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Transition Scenarios for Tropical Agriculture

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About Orbitas

Orbitas examines climate transition risks for capital providers financing tropical commodities.

These risks are currently not factored into the financing of companies within the tropical commodities sector. This leads to suboptimal outcomes for capital providers themselves, the companies and sectors they finance, and for the planet.

Orbitas is currently focused on climate transition risks in Colombia, Indonesia and Peru. By combining cutting edge economic modeling with traditional financial analysis, Orbitas will shed light on the emerging climate transition risks and highlight opportunities for smarter financing.
Orbitas is an initiative established by Climate Advisers Trust (CAT). Orbitas is grateful to the Norwegian Agency for Development Cooperation (NORAD) for their generous financial support.

ABOUT VIVID ECONOMICS

Vivid Economics is a leading strategic economics consultancy with global reach. We strive to create lasting value for our clients, both in government and the private sector, and for society at large.

We are a premier consultant in the policy-commerce interface and resource- and environment-intensive sectors, where we advise on the most critical and complex policy and commercial questions facing clients around the world. The success we bring to our clients reflects a strong partnership culture, solid foundation of skills and analytical assets, and close cooperation with a large network of contacts across key organizations.

EXECUTIVE SUMMARY

The world's food system is highly complex. Responsible for feeding a growing and increasingly wealthy global population, a sector that comprises a small number of large agribusinesses, many medium-sized family farms and millions of smallholder farmers has already had to respond to rapidly moving market conditions and shifting policies, as well as the current the COVID-19 pandemic.

The physical effects of climate change, the deteriorating state of natural capital and the emerging crisis in farm labor are stresses that the food system will have to contend with over the coming decades. Companies operating in the food sector will bear the brunt of it. With a business model that is premised on delivering high volumes at tight margins across highly integrated but dispersed supply chains, many agricultural firms may already be insufficiently resilient to respond to these pressures.

However, 'climate transitions' - the policies, regulations and changes in corporate and consumer behavior that will be necessary to keep within the 1.5-2°C temperature rise goals set out by the Paris Agreement – represent a further source of potential disruptions that the food sector will have to deal with. This is particularly true for firms operating in, or dependent upon, commodities grown in tropical regions where the food system competes for land with high carbon value forests, peat lands and mangroves that are rich in biodiversity and essential to combatting climate change. The future success and failure of agricultural companies, as well as their investors, will hinge upon their ability to adapt to these climate transitions.

This report, the first in a series, explores the implications of climate transitions for the agricultural system across a suite of scenarios that are designed to reflect climate responses that range in ambition from Business as Usual to policies and other actions that keep global temperature increases below 1.5 °C . Across all these climate scenarios, we find an agricultural sector that in 2050, is significantly different from today.

- **Agricultural markets expand to feed a growing and increasingly wealthy global population.** Food production is set to increase by 50% by 2050 with process rising by 10-40%. Although this represents an opportunity for the food and agriculture sector, food consumption does not expand as a share of household budgets due to growth in incomes.

- **Deforestation ends around 2050 and as early as 2030.** Expected expansions of carbon pricing policies around the world increase the cost of deforestation, particularly in tropical areas where forests' carbon sequestration potential is high. In one 1.5°C scenario, net deforestation ends in 2030 as the carbon price reaches ~9$/t$CO_2$ and increased cropland productivity allows the agricultural system to meet food demand using less land. Even in a much less ambitious scenario in which emissions stabilize near current levels, net deforestation decreases throughout the first half of the century and stops around 2050, when carbon prices make land conversion excessively expensive.

- **Nature-based solutions offer new revenue streams for landowners.** Afforestation and forest restoration and forest conservation represent low-cost climate change mitigation options and, even very low carbon prices can incentivize the development of offset markets that boost nature-based solutions to climate change. Across all scenarios, carbon prices drive most of the re/afforestation on top of NDC commitments. This leads to substantial financial flows to the forestry sector and alternative sources of income for landowners.

- **Biomass is in high demand from the energy sector to produce bioenergy and biofuel.** In the land use system, this translates to an increase in production of second-generation bioenergy crops, like miscanthus and switchgrasses. In one 1.5°C scenario, bioenergy crops will constitute more than 30% of total crop production.

- **New land for agriculture is scarce and shifts the market dynamics for commodities.** Demand for bioenergy combined with the higher cost of deforestation and the creation of new markets for nature-based solutions will increase the scarcity of agricultural land. As food demand increases with the growing population, competition across the different uses, including energy, food, feed, and carbon sequestration, will increase, leading to the following cascade effects:

  - ◊ **Land is more expensive.** Nearly all scenarios show an increase in land prices above BAU. In the scenario with the strongest policy action, average costs of cropland exceed 1000$/ha, roughly 50% higher than BAU. This is because land protection policies remove land from agricultural production and high carbon prices make it very costly to convert unprotected forest land to cropland.
  - ◊ **Agricultural commodities fetch higher farm-gate prices.** Relative to 2020 values, prices in the BAU remain stable (+4% in 2050). All other scenarios show substantial price increases, ranging from +10% in the 3°C scenario up to 44% in a 1.5°C scenario. Despite rising prices, consumer welfare is relatively stable, as GDP increases offset rising food prices, with a stable share of household expenditures going to food.

- **Agriculture is more technologically advanced, more productive, but also more capital-intensive.** By 2050, investments in technological change are between 6% and 30% higher relative to BAU. Increasing crop yields by 1.6% per year means that annual capital investment needs will have reached $1.2 trillion in 2050.

All in all, climate transitions present a new set of risks and opportunities for the food system and for tropical commodity producers in particular. Rising demand and prices for traditional commdities and potential new revenue streams offer the possibility of improved returns and higher incomes. At the same time, competition for land and the imperative to reduce greenhouse has emissions and protect forests will raise costs and require investments in productivity improvements and sustainable supply chains.

Incumbents in the agricultural system will need to examine their practices in order to adapt as the food system changes, including the transitions described in Table 1.

Table 1 Dimensions of transition risk and required industry shifts

Dimensions of transition risk		Required industry shifts
Policy & Legal	**Reduce reliance on land conversion**	Increased protections for natural areas and the liabilities associated with developing on these lands should drive firms to reduce their land use footprints, particularly in tropical environments that have historically suffered from deforestation. Assets should increasingly be located further from high conservation value areas, and those nearby will increasingly transition toward mixed-use agriculture.
	Abate operational emissions	Inputs and operations will become more expensive. Therefore, firms should reduce operational emissions costs throughout the supply chain, passing on cost increases where they can. Vertically integrated firms will be more exposed because they are responsible for emissions in several parts of the supply chain but have more control over operations across the supply chain and can therefore manage their operational carbon liabilities internally.
Markets	**Invest in transparent supply chains**	Abating supply chain emissions should lead firms to invest in supply chain transparency to reveal opportunities for emission reductions. For example, processing, packaging, and retail firms should demand clearer sourcing data to protect themselves from liabilities and differentiate sustainable products.
	Prepare for shifts in consumer demand	Changing relative prices of goods based on their emissions intensities should cause consumers to rebalance what they purchase. In some cases, these shifts exacerbate trends already under way, such as higher demand for plant-based proteins. Firms should alter their offerings to consumers in line with these trends.
Technology	**Pivot toward alternative markets**	Increasing competition for land from bioenergy and afforestation will drive rising values for agricultural land. Firms should look for opportunities to enter these markets, such as investing in integrated or mixed-use production (e.g. agroforestry).

	Invest in agile sourcing	Midstream and downstream firms without exposure to land ownership and primary production are not insulated from these shifts. These firms should adjust to these changes in the supply chain, and the consequent uncertainty in production and costs, through innovative measures such as flexible sourcing tied to improved sustainability performance over time.

Source: Vivid Economics, based on TCFD risk assessment framework

For investors, reducing exposure and capitalizing on opportunities is possible if they take immediate actions. They should integrate climate- and nature-related risk into their portfolio decisions, including restructuring their investment practices to assess transition risks. After choosing to invest in companies, asset owners should engage with investees across the risk categories detailed above. This should include requesting disclosure of how investees plan to minimize these risks and take advantage of opportunities.

Proactive investors should also position themselves to take advantage of nascent markets, including nature-based solutions, bioenergy markets, and transparent supply chain opportunities. These opportunities are likely to require investors to take proactive action, but the potential rewards are significant. Exposure to growth industries counteract the carbon exposure from investments in traditional agriculture. They also offer potential acyclical sources of operating income for investors by diversifying the commodity markets where their investments generate revenue.

Finally, investors should be engaging with policymakers to ensure emerging markets are structured in such a way that private finance can play a role in bringing about a swift and just transition. This report quantifies the significant additional investment required, which can't be fulfilled through public investment alone. Mobilizing private capital is therefore essential to align finance with the climate transitions projected in this report. Failure to do so risks agriculture lagging behind in the low-carbon transition already under way.

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1 INTRODUCTION

The world's food system is complex and highly susceptible to the worse impacts of climate change. Large portions of the food chain have long been dominated by large agribusiness conglomerates operating high volume, tight margin businesses. Integrated global processors, companies like JBS, Tyson, Bunge, or Olam dominate supply chains for the world's agricultural commodities including wheat, beef, corn, soy, chicken, or oil palm. The business model varies somewhat by commodity, but these large processors often purchase raw materials from either independent or contracted individual farmers and ranchers and sell to large food retailers, including Sysco, Tesco, or Kroger. This model, focused on producing huge quantities of commodified food as cheaply as possible, is also inherently fragile. First, tight margins mean even small changes in the unit costs of production can disrupt industries; and second, closely integrated supply chains mean that disruptions at any point along the chain spill over across the chain. The COVID-19 pandemic is an example of that fragility; businesses at both ends of the supply chain have been impacted. Widespread restaurant and food service closures have meant that suppliers have quickly changed product packaging and distribution to shift from wholesale and restaurant supply to retail and direct-to-consumer sales. This shift has backed up processing facilities, many of which have COVID-19 related staffing challenges of their own, which in turn has forced upstream producers to destroy their product due to lack of sales or processing capacity (Jeffery & Newburger, 2020). Examples abound - farmers dumping milk, ploughing produce back into fields, euthanizing livestock, or letting perishable food rot unsold, all while the world experiences increasing food insecurity. These are not symptoms of a healthy, resilient food system.

COVID-19 offers a sense of crises to come. While not every catastrophe includes rapid-onset radical shocks to how we consume food globally, the central role that agriculture plays in our lives and its reliance on natural inputs expose the industry to crises that have been developing for decades:

- **Climate change:** Agriculture and forestry activity accounted for 23% of global anthropogenic emissions in 2016 (IPCC, 2019). They are directly responsible for 44% of global methane emissions, most of which come from ruminant livestock, and 81% of nitrous oxide emissions, much of which comes from fertilizer use. These activities also drive indirect emissions through unsustainable destruction and degradation of forest land, with agriculture and mining accounting for more than half of global deforestation (Curtis et al., 2018). The current trajectory of growing emissions, as agriculture continues to expand to feed a larger, wealthier global population, is incompatible with a world that limits global warming to below 1.5, 2 or even 3°C.

- **Nature and biodiversity:** Agriculture is directly dependent on natural ecosystems for a huge share of its inputs, including water and pollination services, which are impossible or expensive to replace with technological alternatives. In addition to agriculture's contribution to deforestation, overapplication of agrichemicals has caused incredible damage to both soils and ecosystems, and over-withdrawal of water has contributed to increased risks of wildfires and droughts in many areas. The current global agriculture system bites the hand that feeds it, with disastrous consequences for both biodiversity and agriculture's own cost base.

- **Farm labor:** Upstream producers in food supply chains are perhaps more squeezed than they have ever been. In the US, for example, long-term average farm gate prices for global commodities remain low, farm debt is at an all-time high, and bankruptcies have been increasing for the last decade even before COVID-19. More than half of all US farmers have lost money every year since 2013 (USDA, 2020). Farmers and ranchers form the base of supply chains upon which agriculture depends, and many are having difficulty staying in business in the current food system.

Fragility portends change. Systems remake themselves to guard against the last shock, and the COVID-19 pandemic has offered a disruption that will affect the food system for years to come. The building pressures of climate, nature, and farm labor suggest that the agriculture system will change further in the coming years. The food system has much more chance to adapt to these pressures than the short-term shocks associated with COVID-19, but the three pressures will be as forceful in requiring actors within the existing food system to adapt. The confluence of these forces has resulted in other parts of the food ecosystem beginning to respond, and agricultural players are starting to face pressure from multiple angles:

- **Policymakers:** Agriculture, long exempted from some environmental controls and the beneficiary of production subsidies, is increasingly being included in sustainable transition policymaking. Net-zero policy is a good example: Sixty carbon pricing initiatives are implemented or scheduled around the world, covering 21% of global emissions (World Bank, 2020). In the past these policies have focused on the energy sector, but schemes increasingly include forestry and agriculture in emissions caps, and are rewarding land-use mitigation through soils or habitat restoration. Early-adopter jurisdictions including New Zealand, California, Spain, and a number of Canadian provinces all have provisions for crediting Nature Based Solutions (NBS), and the first offset projects are now providing their developers with steady streams of carbon credits (Michaelowa et al., 2019). Subsidies are also undergoing reforms; the European Green Deal is motivating renewed scrutiny of the environmental commitments in the EU's Common Agricultural Policy, the main subsidy vehicle for European agriculture (European Commission, 2020). Other jurisdictions may follow or be encouraged to follow through trade policies like the EU's Border Carbon Adjustment tax under discussion (Abnett, 2020).

- **Consumers**: Food consumption patterns were already changing before COVID-19, which accelerated existing consumer trends in much of the world toward foods perceived to be more sustainable and locally sourced. Sales of alternative proteins for example, including brands like Impossible and Beyond, increased 264% in the first two months of widespread lockdowns globally (Patton, 2020). Customers in the developed world have increasingly demonstrated a willingness to offer price premia for organic and other green labelled products, with organic sales growth outpacing general market growth by 2.6% in 2019 (Organic Trade Association, 2020). Agricultural producers unable to adapt to the changing realities of consumption have already suffered; Dean Foods and Borden Dairy, two of the US's largest milk suppliers, went bankrupt in the past year (Isidore, 2020).

- **Competition**: Other players are beginning to emerge in agriculture globally, developing new models of food production or reinventing old ones. Broadly termed regenerative or sustainable agriculture, many farmers, ranchers, food processors and investors are working to shorten supply chains and bypass the large conventional agriculture companies that dominate today's market. While still only a tiny share of agricultural revenue, these models are designed to be responsive to the coming changes in the food system and are growing quickly. The financing to back these transitions is becoming more available from pioneering investors in the space, which are currently small but growing rapidly in scale and number. Conventional players risk being displaced if they fail to offer a compelling response to the forces reshaping the food system.

