelling results can be assessed and complemented with information not provided by the models using the reporting framework provided. It follows that the proposed framework's key addition to existing analytical frameworks of AFOLU pathways is not its level of detail in any particular area of AFOLU. Existing models excel in their analysis of the precise areas that they have been designed to analyse. For instance, GLOBIOM provides a detailed analysis of the physical transformation of the AFOLU sector [10,86], and GCAM captures well the interactions between the land use system and other key systems, like the water and energy systems [8]. However, the same models struggle to analyse with detail areas that lie beyond their key focus. Our approach will complement previous analytical work in that it systematically takes all above identified drivers of transformation into account and comprehensively build and analyse AFOLU pathways, and avoids predominantly focusing on one or a subset of drivers, as is sometimes done elsewhere [34]. Thereby it captures the systemic dimensions of the AFOLU sector and synthetically characterises decarbonisation strategies. Furthermore, the framework is also unique in its systematic approach to pathway narratives – which facilitate engagement with non-experts and enhance policy relevance of the pathways.

5.2. The Peruvian AFOLU pathway: an example of an AFOLU analysis going beyond an emission accounting approach

Although the reporting framework for AFOLU used in DDPLAC did not facilitate an analysis of the sectoral drivers of decarbonisation, the Peruvian team's analysis of AFOLU went beyond the accounting approach used in the reporting framework and narratively analysed the drivers of transformation in detail. This analysis did not use the framework proposed in this method, but builds on similar principles regarding the role of narratives, and regarding the holistic approach to decarbonisation drivers.[1] Hence, it will be used here as an example providing insights into the methodological choices made in the development of the DDP AFOLU pathway design framework proposed in this paper.

The LULUCF sector account for a majority of Peruvian emissions (50.6% in 2012), and reducing deforestation was therefore a key objective in the Peruvian team's AFOLU pathway. The Peruvian team worked with the Policy Analysis System (POLYSIS) model, due to its flexibility in modelling land use and a wide variety of market structures [17]. Coupled with this model, they used the AFOLU reporting framework used in DDPLAC, and developed relatively elaborate pathway narratives. The accounting framework used for AFOLU in DDPLAC shows that AFOLU emissions reduce by 58% between 2010 and 2050, mainly thanks to LULUCF emissions, which fall by 74%, while agricultural emissions increase by 17%. The reduction in LULUCF emissions stem from drastic but not complete reductions in deforestation. At the same time, increases in animal grazing density and agricultural yields indicate that agricultural production is intensified, while agricultural land use increases.

The pathway narrative, often described with quantified hypotheses, enables an understanding of the underlying transformation and focuses on explaining the reduction in deforestation. Looking at land use change, the most important direct driver is the reduction in agricultural expansion [17]. However, to engage in dialogue with stakeholders and policy makers, the underlying processes driving deforestation and agricultural intensification must be identified. Multiple processes are discussed in detail in De La Torre Ugarte et al. (2021) [17], three of which will be discussed here. Firstly, the lack of enforced land rights is identified as a driver of deforestation in Peru, and the pathway involves an extension of land rights to areas where they are not currently existing or enforced. Secondly, rural poverty explains deforestation in multiple ways, for instance through poor rural communities' dependence on clearing primary forest to replace loss of agricultural soil productivity. Hence, the pathway sees numerous interventions to reduce rural poverty. Thirdly, rice in the coastal- and amazon regions is frequently cultivated using flooding techniques causing important methane emissions, while the expansion of rice in the amazon region drives deforestation. Hence, the pathway sees dietary shifts away from rice and toward roots and tubers - all while the daily per capita calorie intake increases in Peru, meaning that food availability improves. This transformation comes with a co-benefit in revenues to smallholders in the Peruvian highlands, who produce a large share of the roots and tubers in Peru [17].