The timing and extent of response from these three groups is uncertain, but action is inevitable. That leaves current incumbents and their investors with the simple choice to either reinvent themselves as resilient to the oncoming pressures and account for emerging risks or be disrupted if they fail to do so.

The rewards for successful adaptation are likely to be large. Population and GDP growth mean that demand for agricultural products is increasing. Those players savvy enough to navigate the transition effectively will find themselves with a larger market to operate within.

This report seeks to explore the coming transitions in the global agriculture system and equip investors with an understanding of the associated thematic risks and opportunities. Section 2 describes the scenarios and modelling used to compare alternative possible futures and introduces key commonalities and differences in the findings between scenarios. Section 3 explores risks and opportunities in more detail, grouping findings according to the investor risk framework put forward by the Task Force for Climate-related Financial Disclosures (TCFD). Section 4 concludes with implications for investors. Detailed annex material illustrates key findings for particular commodity supply chains and the methodology associated with the scenario analysis undertaken for this report.

This report represents the first in a series. This paper seeks to introduce overarching shifts and trends in global agriculture. Subsequent publications by Orbitas build upon the modelling efforts of this report to better quantify and illustrate financial risks in particular countries and commodity supply chains.

2 SCENARIOS

Scenario analysis allows the agriculture system to take a disciplined approach to future uncertainties and protect returns. A scenario describes one possible future development pathway given a set of assumptions. Such pathways do not represent forecasts, but rather hypothetical constructs that allow strategic alignment before the coming transition. Investors can use scenario analysis to better understand future risk and opportunities in agriculture, a best-practices approach advocated by the TCFD and other investor-facing institutions (TCFD, 2017). This report supports that aim, summarizing the results of a quantitative scenario analysis undertaken to explore the different dimensions of risks and opportunities associated with future transitions in the global agriculture sector. The remainder of this section motivates the scenarios developed to explore the coming transition, introduces findings common across scenarios, and highlights some of the primary differences in results.

Past work on climate risk underpins this analysis. TCFD categorizes climate change risks into two main categories: transition risk, which is associated with the shift toward a net-zero emissions economy; and physical risk, in which changing weather patterns have implications for society and business activity (TCFD, 2017). Since the TCFD published its recommendations, international and financial institutions have increasingly sought to conduct the scenario analysis and risk quantification exercises prescribed by the TCFD. Physical risk disproportionately affects agriculture as a sector because of its large land footprint and direct reliance on nature, so it has been the focus of a variety of high-profile pieces of work that highlight climate risk in agriculture, including the IPCC's Special Report on Land Use as well as regionally-focused adaptation studies such as the EU's PESETA IV initiative (JRC PESETA, 2020). Other work, including the Food and Land Use Coalition's (FOLU) Growing Better Report and the World Resources Institute's (WRI) Creating a Sustainable Food Future focus more on the challenge of changing the food system to be more sustainable (The Food and Land Use Coalition, 2019; World Resources Institute, 2018). This report builds directly upon FOLU and WRI work by modelling the specifics of transition, and the consequences for incumbent actors in today's food system in ways that are actionable by the finance and investment community. This report focuses on the three most quantifiable transition risks, described in Figure 1. Section 0 of this report explores these dimensions of risk in turn.

Figure 1 Three dimensions of climate transition risk

Policy and Legal	Direct regulatory liabilities from emissions and area protection
Markets	Higher input prices and changing market conditions
Technology	Competition for land from emerging low carbon technologies and their markets

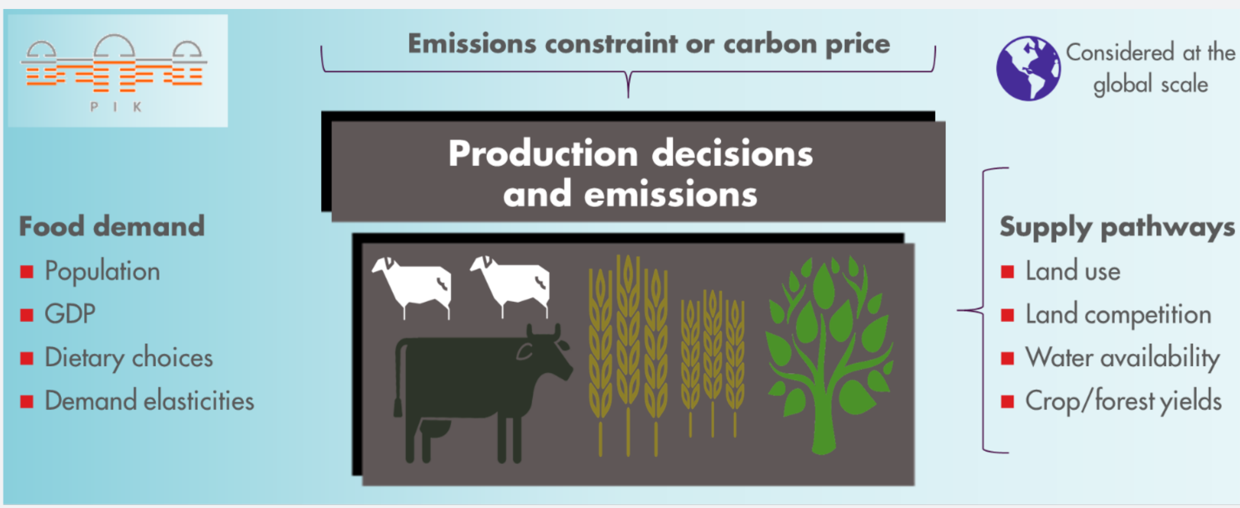
Source: Vivid Economics

Our Scenarios

This report considers five scenarios designed to span the three dimensions of transition risk shown in Figure 1. Many assumptions in these scenarios are consistent across the set, including overall trends in population and GDP as well as global trade patterns for agricultural goods. Other characteristics, including the role of bioenergy in decarbonization, and the expected increases in agricultural productivity are varied across scenarios to explore different dimensions of risk. In only two scenarios does global temperature rise remain well below 2°C over pre-industrial levels, in line with the Paris Agreement. Achieving these targets requires the global economic system to reinvent itself, either by enhancing efficiency of supply or by reducing the demand for carbon intensive products. These scenarios are implemented using the Potsdam Institute for Climate Change's (PIK) open-source Model of Agricultural Production and its Impact on the Environment (MAgPIE) (Dietrich et al., 2019). Box 1 below introduces the MAgPIE model, while more information about the methodology used in report scenarios can be found in Appendix B.

Box 1 The MAgPIE model

Our analysis relies on MAgPIE, a spatially explicit partial-equilibrium model, in which food demand is estimated using population, GDP, dietary assumptions, and demand elasticities from the Global Trade Analysis Project (GTAP) database. The model then determines the least cost way to meet that food demand, while accounting for biophysical constraints including those on land and water, as well as potential crop yields. This framework allows land use competition between varying uses to be modeled explicitly.



The model relies upon seven categories of scenario assumptions to model agricultural production and its corresponding prices and distribution. They span the categories of climate risk introduced in Figure 1, and include:

- **Socioeconomic characteristics:** These assumptions determine future growth characteristics, such as population and GDP, which are required in order to estimate food demand. All scenarios described in this work use the Shared Socioeconomic Pathways (SSP's) utilized by the IPCC.
- **Carbon policy:** Policies like carbon taxes or emissions trading schemes are incorporated into the land use sector to varying degrees across scenarios.

- **Nature policy:** Land area protection and incentives for restoring biodiversity, which restrict possible land uses by design, are represented in scenarios to varying degrees.
- **Diet change:** Diet composition and changes in its trajectory are used to represent changing consumer preferences. Meat consumption, for example, is generally expected to increase with population and GDP; however, it may decline in wealthy countries in scenarios with ambitious climate action.
- **Bioenergy demand:** The energy system's appetite for biomass depends on the future of a variety of uncertain technologies, including Bioenergy with Carbon Capture and Storage (BECCS).
- **Trade:** The future of trade in agricultural goods has huge implications across the land system. Trade policy is largely unchanged across scenarios in this work, with trade volumes allowed to flex some with production, but without substantial changes to the relative scale or patterns of trade.
- **Investment cost:** The future of agricultural productivity is determined in part by the expected returns to productivity investments. These returns are higher in scenarios that rely on ambitious technological development in agriculture.

Assumptions are informed by literature and scenario narrative, and detailed further in Appendix B.

Scenarios are designed based on internally consistent narratives. While literature and past modelling efforts inform the plausible ranges of assumptions, scenario narratives are an important tool to select sensible combinations of assumptions**:**

- **4°C Business As Usual**: Representative of recent trajectories and existing policy measures, this models a world in which little is done to address rising emissions. It includes only currently implemented land use policies globally and serves as a point of reference to which other scenarios can be compared to isolate the implications of action. Warming in this scenario is likely to be well above 3°C.

- **3°C Already Committed Action**: A future in which some action is taken to stabilize, but not reduce emissions. A very low carbon price is introduced gradually in the coming decade, but pricing is not ever fully integrated into the land sector. This results in limited compensation for negative emissions, and by extension international markets for offsets and nature-based solutions are small. Outside of the land use sector, global energy demand increases until mid-century and there is some uptake of low-carbon sources, such as bioenergy and biofuels, though adoption is limited by the low carbon prices. Warming is kept to near 3°C.

- **2°C Moderate Ambition:** A world that aims to limit warming to 2°C but fails to reach that target due to lack of international coordination and insufficiently ambitious policy. Carbon prices are introduced, but lack of international support for and coordination of offset markets and limited emissions trading schemes keeps global average prices relatively low. Society recognizes the role that consumption habits play in climate change and starts to reduce the share of the most emissions intensive meats in their diets. Consumers' awareness of environmental issues helps stabilizing energy demand in industrialized countries. In the transport sector, internal combustion engine (ICE) sales bans lead to a rapid scale-up of ultra-low emissions vehicles and a decline in oil demand. Energy efficiency increases significantly across sectors thanks to the development of effective standards. Bans on coal-fired electricity generation and rapid deployment of renewables result in cleaner electricity generation and decrease the carbon intensity of the power sector. The decarbonization of carbon intensive industrial sector, such as iron and steel and petrochemicals, is slow as only mature technologies can be deployed at scale in the short-medium term, resulting in some reliance on offsets and negative emissions.

- **1.5°C Strong Ambition LI (Land Intensification pathway):** This scenario represents a world in which well below 2°C targets are met through robust international markets for carbon trading and investment in technological change. Agricultural yields improve even faster than they have historically, with technologies like CRISPR and precision agriculture pushing the frontier of productivity in developed countries while technology transfer and agricultural extension programs fuel rapid catch-up productivity growth in developing countries. Yields are also improved globally by the increased prevalence of polyculture cropping and regenerative agriculture techniques. In the power sector, demand does not decline, but energy supply is less carbon intensive thanks to substantial investments in technological innovation. Solar hydrogen, methanol and new forms of biomass outcompete fossil fuels early on and investment in renewables continues to increase in the medium term. Technology investments also enable currently speculative negative emissions technologies like bioenergy with carbon capture and storage (BECCS) to take off at scale.
- **1.5°C Strong Ambition LP (Land Protection pathway):** Targets well below 2°C are met through coordinated international action. Like the 1.5°C Strong Ambition LI scenario, robust international offset markets develop to support a relatively high carbon price and strong land sector participation in which negative emissions are fully compensated to the same degree that positive emissions are punished. Bioenergy is limited by society due to concerns about its negative development impacts, but a market remains for sustainable bio-based feedstocks. New protection policies and better enforcement expand the natural area that is effectively protected, allowing forest cover to regenerate and expand substantially. Society also recognizes its role in sustainable consumption, collectively shifting diets away from derivatives of ruminant meat, one of the most emissions intensive agricultural products. Although the supply-side investments are not as significant as in the Land Intensification pathway, increased consumer awareness helps reduce energy demand, favouring a swift decarbonization of the energy sector. In the transport sector, for instance, ride sharing combined with a rapid phase-out from ICE vehicles result in a decline in the total distance driven and reduced fuel consumption. In the industry sector, behavioral changes lead to an increase in recycling rates and reduce demand for industrial commodities.

The narratives described above are represented in our modelling exercise by a set of key metrics that differ across scenarios summarized in Table 2. Differences in policies, innovation and consumption have specific knock-on impacts on model outputs such as food prices or emissions, which will be discussed in detail throughout the rest of the paper.

Table 2 Five scenarios span key transition risks for agriculture

Scenario	Mitigation policy*	Annual bioenergy demand	Productivity increase by 2050 relative to 2020	Area protection	Ruminant meat fadeout***
4°C Business as usual	Currently implemented policies only. Consistent with a 3-4° global temperature increase.	27 EJ by 2100	37%	352 Mha (IUCN Category I, II)	No fadeout
3°C Already Committed Action	\$13 per tonne CO_2e by 2050. Consistent with a 2-3° global temperature increase.	70 EJ by 2100	46%	352 Mha (IUCN Category I, II)	No fadeout
2°C Moderate Ambition	\$30 per tonne CO_2e by 2050. Consistent with a 2-3° global temperature increase.	70 EJ by 2100	48%	352 Mha (IUCN Category I, II)	25% fadeout by 2050
1.5°C Strong Ambition LI	\$115 per tonne CO_2e by 2050. Consistent with a below 2° global temperature increase.	157 EJ by 2100	108%	352 Mha (IUCN Category I, II)	25% fadeout by 2050
1.5°C Strong Ambition LP	\$115 per tonne CO_2e by 2050. Consistent with a below 2° global temperature increase.	70 EJ by 2100	60%	2707 Mha (IUCN Category I to VI, both designated and proposed)	50% fadeout by 2050

Note: *Carbon prices presented are global averages in 2050 and are in 2019 USD.
**Ruminant meat fadeout – this is a gradual decrease in the role of ruminant meats (beef, lamb, mutton, and goat) as a protein source. Fadeout scenarios replace ruminant meat with less carbon intensive protein sources, including poultry, fish, eggs, and alternative meats.