The pathway narrative proves to be essential for understanding the drivers of transformation, and for identifying actionable policy levers. Furthermore, the narrative underscores the necessity of a bottom-up approach, by fundamentally relying on country-specific circumstances and objectives. The overall analysis demonstrates the usefulness of integrating many of the drivers identified above: the Peruvian team's work on diets enables the identification of an additional transformation for reducing deforestation. Furthermore, the insights regarding potential socio-economic benefits to smallholder farmers in the highlands of shifting dietary preferences exemplifies how integrating key sustainable development objectives into pathways enable researchers and policy makers to propose pathways and mitigation options that exploit the potential synergies with other development objectives.

6. Conclusion and further research

This paper has proposed a comprehensive low-GHG development pathway design framework for AFOLU, which is informed by gaps identified in the literature, the experience of working with AFOLU pathways in the DDPLAC project, and by a review of key drivers and sustainable development issues identified for the sector. The proposed analytical framework integrates country specific conditions and policy outlooks through its bottom-up approach, starting with the development of country scenarios for which global coherence and Paris-consistency is ensured through a narrative approach. Furthermore, the framework seeks to enable a detailed analysis of the physical transformation of the sector, while providing sufficient flexibility to integrate a multitude of mitigation options according to national conditions and priorities. As mentioned above, the framework seeks to complement existing quantitative prospective models by providing a structure that modellers can use to collate information from different models, or to integrate dimensions of the AFOLU transformation not covered by any model at their disposal, in order to arrive at a comprehensive analysis of the AFOLU transformation.

Capturing co-benefits and trade-offs with food security (beyond looking at the national availability of food), biodiversity, jobs and poverty remains a challenge in the proposed pathway design framework, although advances are made regarding the description of the biodiversity impacts of the pathways comparing to the framework used in DDPLAC. Hence, further research is required to better integrate an analysis of the co-benefits and trade-offs SDG's. This is particularly true for jobs and poverty, a subject currently not treated by the method. Studies on the biophysical and the socioeconomic aspects of the transformation of the agriculture sector exists in silos. Some studies explore the historical interactions between the two [87,88]. However, little research exists on the interactions between decarbonisation, wages and jobs in the agriculture sector. Capturing the dynamic between the decarbonisation and the socio-economic transformation of the agriculture sector therefore require further research. The challenge for this research consists in combining the separate research streams on the biophysical and the socio-economic transformation of the agriculture sector, understanding the wide variety of historical pathways of structural transformation and of current national circumstances [89,90]. As

[1] The method proposed in this paper has not been used to produce any final AFOLU pathways which could be used as examples for this paper.

was mentioned at the outset of the paper, long term strategies (LTS) could be instrumental to reconcile climate and sustainable development objectives, including poverty reduction and jobs, but must be based on an understanding of how climate mitigation actions and socio-economic development interact. Exploring these questions further would yield insights into which synergies to promote and which trade-offs to avoid.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Annexes.

A. Method and analysis of AFOLU pathways from DDPLAC

This annex will outline the details of the AFOLU reporting framework used in DDPLAC, and of the *storyline* and *dashboard,* developed as part of the DDP pathways design framework for AFOLU proposed in this paper.