Source: Vivid Economics

The development of climate policies and introduction of carbon pricing have some common effects across scenarios:

- **Deforestation ends around 2050**. As the carbon price phases in, the cost of deforestation increases, particularly in tropical areas where forests' carbon sequestration potential is high. In the 1.5°C Strong Ambition LI scenario, net deforestation ends in 2030 as the carbon price reaches ~9\$/tCO_2 and increased cropland productivity allows the agricultural system to meet food demand using less land. In all other scenarios, net deforestation decreases throughout the first half of the century and stops around 2050, when carbon prices make land conversion excessively expensive.

- **Nature-based solutions.** Afforestation and forest restoration represent a cheap sequestration option, and even very low carbon prices can prove effective in incentivizing the development of offset markets and nature-based solutions to climate change. Across all scenarios, carbon prices drive most of the re/afforestation on top of NDC commitments. This leads to substantial financial flows to the forestry sector aimed at compensating the use of forest as a carbon sink.

- **Increased biomass demand and production.** To meet climate targets, the energy sector will increase its demand for biomass to produce bioenergy and biofuel. In the land use system, this translates to an increase in production of second-generation bioenergy crops like miscanthus and switchgrasses. In the 1.5°C Strong Ambition LI scenario, bioenergy crops will constitute more than 30% of total crop production. Although this value is driven by the assumption on bioenergy requirements in the energy sector, most low-carbon scenarios are likely to require a substantial ramp-up in biomass production before 2050.

- **Increased competition for land.** Demand for bioenergy combined with the higher cost of deforestation and the creation of new markets for nature-based solutions will increase the scarcity of agricultural land. As food demand increases with the growing population, competition across the different uses, including energy, food, feed, and carbon sequestration, will increase, leading to the following cascade effects:

  - ◊ **Increased value of agricultural land.** Except for 1.5°C Strong Ambition LI, all scenarios show an increase in land prices above BAU. In 1.5°C Strong Ambition LP, average costs of cropland exceed 1000$/ha. This is because land protection policies remove land from agricultural production and high carbon prices make it very costly to convert unprotected forest land to cropland.

  - ◊ **Higher farm-gate prices for agricultural commodities.** Relative to 2020 values, prices in the BAU remain stable (+4% in 2050). All other scenarios show substantial price increases, ranging from +10% in the 3°C scenarios up to 44% in the 1.5°C Strong Ambition LP scenario. Despite rising prices, consumer welfare is relatively stable, as GDP increases offset rising food prices, with a stable share of household expenditures going to food even in the 1.5°C Strong Ambition LP scenario.

  - ◊ **Higher investments in productivity enhancing technologies.** By 2050, investments in technological change are between 6% and 30% higher relative to BAU.

Although all scenarios share common characteristics, some key differences are indicative of the effects of specific policy and other assumptions on the land-use system (Table 3). For instance, low carbon prices effectively halt deforestation by 2050, but they fail to generate net reforestation. In the 3°C pathway, land conversion yields close to 30Mha of net forest loss by 2050, but the high carbon prices imposed in both 1.5°C scenarios result in hundreds of Mha of reforestation. Finally, cropland expands in all scenarios except the 1.5°C pathways, where high carbon prices make land conversion and emission intensive agricultural activities significantly more expensive.

The 1.5°C pathways represent very different ways of delivering upon the Paris Agreement. The land use change figures presented in Table 2 illustrate the different dynamics at play when comparing between scenarios. Although payments for carbon sequestration incentivize reforestation in both scenarios, land scarcity limits net forest change to 280Mha in the land protection variant (130Mha less than in 1.5°C Strong Ambition LI). The land is instead utilized as low-intensity pasture and cropland:

- **Pasture:** The strong diet shift in the Land Protection pathway does not result in an equivalently strong reduction in pastureland. Instead, the combination of reduced demand for ruminant meat and high carbon prices leads to a change in management practices: pastureland only decreases by ~360 Mha, 60Mha less than in BAU, but extensive grazing replaces intensive cattle ranching because of the emissions intensity associated with these practices. In 2050, pasture intensity - measured as tons of forage per hectare of pastureland – is 23% less than in BAU and lower than in any other scenario.

- **Cropland**: The decline in cropland achieved in the Land Protection pathway is close to a tenth of that in the Land Intensification pathway. In the latter, the low cost associated to investment in technological innovation allows the agricultural sector to rapidly increase its productivity, and to reduce the amount of cropland needed to feed the world.

Table 3 Differences in land-use change

Change by type of land use (2020 -2050)	4C Business as usual	3C Already Committed Action	2C Moderate Ambition	1.5C Strong Ambition LI	1.5C Strong Ambition LP
Change in forest land	-111 Mha Deforestation continues up to 2100	-29 Mha Deforestation stops between 2050 and 2055	+18 Mha Deforestation stops between 2040 and 2045	+411 Mha Deforestation stops between 2025 and 2030	+280 Mha Deforestation stops between 2025 and 2030
Change in cropland	+304 MHa	+212 MHa	+148 MHa	-312 MHa	- 40 MHa
Change in pastureland	- 415 MHa	- 415 MHa	- 432 MHa	- 403 MHa	-357 MHa

Source: Vivid Economics

These findings have substantial implications for the agricultural sector, creating risks, but also important opportunities for agricultural firms and their investors. Table 4 summarizes expected transitions across agriculture. The introduction of a carbon price and the enforcement and expansion of protected areas will stop deforestation, threatening agricultural supply chains that currently rely on deforestation. Additionally, carbon prices will incentivize the use of managed forest for Carbon Dioxide Removal (CDR), creating new markets for nature-based solutions (NBS) to climate change. Bioenergy crops will also play an increasingly important role in land-based mitigation, and their value in the agricultural sector may surpass that of many soft commodities. Finally, the combination of demand for NBS, energy crops and food will increase land competition which will in turn drive up the value of land, creating opportunities for landowners but risks for downstream companies.

Table 4 Summary of links between modeled policies and risk dimensions

Risk dimension	Mechanism	Description
Policy & legal	Protected areas increase risk for supply chains relying on deforestation	The introduction of a new protected areas and the enforcement of existing ones will threaten agricultural supply chains that currently rely on deforestation and threaten ecosystems, particularly in highly biodiverse areas.
Markets	Carbon prices make land clearing practices costly	Currently, producers of soft commodities such as soy or palm oil can source their product inexpensively by clearing tropical forest, a practice which not only destroys highly biodiverse ecosystems, but also contributes to carbon emissions. Effective carbon pricing would actualize the environmental damage associated with deforestation,

		increasing the cost of forest clearing, and making alternative, sustainable practices more appealing.
Technology	New markets for nature-based solutions	Natural forest restoration, as a very low-cost mitigation strategy, is expected to be taken up first and generates most of the early benefits because emissions reductions are more easily calculated, and accounting mechanisms have already been developed in some carbon markets. Projects that avoid deforestation are often further away from commercialization since they involve more complex compensation mechanisms.
	Bioenergy crops will play an increasingly important role in land-based mitigation	Under the high demand pathway considered in the 1.5°C Strong Ambition LI scenario, the size of the global bioenergy market will reach an annual $303 billion by 2050, surpassing the 2050 market value for soybeans ($199 billion). This is nearly 70% the size of today's global natural gas market, which in 2018 sat at $445 billion (IEA, 2019; US Energy Information Administration, 2020).
	More intense competition will drive up value of agricultural land and commodity prices.	Although landowners could benefit from the increasing land values, these rents will be transferred through the supply chain. This could increase risks for downstream firms that would be left paying higher prices without exposure to the upside opportunities associated with land ownership. Note that many of the largest integrated food processors, such as JBS or Tyson, have models that involve very little land ownership.

Source: Vivid Economics

Following TCFD's framework, the next section will categorize the risks and opportunities associated with the different scenarios and expands on their implications for actors within land use sectors.

3 INDUSTRY TRANSITION RISKS & OPPORTUNITIES

This section expands on the risks and opportunities related to climate action, bringing together literature and modeled results to create a coherent story that can help the investment and finance community understand the future of land-use sectors. The first section introduces some key considerations that are common across scenarios and provide a brief description of how the TCFD framework is used to organize transition risks and opportunities throughout the section. A policy and legal risks section describes the potential issues that companies relying on deforestation of carbon-intensive processes may face. This section will be followed by one on market risks, dealing with the implications of emission costs and consumers' awareness for agricultural supply chains. A technology section then focuses on the opportunities related to the creation and expansion of markets for bioenergy and carbon offsets.

Across scenarios, agricultural markets expand to feed a growing and increasingly wealthy global population. Under all five scenarios, production volumes grow by about 50% by 2050 to meet growing caloric budgets worldwide (FAO, 2012) . Total caloric budgets are set to expand due to both population growth and increased food consumption as developing countries become wealthier, with Sub-Saharan African and South Asian budgets growing most. This growth helps contribute to rising food prices, with increases between 10 to 40%, depending on the scenario. Despite this, rising incomes mean that food as a share of household expenditure falls, on average, by about one percentage point from 4% to 3% by 2050. Market growth varies somewhat by commodity, but in general increasing production volumes and prices combine to suggest a rosy future for agriculture.

The introduction of carbon policy also creates new opportunities for agricultural firms and landowners. Pricing carbon creates a market for land-based sequestration that competes with agriculture, driving up rents and commodity prices and offering landowners a wider range of productive opportunities for their holdings. New options for landowners will depend on the details of the regional and local policies implemented in their jurisdictions and the extent to which negative emissions are rewarded through offset markets, but in general landowners will benefit from areas that can effectively store carbon, either by planting forests or bioenergy crops. In many places, agricultural landowners may stand to benefit by more than they would be expected to pay in emissions costs if they kept land under cultivation, making them a possible net beneficiary of carbon policy.

Participation in these expanding markets, however, will require radical industry transformation. Future growth will expand agricultural market volume and climate policy could increase value – but will come in the context of reduced land availability for agriculture, both in limiting scope for future expansion and in reducing area currently under production. To align with Paris climate targets, as much as 600 million hectares are taken out of agricultural production by 2050, but even scenarios that fail to meet 2-degree targets will need to dramatically curtail the current growth in cultivated area. The land competition that results from net-zero policy will have impacts throughout the value chain, requiring greater investment in sustainable management practices, and more flexible and resilient supply chains to keep pace with demand while also adjusting to shifts in policy. Table 5 lays out the required industry shifts that will need to be made in response to each dimension of transition risk. Firms and landowners that fail to navigate these transitions will find it difficult to compete.

Table 5 Dimensions of transition risk and required industry shifts

Dimensions of transition risk		Required industry shifts
Policy & Legal	**Reduce reliance on land conversion**	Protections for natural areas and the associated liabilities will drive firms to reduce land use footprints, particularly in tropical environments that have historically suffered from deforestation. Assets will increasingly be located further from high conservation value areas, and those nearby will increasingly transition toward mixed-use agriculture.
	Abate operational emissions	Firms will reduce operational emissions costs throughout the supply chain and pass on the costs where then can. Inputs and operations will become more expensive. Vertically integrated firms will be more exposed because they are responsible for emissions in several parts of the supply chain but will have more control to reduce operational carbon liabilities.
Markets	**Invest in transparent supply chains**	Carbon costs will drive investments in supply chain transparency to drive abatement measures through the supply chain. Processing, packaging, and retail firms will demand clearer sourcing data to protect themselves from liabilities and differentiate sustainable products.
	Prepare for shifts in consumer demand	Changing relative prices of goods based on their emissions intensities will cause consumers to rebalance what they purchase. In some cases, this will combine with shifts in preferences already occurring.
Technology	**Pivot toward alternative markets**	Increasing competition for land from bioenergy and afforestation will drive rising values for agricultural land. Integrated or mixed-use production, such as agroforestry, will become more common as producers seek exposure to these markets.
	Invest in agile sourcing	Mid- and downstream firms without exposure to land ownership and primary production will need to adjust to these changes in the supply chain, and the consequent uncertainty in production and costs.

Source: Vivid Economics, adapted from TCFD transition risk categories

Firms that make the necessary investments to manage risk will be able to take advantage of expanding markets and rising prices. Firms that make proactive adjustments to their management practices by investing in research and development and yield improvements will enhance supply chain resilience and consolidate market position to benefit from market growth. They can also gain first-mover advantages by tapping into emerging markets in energy production and carbon storage. The scale of these opportunities varies by scenario – not just by level of climate ambition, but also by how mitigation targets are met through government policy and broader societal shifts. We expand on these transformations and what they mean for agricultural firms and their supply chains in the following sections.

3.1 Policy & Legal

Increased policy action to safeguard forest land and biodiversity has already translated to increased risks and liabilities for supply chains relying on deforestation. Liabilities for firms operating near protected areas will continue to increase as governments impose further restrictions to stop deforestation. In parallel, the adoption of GHG pricing policies make the production of emission intensive commodities more expensive. Although the overall impact on firms' profit will depend on factors such as a company's vertical integration or position along the supply chain, the higher risk of asset stranding will incentivize the adoption of sustainable land-use practice.

Policymakers are already starting to act in the land use sector to contain land-based carbon emissions. Because forests represent large sources of relatively inexpensive abatement (Busch et al., 2019), forestry policy has been an early testing ground for meeting climate commitments through two main tools: area protections and emissions pricing policies.

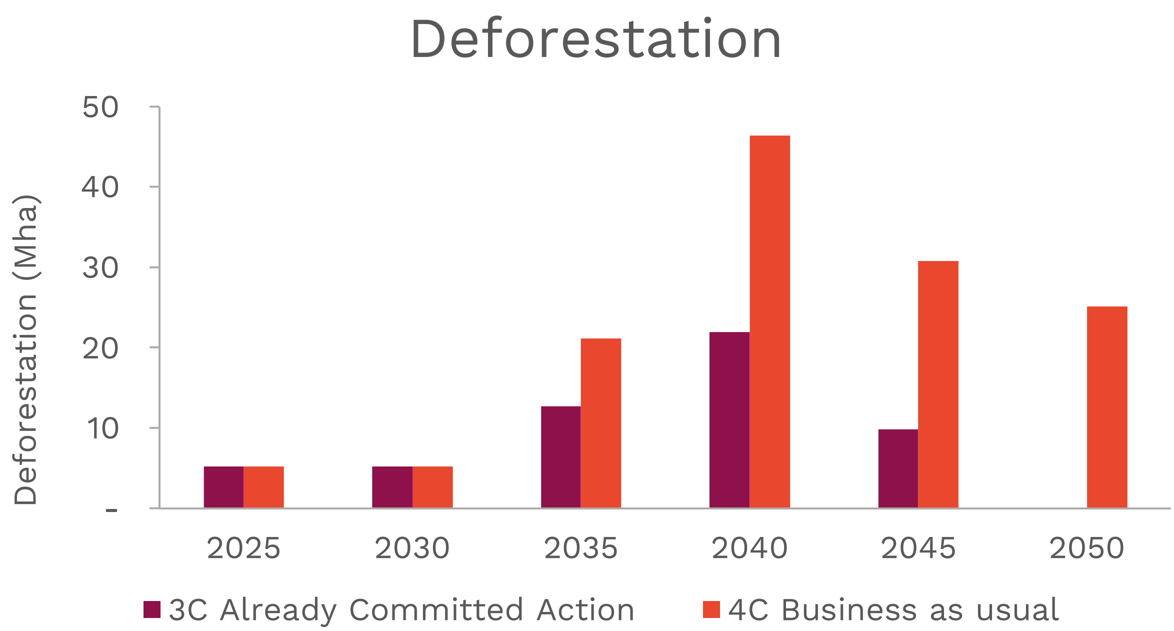
- **Area protection** – Many national governments have expanded their land conservation efforts, as well as increased the monitoring and enforcement of existing designated areas. Several large agricultural exporters, including Mexico, China, and India are on track to meet or exceed their national targets under Aichi Biodiversity Target 11, and pressure is mounting for governments to adopt more land conservation policies (UNEP-WCMC et al., 2018).

- **Emissions pricing** – Domestic carbon markets and international linkage agreements are increasingly being designed to include coverage of the land use sector. For example, New Zealand's Emissions Trading Scheme will cover agricultural emissions starting in 2025 ((ICAP) International Carbon Action Partnership, n.d.).

Agricultural supply chains that currently rely on deforestation are at risk of asset stranding as area protection policies are adopted to conserve carbon sinks. Under the business as usual scenario with no climate policy, 134 million hectares of forestland are lost by 2050. The 1.5°C Strong Ambition LP scenario, which includes a high carbon price as well as an expansion of protected areas, sees net increases in forestland by 2050, both through restoration of degraded land and new forestry.[1] Figure 2 shows that even a very weak carbon price, as is the case in the 3°C Already Committed Action scenario, halts deforestation by 2045. Because climate mitigation targets that limit warming to below 2°C rely on large net carbon removals, deforestation in the 1.5°C scenarios stop before well before 2050 and forest restoration starts in 2025. This comes at the expense of agricultural land, which by 2050 loses between 286 and 604 million hectares relative to the business as usual trajectory, putting agricultural assets at risk of stranding. The areas with the biggest shifts are all tropical agricultural commodity powerhouses – South America in particular, as well as Southeast Asia, Africa and China. Agricultural assets in these areas will at the very least have to stop expanding and may be required to restore forest, depending on whether policies mandate restoration of past degraded land. Business models and assets built upon expanding production area must change.

[1] Protected area expansion also includes better management of existing protected areas and a freeze on protected area downgrading, downsizing, and degazettement.

Figure 2 A 'stabilizing' carbon price halts deforestation by 2050



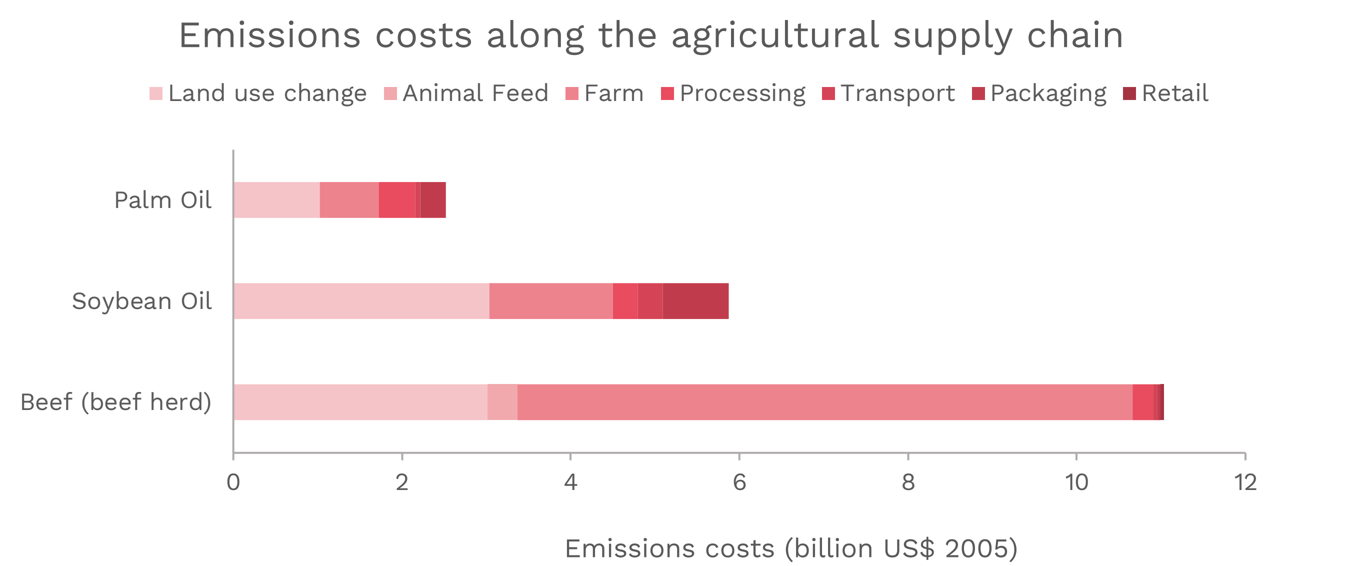
Note: Deforestation is calculated as the change in primary and secondary forest over the preceding five years and does not include loss or degradation of non-forest carbon sinks. Only the 3°C Already Committed Action and business as usual scenarios are presented here. In the scenarios not included, deforestation ceases by 2040 for the disorderly scenario and 2030 in the technology and 1.5°C Strong Ambition LP scenarios, though forest cover changes are net positive as soon as 2025. Deforestation in the business as usual and stabilizing scenarios peaks in 2040 due to declining population growth, leading to decreases in the demand for additional agricultural land.

Source: Vivid Economics

Agricultural companies operating near protected areas are already facing liabilities, which will only increase under scenarios that further limit deforestation. National moratoria and embargoes on production have been implemented domestically in many tropical exporting countries and are already resulting in legal liability and asset stranding for producers of deforestation-linked tropical commodities. AgroSB, a Brazilian cattle producer, and JBS, its buyer, were together fined more than $25m for deforestation in the protected area Lagoa do Triunfo in the Amazonian agricultural frontier (Phillips et al., 2019). Five international commodity giants were fined $29m for buying soy grown in areas without deforestation licenses (Spring, 2018). Because most tropical agricultural commodities are also major export crops, supply chains are exposed to policy risk not just in the country of production, but also in the jurisdictions where products are processed, stored, traded, and sold. For example, the adoption of the Carbon Border Adjustment Mechanism under the European Climate Law would increase regulatory and reporting costs for exporters into the EU (Nordin et al., 2019). Governments have also addressed commodity-linked deforestation unilaterally and independently of linked carbon pricing schemes. For example, France has announced plans to ban deforestation-linked soy, palm, and beef by 2030, introducing more risk of stranding as other importing countries follow (La, 2018).

As emissions pricing policy is introduced into the land sector, emissions-intensive supply chains will face higher costs. Emissions costs per commodity depend on emissions intensities, mitigation targets, the emissions cost in the land sector, and the production volume of the commodity. Figure 3 illustrates total emissions costs along the supply chain for beef, soy, and oil palm. Each is linked to deforestation, meaning a large proportion of their total emissions are incurred when converting carbon-rich tropical forests to crop or pastureland. To the extent that these commodities will continue to be allowed to convert land, they will increasingly be required to pay for the associated emissions. Emissions intensities are particularly high in the beef supply chain, driven by the release of nitrous oxide from the application of fertilizers for feed crops, methane emissions resulting from enteric fermentation and, in some countries in particular, land use change emissions associated with converting forest to pasture (Box 1). These processes lead to annual emissions costs reaching more than $11 billion by 2030 in the 1.5°C Strong Ambition LP scenario, equivalent to 1% of the global beef sector's revenue, which already operates on tight margins. While emissions are particularly high for beef and cattle production, significant emissions are released at each stage of processing vegetable oils as well. Life cycle carbon modelling estimates that each tonne of crude palm produces 0.86 tonnes of carbon dioxide (L. D. C. Chase & Henson, 2010). In fact, while total emissions costs in palm and soybean oil are lower than beef in 2030 in the 1.5°C Strong Ambition LP scenario, the cost as a percentage of sector revenue is notably higher, at roughly 8% for palm oil and 3% for soy.

Figure 3 Tropical commodity emissions costs together reach over $19 billion annually under the 1.5C Strong Ambition LP by 2030



Note: 1.5C Strong Ambition LP; Emissions intensities from Poore & Nemecek (2018) are multiplied with modelled 2030 production results by commodity to yield emissions by each commodity by supply chain position in 2030. The emissions share of each commodity and supply chain position is then multiplied by the total emissions cost to obtain an estimate of emissions costs along the supply chain for each commodity. Emissions costs are GHG certificate prices – these do not include search, information, or trade costs.

Source: Vivid Economics

Firm-level profit impacts depend on the firm's position in the supply chain and its ownership of complementary production processes. Vertically integrated firms will see higher direct emission costs by virtue of being spread across more production processes. For downstream firms in fragmented supply chains, carbon pricing will be reflected in the cost of inputs. Patterns in ownership, market structure and business strategy vary by region and commodity but in general, the production of vegetable oils tends to be more integrated than beef. In oil palm production, economies of scale and the need for fresh fruit to be processed shortly after harvesting give integrated firms an advantage in efficiency (UCS, 2011). Oil palm giants Wilmar and IOI own both plantations and refineries, and are increasingly involved in oleochemical production (Brack et al., 2016). Major players in the soy industry like

Louis Dreyfus and Nidera have extended their reach up and downstream by purchasing both tracts of land for plantations and transportation equipment and infrastructure for distribution (Sebastián Gómez Lende and Guillermo Velázquez, 2018). Cattle production is less vertically integrated in ownership, with contractual agreements and alliances coordinating companies involved in each stage of production (Ward, 1997). More integration in soy and palm means these producers will face more sources of direct emissions costs and possibly higher regulatory burdens. However, they can expect to have more control in mitigating policy exposure and supply chain transparency measures will be less costly to implement. Vertically integrated players are, all else equal, in a better position to reduce their risk exposure via strategies such as passing on cost, implementing improved traceability, and leveraging close supplier relationships, but will need to act decisively to avoid the larger liabilities they face as a result of inaction. Investors therefore must consider the extent to which an investee's management team is aware of impending, jurisdiction specific regulatory constraints, and whether they have a credible plan and balance sheet capacity to effectively manage the uncertainty associated with changes in regulation.

Table 6 Supply chain integration and policy risks

Type of supply chain	Risks and opportunities	Examples
Integrated supply chains	• Vertically integrated firms will face higher emission costs as they cover production processes across the entire supply chain • Vertical integration allows companies to control their operations and mitigate risks and costs along the supply chain	**Oil palm**: Major players own plantations, refineries and are increasingly involved in oleochemical production. **Soy:** Progressive integration both up and downstream, with companies buying land as well as infrastructure for distribution.
Fragmented supply chains	• Upstream firms will have the opportunity to reduce the impact of a carbon price on their operating costs by decreasing the carbon intensity of their production processes. • Overall, a carbon price will increase the cost of inputs for downstream firms. However, the increasing number of reporting tools combined with the growing demand for traceable products represents an opportunity for firms to pass the cost onto consumers.	**Beef**: Contractual agreements and alliances help companies coordinate throughout the supply chain.

Source: Vivid Economics

Heightened risk of asset stranding and emissions costs along the supply chain will incentivize an industry-wide shift to sustainable land use practices. Commodities with high process emissions, such as the cattle and dairy industries, will need to adopt measures to reduce on-farm emissions. Technology options may include the development of feed additives and nitrification inhibitors to reduce emissions from enteric fermentation and fertilizers. Other management practices in the form of rotational grazing, improved animal waste management systems, and adoption of agroforestry practices can reduce emissions in the cattle supply chain and are already implementable at scale. Productivity investments across commodities will be required to improve output per area and reduce reliance on emissions-intensive land conversion.

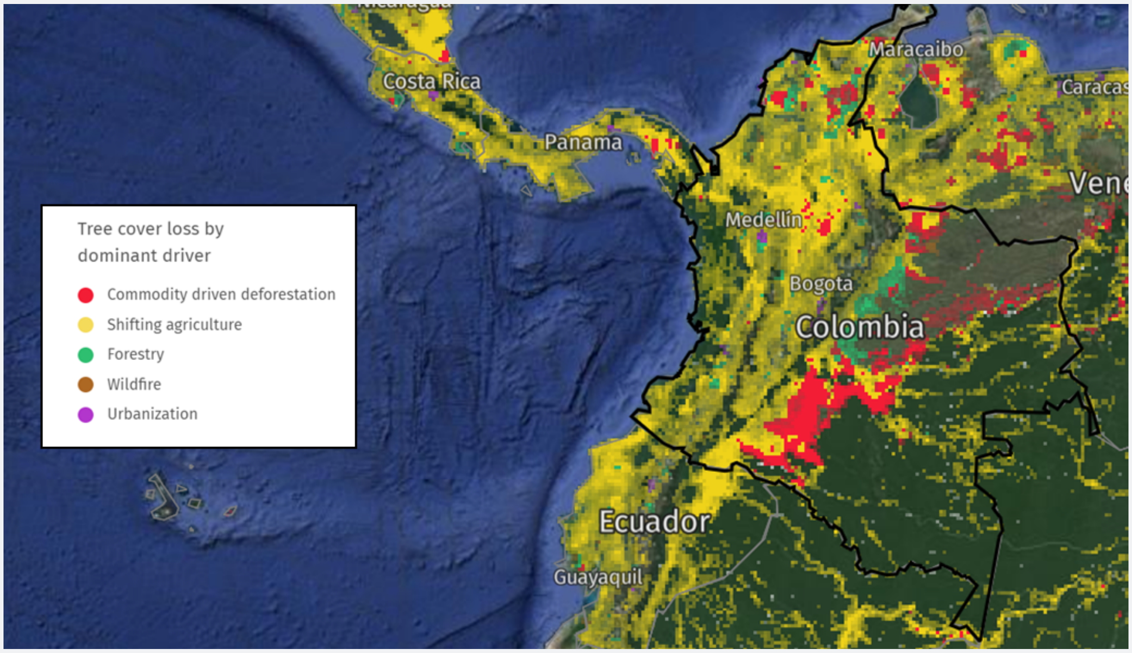
Box 2 Colombian beef exposed because of associated land use change

The high emissions-intensity of the beef sector in Colombia, and its strong ties to deforestation, mean the sector is highly exposed to policy and legal risks. According to FAO data, Colombia has the second highest beef emissions-intensity among the top 20 beef producing countries (FAO, 2019b). This high emissions intensity is driven by high rates of deforestation that have historically accompanied the expansion of beef production in the country. Etter et al. (2006) find that 35% of the total land area of Colombia was cleared by 1998 and that 68% of this cleared land was converted for grazing, mostly for extensive grazing of beef cattle. Figure 4 shows this trend has continued into the past two decades, with large sections of the country experiencing additional deforestation due to shifting agriculture. A recent Colombian court order found that 60% of deforestation in the country is caused by land grabs, the majority of which is used for cattle ranching (Volckhausen, 2019). Consequently, 45% of livestock emissions in Colombia come from deforestation for the planting of pastures (Tapasco et al., 2019). As carbon prices phase into the land sector, the competitiveness of Colombian beef will be negatively impacted due to higher costs of emissions relative to competitors. This could be particularly detrimental to the sector as it already suffers from low productivity and competitiveness (de Wilde et al., 2018).