AFOLU reporting template in DDPLAC

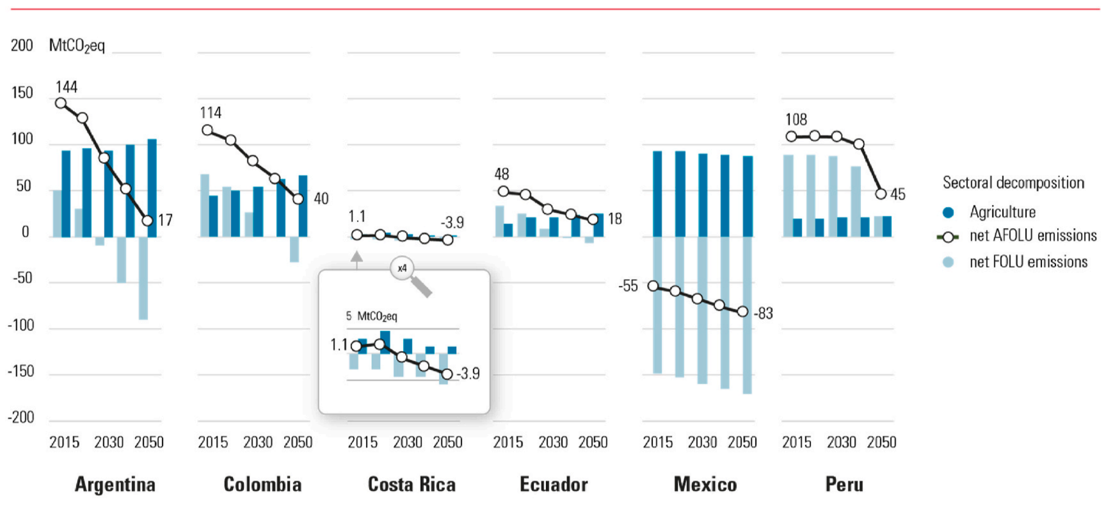
In DDPLAC, the AFOLU reporting framework consisted of 21 quantifiable indicators covering emissions from FOLU and agriculture, as well as a small number of indicators on key activities in the sector. A full description of indicators used in the AFOLU reporting framework is given in Table 3.

Table 3
AFOLU reporting template used in DDPLAC

Category	Indicators
Greenhouse gas emissions	FOLU emissions from: - forestland loss (MtCO2/year) - land remaining forestland (MtCO2/year) - forestland gains (MtCO2/year) - other land use change (MtCO2/year) Management practices emissions from: - enteric fermentation (MtCO2eq/year) - synthetic fertilisers (MtCO2eq/year) - rice paddies (MtCO2eq/year) - other land management practices (MtCO2eq/year)
Consumption: evolution of national diets	- Daily calory intake (kcal/cap/day) - Share of diet consisting of animal products (% of kcal/cap/day)
Production: carbon efficiency of production	Crop production - Yields (kg/ha), as an average across all crops - Fertiliser application (kg/ha) Animal production - Livestock intensity for ruminant animals only (livestock units/ha) - Animal herds (animal heads in livestock units)
Land use	- Cropland (ha) - Grassland (ha) - Forestland (ha)
Bioenergy production	- Land use for bioenergy production (ha)

Analysis of AFOLU pathways build in DDPLAC

This annex analyses the AFOLU pathways developed in the DDPLAC project. The project included institutions from institutions in six countries: the *Escuela Politecnica Nacional* of Ecuador*, Universidad de Costa Rica, Universidad del Pacifico* in Peru*, Universidad de los Andes* and *Universidad di Rosario* in Colombia*, Tempus Analitica* in Mexico*,* and *Fundacion Bariloche* in Argentina. For teams that built more than one deep decarbonisation pathway, the pathway that achieves the deepest emissions reductions in the AFOLU sector by 2050 are analysed. The economy wide analysis undertaken in Bataille et al. [13] indicates that country teams - most of them coming from energy and transport backgrounds - faced difficulties in identifying AFOLU decarbonisation options, as AFOLU accounts for important shares of remaining emissions in 2050 for many countries. Fig. 2 shows the emissions trajectories of the AFOLU sector. All six countries project declining AFOLU emissions from 2015 to 2050, and Costa Rica and Mexico show net negative emissions from the sector by 2050.