Colombian beef exports face substantial market risk, and Colombia is likely to miss out on potential growth in global demand for meat unless practices are changed. Exports of Colombian beef are currently small, at approximately 4% of total production, largely due to low sanitary standards and the poor cost competitiveness of the Colombian beef sector (de Wilde et al., 2018). As international buyers place more focus on emissions and deforestation associated with beef production (Chain Reaction Research, 2018), Colombian beef is likely to look even less attractive unless measures are taken to improve the sustainability of production processes.

There are steps that can be taken by the Colombian beef industry to become less emissions intensive and therefore reduce its exposure to these risks. Mitigation measures that can be deployed in the Colombian beef industry include agroforestry, increasing productive efficiency and restoring degraded pastures (Tapasco et al., 2019). Multiple initiatives are already working to implement these mitigation measures in Colombia. The Colombian sustainable livestock project has helped transform more than 40,000 ha of pasture to incorporate silvopasture systems while the Orinoquia sustainable bovine production initiative has helped improve the productive capacity of livestock systems on a total of 6,900 ha of pasture (Tapasco et al., 2019). Nevertheless, both projects have been ongoing for the past 10 years, clearly indicating that more action is needed to reduce the sector’s emissions intensity.

Figure 4 Tree cover loss in Colombia by dominant driver between 2001 and the present.



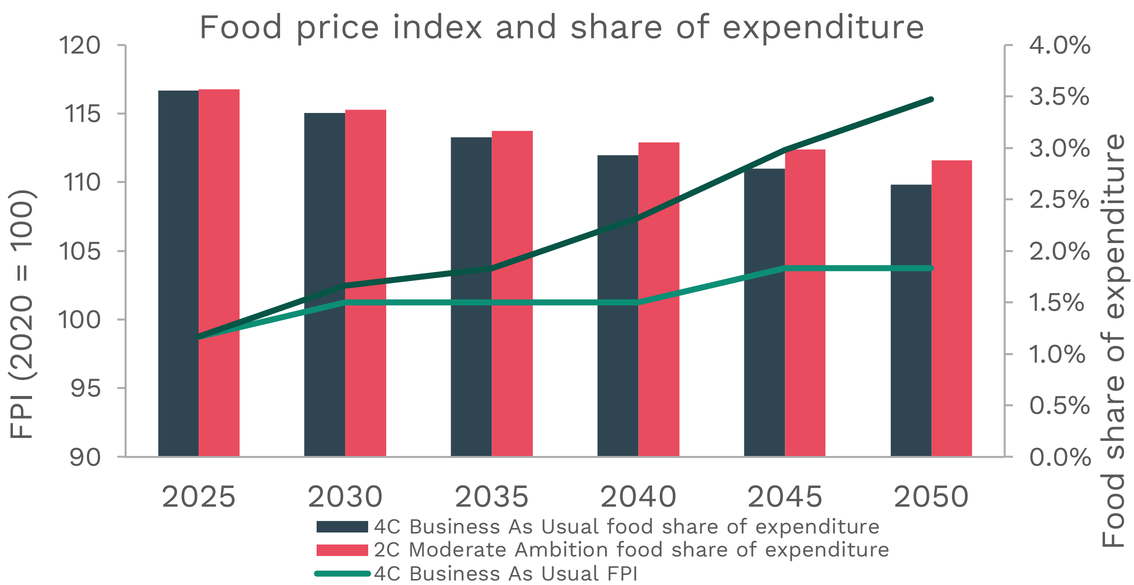
Note: Large sections of the north and west of Colombia have experienced severe deforestation due to shifting agriculture, the majority of which is due to expanding beef production.
Source: Global Forest Watch (2020)

3.2 Markets

Climate policies and carbon prices will affect agricultural commodities across their entire supply chain. For instance, although emission costs will impact only upstream firms directly, they will be reflected in input prices downstream. Additionally, farm-gate prices of most commodities will have to increase to sustain the level of technological change required, particularly under the high ambition scenarios. Finally, consumers will likely change their preferences given the progressively increasing awareness around deforestation and ecosystem degradation. To face these risks, stakeholders in the agricultural sector will need to embrace the shift toward increased transparency and monitoring of supply chains.

Downstream firms operating in fragmented supply chains pay less in direct emissions costs, but upstream emissions intensities are reflected in increased input prices and monitoring burdens. Depending on the rate of cost pass through, processors and distributors receiving raw or intermediate materials pay the cost of their Scope 3 emissions through increased prices. Figure 5 shows the increase in farm-gate food prices that is common across scenarios, with lower temperature targets generally associated with higher prices. As ruminant meat is so emissions intensive, it accounts for a disproportionate share of food price increases. While overall food prices increase 15% by 2050 relative to 2020 under the 2°C Moderate Ambition, prices for ruminant meat increase more than 53%. Firms can guard against Scope 3 emissions costs through sustainable sourcing of inputs, but this will mean investing in monitoring and transparency to vet suppliers. Firms may be able to pass some of these costs on to consumers by charging a premium for sustainability or by participating in labelling and certification schemes. Such monitoring costs, though currently high, may be reduced through wider availability of high-resolution spatial data, as well as the emergence of transparency platforms like Trase and Lucida. Additionally, an increasing number of reporting frameworks and emissions monitoring tools are being developed for downstream firms to quantify emissions in their supply chains (Richards, 2018). For example, the Roundtable on Sustainable Palm Oil (RSPO) has developed a PalmGHG Calculator which can help firms estimate net greenhouse gases released during production (L. Chase et al., 2012).

Figure 5 Rising farm-gate food prices under carbon pricing highlight increasing costs in supply chains



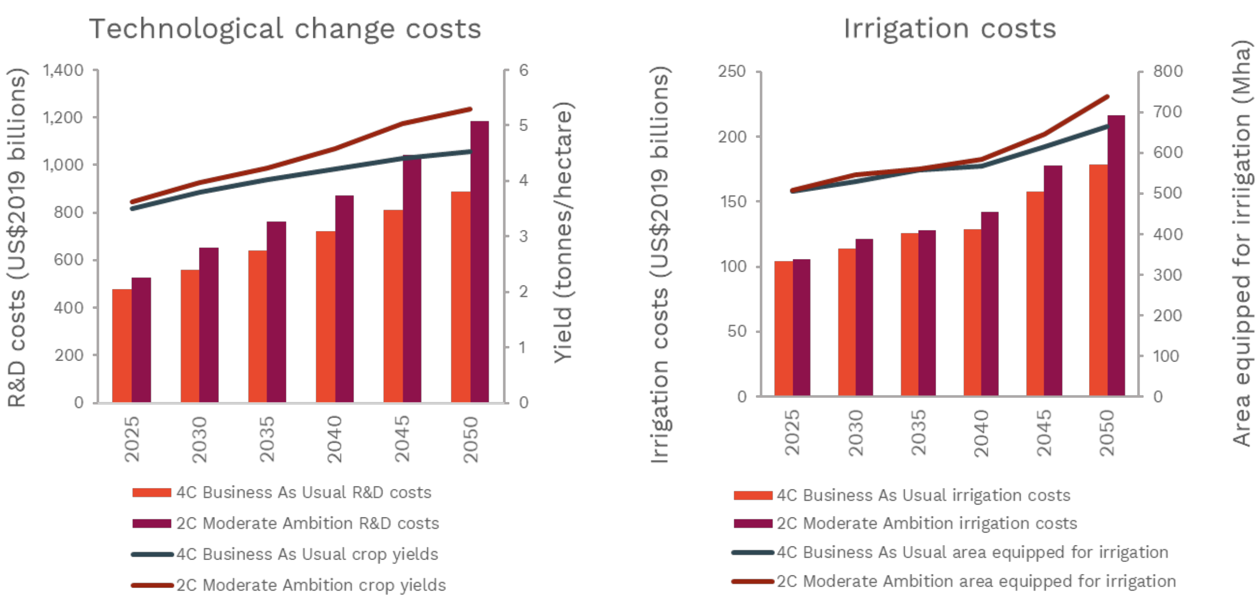
Note: Carbon price takes effect in 2025.
Source: Vivid Economics

Population and development pressures drive investments in farm productivity, also contributing to price increases for raw and intermediate materials. Under a continuation of historic trends and in the absence of a carbon price, yields grow by an average of 1.2% per year between 2020 and 2050. The investment required to support this growth reaches nearly $900 billion annually by 2050, as shown in

Figure 6. Meeting a climate mitigation target requires greater investment. Under the 1.5°C Strong Ambition LP, crop yields grow 1.6% annually from 2020 to 2050, a pace that requires annual investments of at least $1.2 trillion by 2050. These investments will span developments in frontier technologies, such as CRISPR editing of crop varietals or precision nutrient application, as well as agricultural extension services that can fuel catch-up productivity growth in developing economies, through irrigation expansion or improved cropping or management practices. The development of many of these technologies is highly uncertain and may require much greater levels of funding than those called for here. Under business as usual, the percentage of cropland equipped for irrigation increases from 31% in 2020 to 36% in 2050. Carbon pricing increases this percentage to between 49% and 57% by 2050, or 253 Mha of new irrigation globally. Achieving these productivity gains requires a collective investment, and one which, depending on jurisdiction, may be underwritten by policy or bolstered by concessional finance, particularly in cases of smallholders. At best, firms will still have to shoulder some of these costs if they hope to keep pace with global productivity trends, and at worst may be expected to finance most of the cost of research and development and technology deployment. Some countries may choose to reclaim productivity enhancement

spending from larger players by increasing export taxes. Either way, these innovation and agricultural extension costs will be reflected in the price of raw materials downstream.

Figure 6 A carbon price drives up yields by incentivizing innovation and agricultural extension



Note: Carbon price phases in in 2025.
Source: Vivid Economics

Shifting consumer preferences exacerbate demand-side responses to price increases for deforestation- and emissions-exposed products. Increased costs along the supply chain will be passed on to consumers, depressing demand for emissions-intensive products. Ruminant meat is on average the most emissions intensive commodity per unit of production and will see the biggest price increases and resulting reductions in demand. Scenarios with stringent mitigation policy, farm-gate prices for ruminant meat more than double relative to 2020, driven by both emissions costs in the supply chain and increased land competition. The quantity adjustment is highlighted in Table 7, with production falling in absolute terms under aggressive substitution even in the context of growing population and rising incomes. Demand side responses to price increases are likely to be exacerbated by shifting consumer preferences. As unsustainable land management and deforestation-linked supply chains come to be regarded as bad business practice, consumers will demand both greater transparency and a different mix of food products. In addition to demanding less deforestation-linked commodities altogether, consumers may also express preferences for products that are produced sustainably. Labelling and certification schemes, like the Roundtable on Sustainable Palm Oil (RSPO) and Rainforest Alliance Certified Farms, have emerged to help consumers select such options. For example, demand for beef and pork has slowed in OECD countries as consumers become aware of the health and environmental implications and look toward the rapidly expanding alternative protein market for substitutes. In the US, the meat alternatives industry grew by 22% in 2017 and is valued at $1.4 billion (Hirsch, 2017). Sustainable products can command a premium and increase a firm's ability to pass costs onto the consumer, but require investment in both sustainable practice and the supply chain transparency required to demonstrate those practices.

Table 7 Ruminant production volumes under fadeout assumptions

	Production volumes (Mt DM*/year)		
	No substitution	Limited substitution	Aggressive substitution
2020	65	61	58
2030	78	69	60
2040	90	74	58
2050	102	78	53

Note: * Mt DM: Million Tonnes of Dry Matter
Business as usual and 3°C Already Committed Action experience no substitution away from ruminant meats; 2°C Moderate Ambition and 1.5°C Strong Ambition LI see limited substitution; and the 1.5°C Strong Ambition LP highlights the impacts of aggressive substitution away from beef and cattle.
Source: Vivid Economics

Market adjustments will drive a shift toward transparency and increased monitoring of supply chains. Investing in supply chain transparency and traceability is a no-regret strategy for downstream firms in a future in which buyers may pay for their suppliers' emissions and consumers demand greater sustainability. Firms are already signalling their interest in transparency, with 471 companies making commitments to reduce commodity-driven deforestation as of 2017 (Haupt et al., 2018).[2] These pledges are not just a mechanism for firms to address costs in their own balance sheets, but an important means by which downstream firms can exert pressure on primary producers. Adoption of No Deforestation, No Peatland, No Exploitation (NDPE) policies among downstream buyers of Indonesian oil palm has resulted in 6.1 million hectares of stranded holdings and created an expanded market for sustainable growers (Chain Reaction Research, 2017a). It has also handed a comparative advantage to NDPE-compliant growers, who likely would not be economically competitive in the absence of downstream pressure for sustainability. Opportunities within transparency and certification are therefore becoming increasingly investible but have not yet been taken up at scale.

[2] Commitments are highly variable in terms of relevance, scope, specificity, and ambition (Haupt et al., 2018).