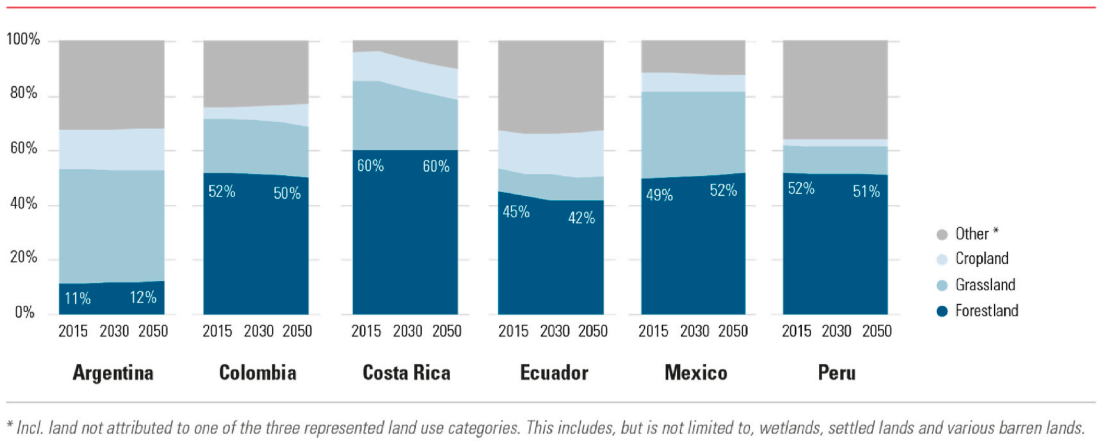
Source: data produced in DDP LAC project, more information available in Bataille et. al. (2020) [90] *and on the DDP Initiative's website* [*https://ddpinitiative.org/sec-lac-data/*](https://ddpinitiative.org/sec-lac-data/)

Fig. 2. Greenhouse gas emissions from agriculture, forestry and land use in national decarbonisation scenarios. Source: data produced in DDP LAC project, more information available in Bataille et al. (2020) [91] and on the DDP Initiative's website https://ddpinitiative.org/sec-lac-data/

Forestry and other land use. The vast majority of overall emission reductions come from land-use, for which emissions are reduced in all six countries – in most cases substantially. Five countries have negative FOLU emissions in 2050 (Fig. 2). Forests are the major driver of FOLU GHG emissions (negative and positive), and other land types play a relatively small role.[2] Annual sequestration in already existing forests explains the lion's share in both Argentina's and Mexico's negative emissions from FOLU, while they are not taken into account by Ecuador and Peru. For Ecuador and Peru, afforestation and reforestation generate the majority of the negative emissions.

Looking at the evolution of land use in the deep decarbonisation scenarios in Fig. 3, the strongest commonality across countries is that forestland surface either increases (Argentina, Ecuador and Mexico) or remains mostly unchanged (Costa Rica), while agricultural land, made up of grassland and cropland, decreases (Costa Rica, Ecuador and Mexico) or remains unchanged (Argentina). Peru and Colombia are exceptions to these tendencies, and instead see slight decreases in primary forestland while agricultural lands increase marginally.

[2] No team included soil carbon, a main carbon sink outside of forests, in their analysis. The dominant role played by forests is therefore at least in part a consequence of the scope of the exercise.



Source: data produced in DDP LAC project, more information available in Bataille et. al. (2020) [90] *and on the DDP Initiative's website https://ddpinitiative.org/sec-lac-data/*

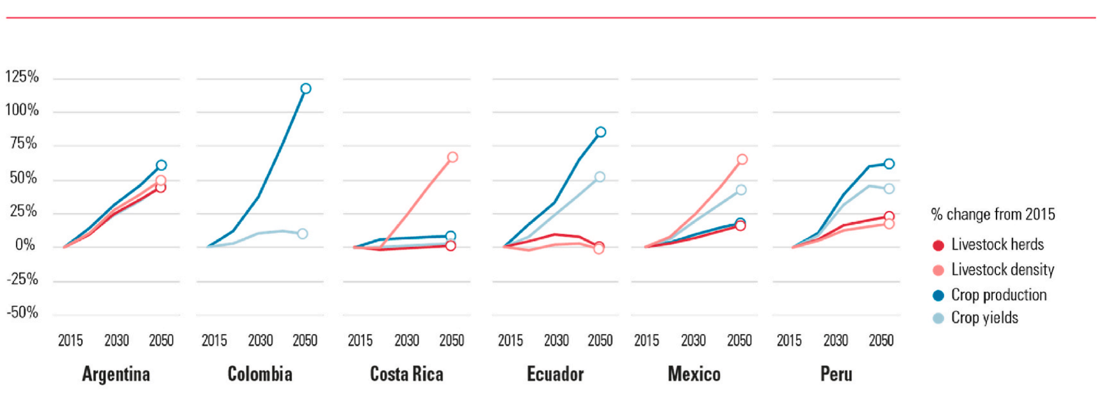
Fig. 3. Land use changed in national decarbonisation scenarios Source: data produced in DDP LAC project, more information available in Bataille et al. (2020) [91] and on the DDP Initiative's website https://ddpinitiative.org/sec-lac-data/ .

Increasing, or at least reducing the loss of, the carbon sink in forests is a key objective in many pathways. Mexico increases its forest surface by increasing the livestock density thereby liberating grassland for afforestation [16]. Argentina, reporting zero deforestation during the period, appears to evade the potential land competition between forests and agriculture by afforesting on non-agricultural land – a mitigation option they report as uncertain and should be subjected to further feasibility studies [14]. In Peru, deforestation does not cease but falls, which the team explains by a reduction in agricultural expansion [17]. Peru achieves this through numerous actions, including by extending land rights to areas where they are not currently existing or enforced and by introducing interventions to reduce rural poverty - which is one underlying driver of deforestation in Peru [17].

Ecuador and Colombia rely heavily on bioenergy production to reduce their energy emissions. Both report that the land dedicated to this purpose increases exponentially. In Colombia it corresponds to 10% of arable land, while it remains marginal compared to the overall arable land in Ecuador. Furthermore, in Ecuador, bioenergy production appears to be linked to some deforestation, which nonetheless ceases by 2040 [15].

Agriculture. Looking at agricultural emissions in Fig. 2, Argentina, Colombia, Ecuador and Peru increase theirs over the period, while agricultural emissions decrease in Costa Rica and Mexico. Except for in Colombia and Costa Rica, the variations are modest. The major source of agricultural emissions in all countries is CH_4 from enteric fermentation, which decrease in Argentina and Mexico and Costa Rica, and increase in Colombia, Ecuador and Peru. The second most important emissions source is N_2O emissions from fertiliser application to managed soils. These emissions increase in the case of Ecuador and Mexico, while they decrease for Costa Rica and Peru. Argentina and Colombia do not provide details on their emissions from fertiliser application.

Increasing food production is a key driver of emissions increases, and all countries increase their production (Fig. 4). Importantly, Mexico and Costa Rica increase their food production while reducing the related emissions. Colombia, Ecuador, and Peru all see substantial increases in crop production, while the increase in animal herds is significantly weaker.[3] In Mexico, the crop and animal production increase equally, and Costa Rica stand out as the only country without substantial increases in food production, with only minor increases in both.



Source: data produced in DDP LAC project, more information available in Bataille et. al. (2020) [90] *and on the DDP Initiative's website https://ddpinitiative.org/sec-lac-data/*

[3] Colombia reported their meat production in a different unit to that which was provided for in the reporting framework. For this reason, Colombia's results on animal production and animal density are not represented in Fig. 4. Colombia's results were as follows: total beef production increased by 31% and beef production per hectare and year increased by 9% between 2010 and 2050.

Fig. 4. Total agricultural production and land productivity in national decarbonisation scenarios. Source: data produced in DDP LAC project, more information available in Bataille et al. (2020) [91] and on the DDP Initiative's website https://ddpinitiative.org/sec-lac-data/ .

The increase in total production is primarily driven by the land intensity of production, which increases in all countries. Crop yields increase drastically in all countries except Costa Rica.[4] Concomitant with the increase in yields is an increase in fertiliser application, which increases in all countries except Peru. The livestock density remains stagnant for Mexico and Ecuador, while it increases for Argentina, Costa Rica and Peru. Fig. 4 shows that all countries intensify either crop or animal production, and Peru and Argentina intensify both. In Peru and Colombia, where reducing deforestation is a key strategy to decrease GHG emissions, increasing the productivity of agricultural land enables a reduction in land conversions from rainforest to cropland [17,19].