3.3 Technology

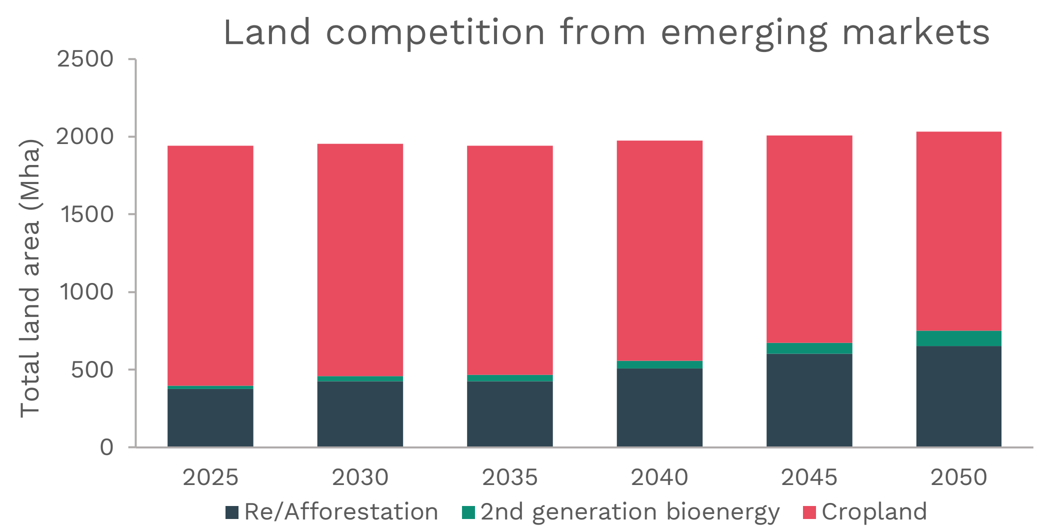
The introduction of a carbon price will sustain the development of new markets for negative emissions technologies, such as that for bioenergy and forest-based carbon sequestration. As the number of potential land uses grows, land competition will increase with important implications for the agricultural sector. Firstly, competition will drive up land values, leading to a "green upside" for landowners, but a potential risk for downstream companies. Additionally, these new markets could represent an important opportunity for farmers and producers to shift away from traditional agricultural production. Finally, low-carbon markets will incentivize the adoption of multi-farming techniques to allow producers to benefit from food production as well as fuel production and carbon-sequestration.

Carbon policy creates the underlying incentives necessary for robust bioenergy and forest-based carbon sequestration markets to develop. The land use sector provides an important resource for both low-carbon energy generation and terrestrial carbon storage, and with some policy supports already in place, landowners are beginning to shift toward bioenergy and forest cultivation. Policy support for forestry projects has been delivered through international agreements such as linked emissions trading schemes and voluntary markets, national and bilateral payment for ecosystem services schemes, and concessional public finance (REDD+-style programmes).[3] Support for bioenergy has already come in the form of research and development financing, tax incentives, national targets, and blending mandates (Carriquiry et al., 2010). While these policies have helped to launch these markets, these packages of support will have to be expanded to attract private sector finance to be deployed at scale (Vivid Economics, 2020). Moreover, the rate at which bioenergy and forest carbon markets will grow will be determined by how quickly these packages are expanded. In all scenarios, including BAU, reforested land increases out to 2040, and even under a low carbon price, as in the 3°C Already Committed Action scenario, bioenergy production more than triples from today by 2030. However, notably higher carbon prices and supporting policies are required to develop these markets quickly enough to keep global warming under 2 degrees, as in the 1.5°C Strong Ambition LI & LP scenarios. These scenarios illustrate two pathways in which different policies interact with high carbon prices to produce divergent land use scenarios. In the technology scenario (LI), a high carbon price with policy support for R&D and deployment of bioenergy uses leads to a booming bioenergy market developing. The 1.5°C Strong Ambition LP scenario, however, has large area protections coupled with a high carbon price to incentivize landowners to invest in large amounts of reforestation.

Emerging markets for bioenergy production and carbon removal will increase competition for land. Productive agricultural land is also generally productive land for carbon storage. As shown in Figure 7, nearly 90 million hectares are converted to production of dedicated bioenergy grasses under the high-growth bioenergy trajectory by 2050 and 386 million are converted to new forest land through reforestation under the same scenario. Opportunities are concentrated in land-rich countries and regions, many of which, by nature of their land endowments, are also large agricultural producers, including China, USA, Southeast Asia, and Central and South America. A substantial amount of bioenergy production is also taken up in Russia and Central Asia, as dedicated second-generation bioenergy crops like miscanthus, reed canary grass, and switchgrass are quite resilient and grow well in temperate climates with freezing winters. That bioenergy and forestry investments are taken on a large scale in many of the same regions indicates a high level of competition and associated price impacts for producers.

[3] In many countries where bioenergy and afforestation represent important potential markets, structural barriers will have to be addressed to boost investor confidence, including in strengthening land tenure laws and ensuring effective governance and institutions.

Figure 7 Bioenergy market potential pathways

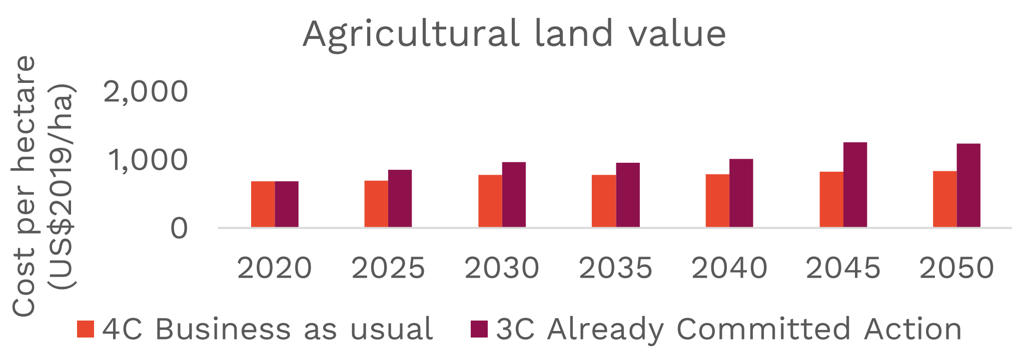


Note: 1.5C Strong Ambition LI scenario
Source: Vivid Economics

Land competition will increase the value of agricultural land. As these markets expand and deepen, bioenergy and forestry will divert land from food production, driving up rents and raw material prices for conventional agriculture (Winchester & Reilly, 2015). Figure 8 illustrates the increasing land values resulting from the 1.5°C Strong Ambition LP scenario, which are more than 50% higher than the business as usual scenario by 2050. Landowners benefit from these increasing land values. These rents will be propagated through supply chains and on to consumers (Doelman et al., 2020), leaving downstream firms paying higher prices without exposure to the upside opportunities associated with land ownership. Farmers and ranchers who rent their land, or smallholders with insecure tenure may also suffer from this. This highlights the importance of 'just transition'[4] thinking as jurisdictions work to design carbon policy.

[4] A "just transition" is an approach that combats climate change and protects biodiversity while assuring workers' rights and livelihoods

Figure 8 Carbon policy increases land value as a result of increasing optionality to grow and store carbon



Note: Reported land costs are long run global averages, and not representative of local real estate prices. Land prices are strongly impacted by local characteristics and policies, but the values reported here are indicative of underlying dynamics.
Source: Vivid Economics

Bioenergy and carbon removal markets represent opportunities for conventional agricultural producers to pivot. The scale of the potential bioenergy market is laid out in Table 8. Under the high demand pathway considered in the 1.5°C Strong Ambition LI scenario, the size of the global bioenergy market will reach an annual $303 billion by 2050, surpassing the 2050 market value for soybeans ($199 billion). This is nearly 70% the size of today's global natural gas market, which in 2018 sat at $445 billion (IEA, 2019; US Energy Information Administration, 2020). The emerging reforestation sector also represents a market on scale with many traditional commodities. The total value of land-based removals (rewarded at the carbon price) reaches as much as $112 billion annually by 2050, approximately 22% of today's entire global forestry and logging products market (The Business Research Company, 2020), under the 1.5°C Strong Ambition LI scenario.

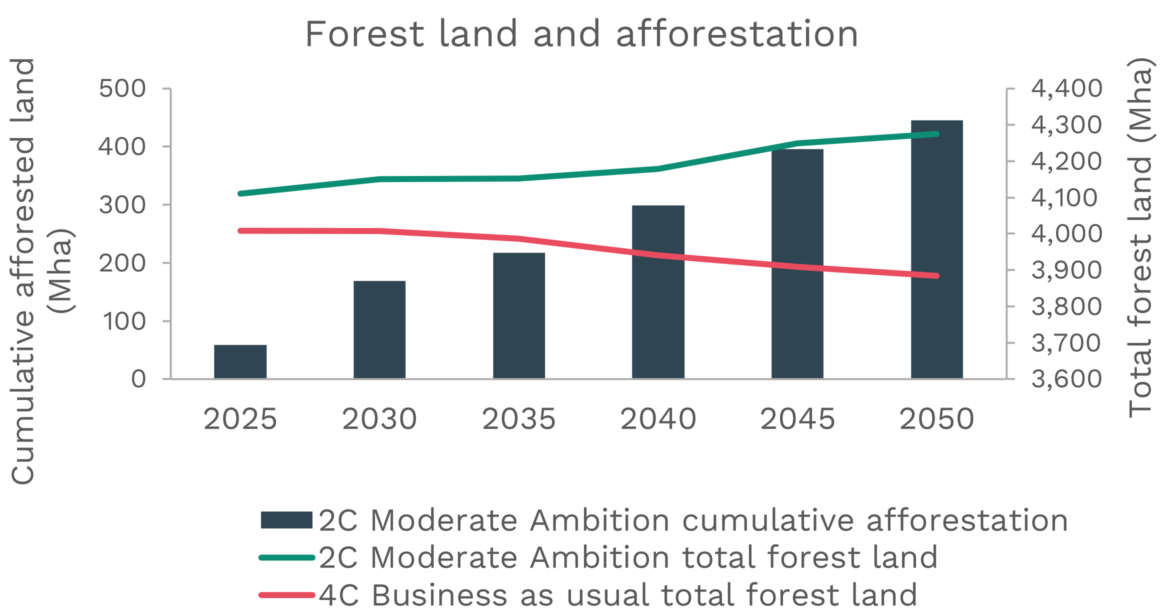
Table 8 Bioenergy market potential pathways

Year	Size of the global bioenergy market based on demand trajectory (US$2019 billion)		
	Low	Medium	High
2020	15-16	15-16	15-16
2025	18	32-34	40
2030	20	51-56	84
2035	18	47-49	105
2040	16	34-38	125
2045	17	26-31	197
2050	16	24-29	303

Note: Calculation based on modelled production volumes and prices – does not account for profit margins.
Source: Vivid Economics

Figure 9 illustrates that, under the high carbon price in the 1.5°C Strong Ambition LP scenario, landowners decide to reforest nearly 450 million hectares of land by 2050. Depending on local prices, supply chain structure, and considerations of land suitability, these outside opportunities will lead landowners to reconsider the most productive use of land. Vertically integrated firms can benefit from both of these markets, but pivoting into a new business area will require agile and active management, and sufficient capital to cover significant upfront costs in land conversion and supply chain reconfiguration. Carbon storage payments can be very profitable, but it will take years for investments to mature. Those firms that aren't landowners may be able to seek exposure to this green upside through contracting with suppliers, perhaps by funding some of the investment required for agroforestry or regenerative agriculture solutions in exchange for predictable prices, supply, and a share of carbon payments. Other mutually beneficial risk sharing arrangements may be possible.

Figure 9 An aggressive carbon price is needed to overcome high establishment costs for afforestation



Note: Calculation based on production volumes and prices – does not account for profit margins.
Source: Vivid Economics

Emerging low-carbon markets will drive a shift toward mixed-use land management. Multi-use farming systems allow land managers to simultaneously benefit from fuel production, sequestration, and/or traditional food production. Such management systems are a low-regret strategy for land managers wishing to proactively manage the low-carbon transition, as this approach minimizes land conversion costs and builds an energy crop or forest stock while incentive schemes are being ratcheted up. For investments that take time to mature (like afforestation), agroforestry and regenerative agriculture are sensible management strategies to maintain an income stream for land while it is being converted to an alternative use. Additionally, as second-generation bioenergy plants are resilient, efficient, and able to grow on marginal land as well as in relatively temperate climates, they represent an opportunity that does not have to displace traditional agriculture (Perpiña Castillo et al., 2015).[5] Furthermore, managing for multiple uses can generate other benefits: landowners spread risk by diversifying production and can take advantage of synergies between productive uses of land, in terms of nitrogen fixing, soil productivity, and resilience to climate change.

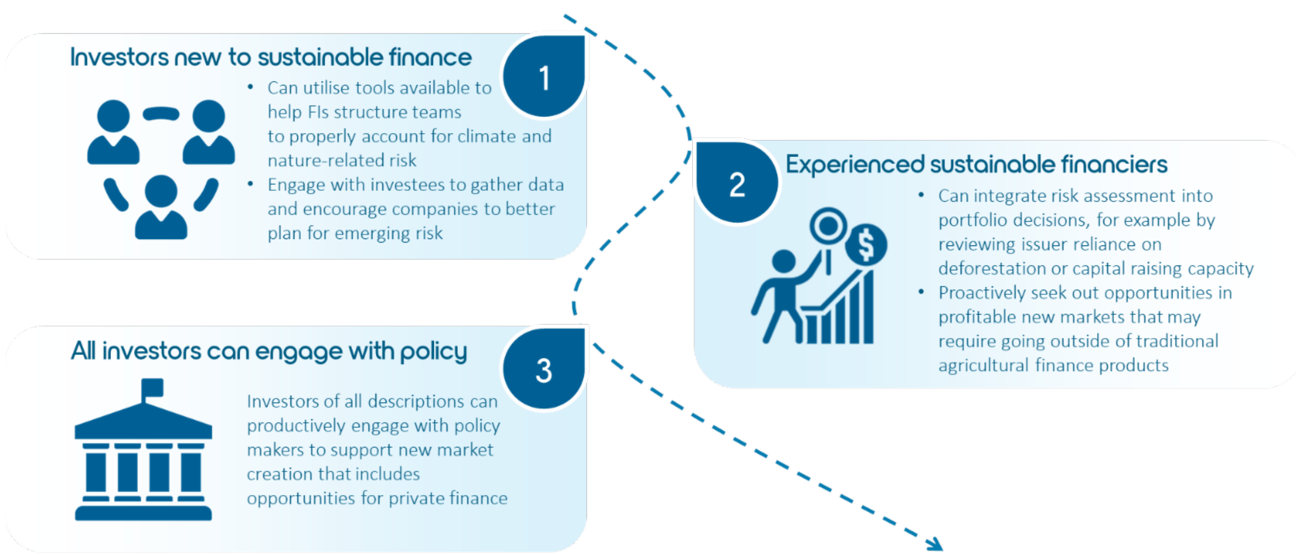
[5] Modelling has only considered the production of grassy and woody biomass for energy production, but agriculture and forestry residues and wastes, as well as solid municipal wastes, can be used for bioenergy production as well (Union of Concerned Scientists, 2014).

4 IMPLICATIONS FOR INVESTORS

The coming transitions in agriculture and land use will create a variety of opportunities and risks for investors to adjust to. Investors in global agricultural commodities will need to adopt climate- and nature-related risk into their portfolio decisions, and restructure themselves if necessary to enable that. After choosing to invest in companies, asset owners need to engage with investees to encourage action to reduce risk and maximize upside opportunity. Proactive investors also need to be positioning themselves to take advantage of markets set to boom, including exploring nature-based solutions. Finally, investors should be engaging with policymakers to ensure emerging markets are structured in such a way that private finance can play a role in bringing about a swift and just transition.

Investors at all levels of experience with the principles of sustainable finance can better their position for the coming transitions in agriculture. Investors brand new to sustainable finance have never had more available tools to begin integrating climate and nature-related risk into their teams and engagements with existing investees. Investors that have already started to do this can go further by implementing risk assessment specifics into investment-level decisions and proactively seeking out new sustainable opportunities, for example in carbon sequestration or supply chain transparency. Forthcoming reports from Orbitas that build upon the analysis presented in this paper aim to equip investors with more detailed information on specific country-commodity pairs for use in such decisions. Finally, investors at all levels can engage with policymakers to support market creation as new policies unfold. Figure 10 below summarizes.

Figure 10 Investors can better integrate climate and nature-related risk into decision making and engagement



Source: Vivid Economics

Investors can work within the current market framework to reduce risk

Investors have a wide variety of tools at their disposal to better understand and prepare for the coming transitions. The framework developed by Task Force for Climate-related Financial Disclosures, and included in Section 3, is only one of many resources that investors and companies can use to better understand and internalize climate-related risks. For instance, Ceres has recently published a collection of case studies identifying current best practices in portfolio climate risk management. Common strategies include time-bound targets for emission reductions, the alignment of portfolios with Paris Agreement targets and the scale-up of investment in low-carbon, climate-positive investments (Ceres, 2020). Additionally, organizations such as WWF and UNEP are partnering with financial institutions to create a new Task Force on Nature-related Financial Disclosures (TNFD). The aim is to broaden the scope of reporting to include nature-related risks other than climate change and to establish what metrics and data financial institutions need to understand their dependencies and impact on nature.

Beyond the broad frameworks laid out by the TCFD and TNFD, a variety of organizations offer practical tools to help implement scenario analysis and improved due diligence standards. Ceres, UNEP-FI and UNPRI all have a variety of materials designed to help investors get started with the principles of sustainable finance, including working groups with investor signatories focused on topics relevant to the agriculture sector, such as deforestation or land use change risks. Some initiatives, such as the Inevitable Policy Response, or forthcoming research from Orbitas, offer investors actionable information on how transition scenarios are likely to impact company valuations or other bottom-line business metrics that can be used to support higher standards of due diligence.

Investors can use such tools to engage with companies and asset owners to develop long-term investment strategies that account for emerging risks. Because the impact of climate change may affect asset returns across the board, divesting from particular asset classes may not be enough to avoid nature-related risks (TCFD, 2017). Therefore, it is important that investors work together with investees and encourage companies to consider the following actions:

- **Decarbonize inputs, including electricity and agrochemicals.** As illustrated in Sections 2 and 3 of this report, the introduction of a carbon price will make carbon intensive activities more costly. To reduce their emission expenditure, firms involved in particularly energy intensive supply chains, like poultry, or processes such as meat packing should start investing in energy efficiency and decarbonizing their energy sources. The same is true for agrochemicals as the manufacturing of pesticides and synthetic nitrogen fertilizers require large amounts of energy and natural gas, and their application can be incredibly damaging to ecosystem health and biodiversity. In 2014, wheat and rice producers in the United States spent about a third of their total cash expenses on energy-based fertilizers and pesticides (USDA, 2016). With a carbon price and increasing land protections, their cost is only going to increase making sustainable agricultural practices progressively more appealing.

- **Diversify business models**. Currently, the largest meat producers rely on highly efficient large-scale production systems to sell substantial volumes of meat with small profit margins. The introduction of carbon prices could erode companies' profits and disrupt their system of production. To mitigate this risk, companies should be thinking about diversifying their business models to both reduce downside and position themselves for upside:

    - ◊ **Diversify production portfolios:** Investing in a range of low-carbon products could help companies reduce exposure to specific inputs and geographies. Companies invested heavily in beef, for example, could consider diversifying their protein sources to be less reliant on fragile supply chains for feed and inputs. JBS, the largest meat processing company globally, has recently bought Pilgrim's Pride, the second largest US chicken producer, along with other beef, pork and poultry companies around the world. Exploring meat alternatives, which have much lower carbon footprints, could combine benefits of diversification with decarbonization. JBS has done this by acquiring a US company called Planterra Foods launching its own brands of plant-based meat, one in the US called Ozo, and one in Brazil called Seara (The Counter, 2020). As plant-based meats can often include large quantities of soy, companies need to ensure they do not end up substituting a product in an at-risk supply chain for another one with similar risk exposure.

- ◊ **Explore and encourage alternative land management models**. There is increasing evidence that agriculture conducted with thoughtful soil management can promote net carbon sequestration in grasslands and mixed agroforestry plots. For livestock, carefully *extensifying* management and mixing it with other crop production could be a low-carbon alternative to intensive feed lots and factory farms. A variety of models are possible and still being explored, including agroforestry, but broadly regenerative and polyculture agriculture can dramatically reduce emissions, improve ecosystem health and even achieve net negative emissions thanks to soil sequestration. Moreover, reduced reliance on chemical inputs can result in net profitability increases. Where it is not possible to shift livestock away from intensive operations that rely heavily on feed, companies could resort to feed additives, such as lemongrass or seaweed that can help reduce methane emissions by a third or more.

- ◊ **Explore alternative land ownership models**. The opportunities associated with carbon policy are likely to accrue to landowners. The prevalence of land ownership among large agricultural companies varies by commodity, but companies in many supply chains own almost none of the land from which they source products. Companies could explore alternative models of production in which they take a greater role in land stewardship or carbon and biodiversity offsets in order to gain greater exposure to the emerging markets in these areas. Any transfers of ownership would need to be done carefully and inclusively as part of a just transition.

- **Shore up supply chain liabilities, including deforestation**. The Policy and Legal risks portion of Section 3 outlines how supply chains engaging in deforestation increase their climate risk exposure. At this time, numerous initiatives including Trase and Chain Reaction Research are actively trying to estimate the value at risk for companies through this channel, which can be a valuable resource for investors. Additionally, investor initiatives like UNPRI and Ceres initiatives on sustainable forestry and agriculture have worked on identifying the legal and regulatory risk associated with deforestation and ecosystem degradation. Investors can use these resources to reduce their risk exposure.

Investors can also explore ways to participate in profitable new markets outside traditional agricultural finance and investment

Once investors have built capacity to assess risk in their existing portfolios, they can begin incorporating risks and opportunities into forward-looking investment decisions and portfolio management. Follow up analysis based on the modeling presented in this report will be released by Orbitas later in 2020. A series of analyst reports on palm oil in Indonesia and Peru, as well as beef cattle in Colombia, will explore these country-commodity pairs in detail, outlining modeled impacts on profitability and a variety of other metrics for companies active in these supply chains. This information, alongside investor's own due diligence and data gathering efforts can support decision making at the investment level. For example, investors could seek to identify issuers' dependence on deforestation or stranded assets to generate operating income, or review the capital raising capacity of currently bankable issuers under various transition scenarios. Such information could then be folded into investment decisions and portfolio strategy.

Beyond downside risk, a transition to a low-carbon and climate-resilient world will result in a sizeable green upside opportunity that may require proactive investor engagement to unlock. Under current NDCs, it is estimated that global carbon markets could mobilize annual trade of US$185 billion by 2030 across energy and land-use and between US$350 billion and US$1.9 trillion by 2050 under 2 degree-consistent targets (Ecofys and Vivid Economics, 2016). In this context, investors need to explore the opportunities connected to the transition, particularly those linked to the development of nature-based solutions (NBS) to climate change. The global offset market could grow from less than a billion dollars in 2016 to about $200 billion in 2050 (Bloomberg, 2019), about five times the size of the soy food market. However, the full development of the offset market will require significant transformations in the forestry and agriculture sectors and a massive scale-up of investment, whether in land acquisition or land management operations and supporting infrastructure. Investors can be thinking about two areas of rapidly growing opportunity:

- **Nature-based solutions in forestry:** The creation and expansion of carbon markets is already beginning to unlock revenue streams and allow a shift to new mechanisms for sustainable forest management practices suitable for private investment. Examples include: green bonds that securitize sustainable farming projects that are either too small for investors or that are developed by a government or NGO; distressed asset models where investors purchase and restore deforested land and capitalize on the value stream from its carbon stock; stewardship models where leaseholders receive carbon benefits for their restorative land management; or carbon farming agreements where investors put the initial capital needed to purchase the land and to afforest it and then receive a periodical payment as the carbon sink starts generating revenues. Investors can explore these models by encouraging well-positioned companies in their portfolios to invest strategically, seeding and scaling-up funding in specialist funds, working with banks to finance and securitize forest projects and sell these on to capital markets, and they can promote the use of green bonds to credibly channel large investment commitments into forest finance markets. A forthcoming Forest Finance paper from the Inevitable Policy Response project explores these opportunities in greater detail.

- **Regenerative agriculture:** Polyculture, agroforestry and regenerative agriculture models could be explored by incumbent actors, as discussed in Section 3.3, but these models are currently developing largely outside of conventional investment opportunities. Regenerative agriculture broadly often requires transition finance, as yields suffer in the short term after farms stop using extractive conventional agriculture techniques such as those that rely upon agrochemicals and tillage. The increased profitability, higher prices for outputs, and sometimes improved total land productivity that come with regenerative practices can take years to establish. Conventional agricultural lenders are often unwilling to finance such transitions, but a variety of models are being explored to connect farmers with the financing they need, ranging from cooperatives to insurance provision. The market is maturing enough, with ticket sizes occasionally approaching $40-50 million and commercially competitive returns, for investors of all sizes to be able to start getting involved (1 2 Tree, 2020).

Policy shifts may require engagement with policymakers to ensure a role for private sector finance in emerging markets

Investors should consider moving rapidly and proactively engaging with policymakers to identify where the most investible opportunities are and support market creation. By collaborating with public institutions, investors will be able to guide the development of novel markets that work well for private financing and can scale up quickly. To participate in global markets, mitigation options must be credible, with policies establishing accurate baselines, addressing concerns regarding leakage and permanence, and avoiding the double-counting or double-claiming of mitigation outcomes. In this context, investors' aim should be to support national governments by ensuring that countries adopt the right policy mix within a credible system of international rules. Investors can also help ensure the nature-based mitigation markets and policies incorporate considerations like the Just Transition and protection of biodiversity. Good performance on broad Environmental, Social and Governance (ESG) criteria helps not only strengthen mitigation effort but also long-term sustainability and may accelerate the scale up of finance by addressing areas of stakeholder concern and possible opposition.

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Appendix A: Commodity Deep Dives

This Appendix considers the specific risks and opportunities associated with select agricultural commodities: Palm oil, beef and soy. These tropical soft commodity supply chains are highly exposed to transition risk, as they are closely linked to deforestation in carbon-dense and ecologically valuable areas, and each of them is exposed through high emissions intensities along the supply chain. In this section we describe how societal shifts the world is expected to undergo in the transition to a low-carbon economy play out in commodity supply chains and markets.

The market for tropical soft commodities has surged over the past 20 years, fuelled by international demand, mostly in the European Union and China. Liberalized trade policy supports the development of valuable export markets in a few producing countries. A study found that eight countries account for the majority of palm oil, soy, and beef exports (Persson et al., 2014). Between 1990 and 2008, palm oil, soy, and beef together were responsible for 76% of agriculture-driven deforestation, or 2.6 gigatons of CO_2 per year (Brack et al., 2016; Pendrill et al., 2019). Between 29% and 39% of deforestation-linked emissions were driven by export markets (Pendrill et al., 2019). While there are indications that policies put in place to curb tropical deforestation are working, but it is too early to draw firm conclusions. Government-led policy, including expansion of protected areas and REDD+ policy support, as well as bottom-up voluntary commitments, pledges, and moratoria have resulted in a levelling off and even a decline in deforestation in recent years. (Boucher et al., 2011; Haupt et al., 2018). However, there is much debate surrounding actual rates of tropical deforestation and speculation that a levelling off in deforestation is an artifact of specific and localized land use dynamics (Nepstad et al., 2014; Trase, 2018).

A.1 Oil palm

The following section examines the risks and opportunities faced by the oil palm supply chain. Demand for oil palm has increased over the past two decades due to its caloric efficiency, low cost of production, and versatility. However, palm oil is one of the most emission-intensive vegetable oils as its production is linked deforestation of tropical peat land. After recent extreme fire seasons were linked to the unsustainable practices surrounding palm oil production, increased consumer awareness has put pressure on the entire supply chain. Additionally, the expansion of protected areas is progressively restricting the land available to plantation owners, increasing production costs. Plantation owners and palm oil producers should invest in certification and on-farm productivity.

Oil palm's efficiency per hectare, low cost to produce, and versatility as an input into processed goods has led to a surge in demand over the past 20 years (Vijay et al., 2016). Production nearly doubled between 2003 and 2013 and accounts for at least 8% of global deforestation (Brack et al., 2016). Because oil palm is best suited to carbon- and species-rich peat forests in the humid tropics, most of its impacts have been concentrated in a few major exporting countries, primarily Indonesia and Malaysia where the effects of its production have been devastating in Sumatra, Kalimantan, and Papua (GFW Fires). For example, oil palm production accounts for 20% of total deforestation on the species-rich island of Borneo (Gaveau et al., 2016).