Some teams provide narrative insights into how improved emissions intensities of agricultural production drive emissions reductions. Regarding animal production, Argentina reduces emissions per cattle head by 40%, through a change in the composition of their feed [14], while similar measures lead to a 14% reduction in Mexico. Literature reviewed in section 5.1 of this paper raises some question marks regarding the Argentinian assumptions on this point. Regarding crop production, both Mexico and Argentina reduce the emissions intensity by improving the nitrogen uptake efficiency, i.e. the rate of applied nitrogen taken up by crops [14,16]. Other explanations in Argentina include crop rotation and the integration of crop residues into the soil [14].

In Costa Rica, Ecuador, Mexico and Peru, dietary changes act as another driver of the transformation of the AFOLU sector. In Mexico, national diets shift away from meat, which lead to a reduction in the number of livestock per capita [16], and Ecuador and Costa Rica both report using meat consumption and diets more generally as a lever for decarbonisation, without providing further insight on how [15,18]. In Peru, where rice is frequently cultivated on recently deforested land in the rainforest, diets shift away from rice and to roots and tubers in order to reduce deforestation rates – all while the daily per capita calorie intake increases in Peru. However, this transformation could moderate the potential production increases and lead to upward pressures on food prices [17].

B. *Elaboration of the DDP AFOLU supporting tool*

To enable users of the method to inform the wide variety of issues included in the storyline and the dashboard, the DDP AFOLU method proposes a supporting tool. The tool enables users to inform all elements and indicators in the storyline and the dashboard in a way that ensures internal consistency in the pathway, including consistency across the two components.

The supporting tool disaggregates biomass consumption according to the product category (the categories in the dashboard are used here too) and the use of the product (e.g. national human consumption, trade). Biomass production is analysed by disaggregation according to product and system of production (defined according to a set of production practices, e.g. fertiliser application and crop rotations for crop production and animal productivity, feed intake and composition and herd dynamics for animal production). Following a calculation of total demand and land-productivity per product, the tool helps users to calculate total land use, and includes a separate section on biomass dynamics (increments and harvests) of forests. Regarding calculations of biomass dynamics in forests, other tools consulted for this paper tended to be simplistic, measuring biomass per hectare simply by a static value, or very complex, relying on a spatially explicit land-use model that tracks the land-use for geographically defined areas, with varying resolution. In order to enable a dynamic analysis of biomass evolution in forests without a spatially explicit model (which multiplies complexity), the tool differentiates hectares in one land use depending on how long it has been in that land use, and thus calculates the existing biomass stock using annual sequestration rates.

The supporting tool aggregates this information to inform the storyline and the dashboard. In doing so, it performs three consistency checks, by signalling significant deviations from important equilibriums in the AFOLU sector. The first and the second concern the use and availability of land as well as the production and consumption of biomass. Third, the supporting tool will calculate GHG emissions based on agricultural practices and land use, relying on the IPCC 2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories. This ensures a rough consistency between the evolution of emissions and the evolution of agricultural practices. In this way, it highlights, and provides a solution for, cases where the two diverge. A fourth consistency check is currently under development. This concerns analysing imports and exports of nitrogen from cultivated fields, to ensure that there is roughly an equilibrium between the two. This consistency check will have the added advantage of enabling users to make more complex hypotheses on nitrogen fertilisation, in particular regarding biological fertilisation from legume plants. Although more complex than the former consistency checks, this one is important given nitrogen's role in ensuring the productivity of the cultivation, and the emissions that its application generate. The check might help ensure that evolutions of yields are supported by corresponding evolutions of nitrogen application, and that when this is not the case the reasons are explored in the storylines.

The tool can be accessed on this link: https://www.researchgate.net/publication/353286957_Supporting_tool_DDP_AFOLU-draft1

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