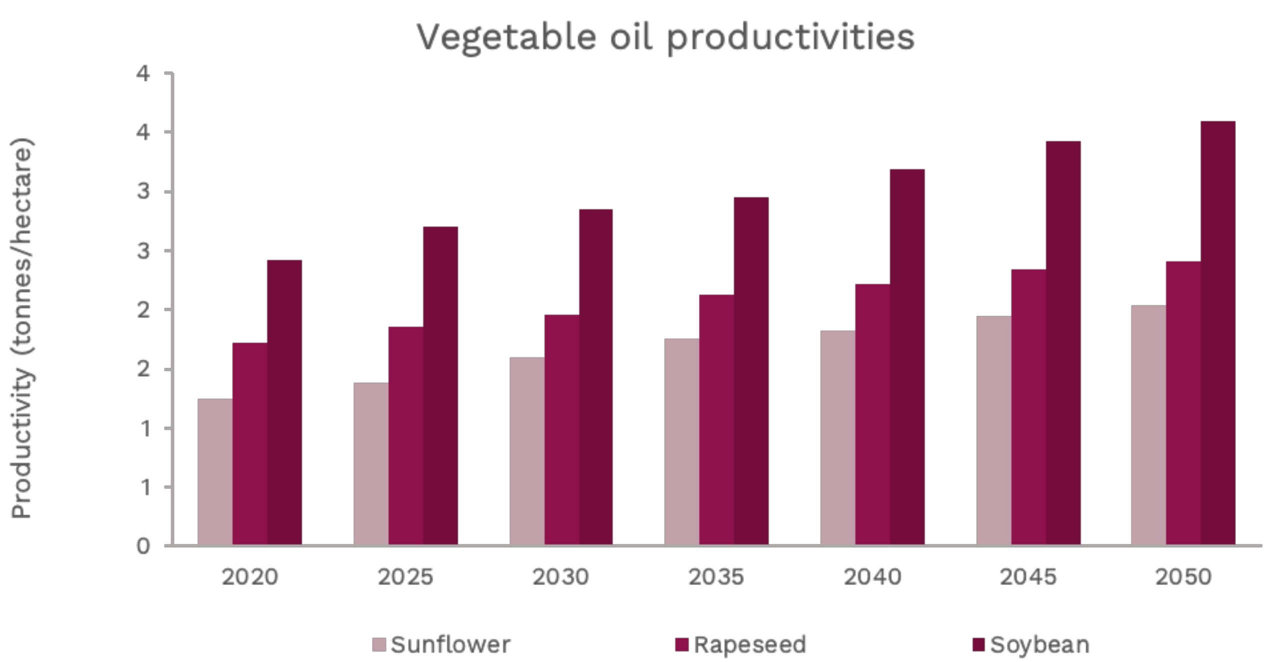
The conversion of tropical peat forest to palm plantation is particularly emissions intensive. The tropical peat forests where oil palm is best grown are vast carbon sinks, sequestering more carbon than all other vegetation types combined (International Union for Conservation of Nature, 2017). Indonesia and Malaysia together produce 80% of the global oil palm crop and they are home to some of the world's most ecologically valuable peat forests.

They have suffered the greatest losses from the burning, clearing, and draining of peat forests and swamps. In Indonesia alone, fires that were set to clear these dense peatlands to make way for oil palm cultivation released nearly 16 million tonnes of carbon dioxide a day in 2015 (International Union for Conservation of Nature, 2017).

Particularly devastating fire seasons have increased consumer awareness, which has turned up pressure on buyers to source sustainable palm. As of 2017, more than 150 oil palm buyers had made forest-related commitments, with many committing to No Deforestation, No Peatland, No Exploitation (NDPE) policies. This has led to stranding of more than 6 million hectares in land holdings in Indonesia alone (Chain Reaction Research, 2017a). Producers switching to sustainable palm production now stand to gain from early-mover advantage (Box 3).

Despite highly damaging effects, oil palm stands at a comparative advantage relative to other vegetable oils by virtue of its high per-hectare productivity, low cost, and versatility as an input in processed consumer goods (Vijay et al., 2016). As competition for land intensifies, oil palm may be favored over alternative vegetable oils as a transition to rapeseed, soy, or sunflower oil would require *more* land conversion to keep pace with demand. However, while oil palm is highly productive relative to other vegetable oils, there is a large yield gap in practice, indicating significant productivity gains can be made. Figure 11 shows that these productivity gains are exploited in the 1.5°C Strong Ambition LP scenario and lead to oil palm having over double the per-hectare productivity as sunflower and rapeseed oils do by 2050. These investments would lower emissions costs by reducing the need for extensive land conversion.

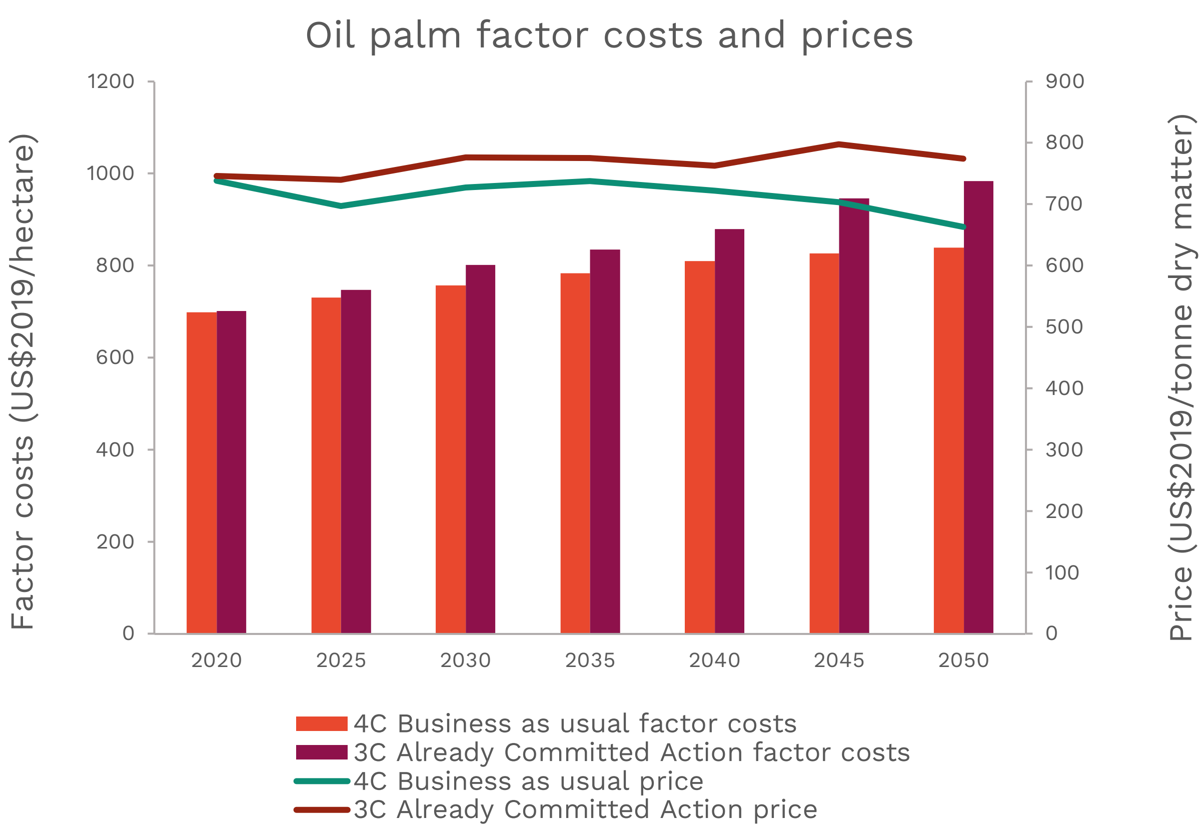
Figure 11 Productivities for vegetable oils including oil palm (1.5°C Strong Ambition LP, 2020-2050)



Note: This figure includes results from the 1.5°C Strong Ambition LP scenario only.
Source: Vivid Economics

Expansion of protected areas restricts land available for cultivation and drives further productivity growth in oil palm. The combined effects of expanded protected areas and a high carbon price mean area under palm oil cultivation is reduced by 10 million hectares by 2050 under the 1.5°C Strong Ambition LP. However, a more than doubling of productivity allows production to keep pace with business as usual trends and demand growth, even as land is taken out of production. Investments in productivity enhancements are fed through the supply chain, leading to a more than doubling of factor costs and a 43% increase in oil palm prices at the farm gate. Figure 12 compares oil palm factor costs and prices under the 1.5C Strong Ambition LP and business as usual scenarios. The business as usual trajectory outlines the no-policy counterfactual, highlighting the impacts of the societal shifts that occur in a 1.5°C Strong Ambition LP. In the absence of pressure from carbon pricing and protected area expansion, factor costs begin to plateau by 2045 and prices fall starting in 2030.

Figure 12 Increased per-hectare factor costs reflect higher competition along the supply chain



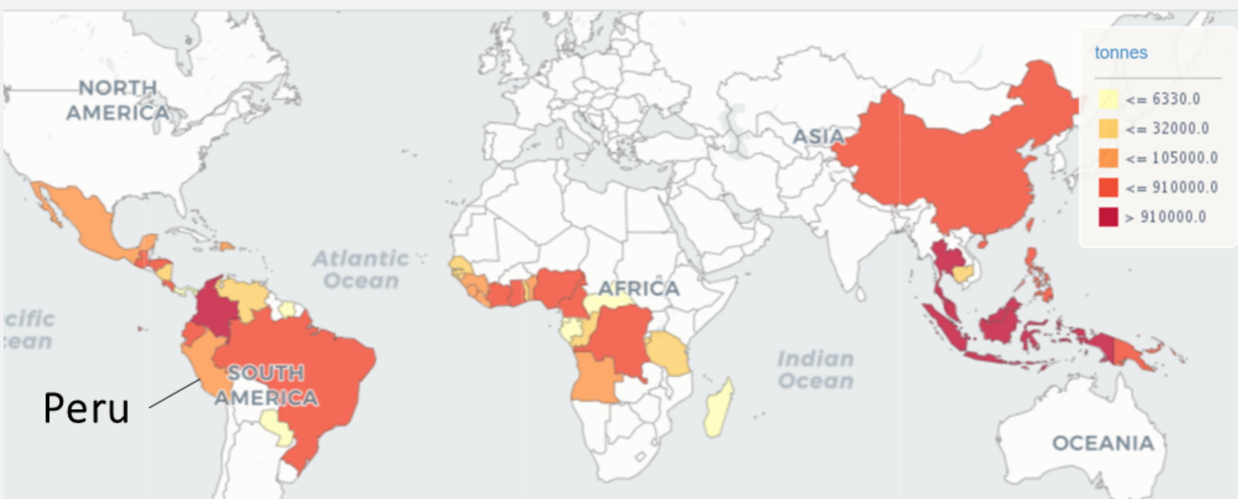
Note: Note that factor costs include cost of capital, labor, and energy. They do not include emissions costs.
Source: Vivid Economics

These findings imply that plantation owners need to be investing heavily in improving on-farm productivity. A reduction in the total area use for palm oil cultivation means there will be greater competition for land suitable for palm oil plantations. If owners do not invest in productivity improvements, they will be outcompeted and replaced by more efficient plantations. This also has implications for oil palm mills. Mills must ensure they source palm from efficient plantations to minimize the risk of supply disruptions due to closure or acquisition of uncompetitive suppliers. While oil palm is already highly productive per hectare relative to other vegetable oils, maximum theoretical yields have been estimated to be nearly three times current yields (Woittiez et al., 2017). Substantial yield enhancements can made through advancements in plant science, including through development of hybrids and parsing of the genomic sequence to enhance photosynthetic processes and pollination requirements, for example. However, the lowest-cost, highest-yield starting point is to close the yield gap for smallholders through agricultural extension services and ensuring smallholders have access to the highest-yielding varieties and best fertilizers (Barcelos et al., 2015).

Box 3 Peru has positioned itself as a leader in sustainable palm oil production, creating opportunities for the domestic sector.

Despite being a small producer, Peru is taking action to become a world leader in sustainable palm oil production. With production of about 100 000 tonnes of palm oil in 2014, Peru produces 0.4% of total global palm oil output (Dupraz-Dobias, 2019; FAO, 2019a). While this makes the country one the world's smaller producers (see Figure 11), Peru is making progress toward reaching an agreement with palm oil producers which could soon lead the country to be recognized as a world leader in sustainable palm oil production. Peruvian palm oil has drawn significant attention from international groups due to the potential effect of the crop's expansion on deforestation of the Amazon (USAID, 2015). This attention has brought with it international pressure on producers to commit to zero-deforestation production of palm oil (Saccone, 2019). After two years of negotiation, in summer 2019, the Peruvian Palm Oil Producers' Association committed to entering into an agreement for sustainable and deforestation-free palm oil production (Saccone, 2019). This commitment could end palm oil related deforestation by 2021 and make the country one of the world's first producers to put an end to all its deforestation-related production. If this shift is achieved, Peru's status as a small producer will likely have played a large role *in this success, enabling it to monitor and enforce the agreement more easily than larger producers.*

Figure 13 Palm oil production by country.



Note: Peru is a relatively small producer of palm oil, contributing less than 0.5% to the global supply.
Source: FAO (2017)

Commitments to sustainable palm oil production have the potential to benefit individual companies which act first and the Peruvian palm oil sector as a whole. After pressure to produce zero-deforestation palm oil, Peru's largest producer, refiner and exporter of palm oil, Grupo Palmas, released its No Deforestation, Do Peatland, No Exploitation (NDPE) policy in 2017 (Chain Reaction Research, 2017b; Monitoring of the Andean

Amazon Project, 2017). Shortly after, the company abandoned plans to develop four palm oil plantations that would have resulted in the deforestation of 23 000 ha of primary forest (Monitoring of the Andean Amazon Project, 2017). Instead Grupo Palmas plans to grow through building stronger relations with smallholder farmers and helping these farmers identify non-forested land where they can expand (Chain Reaction Research, 2017b). Since Grupo Palmas is the first Peruvian company with a NDPE policy, it has enjoyed a first-mover advantage, enabling it to get a head start on building these smallholder relations and establishing itself as Peru's main exporter of deforestation-free palm oil. In addition, large multinational corporations such as Nestlé have committed to zero-deforestation from its suppliers, which presents opportunities for all of Peru's producers (Nestle, 2020). This commitment will likely increase demand for Peru's sustainable palm oil and has already led to investment by Nestle in projects that train farmers to use sustainable agriculture technology to boost productivity and reduce the drive for additional deforestation (Dupraz-Dobias, 2019).

A.2 Beef

Although global consumption of beef is expected to increase in the near term, the sector heavily relies on tropical deforestation to make space for cattle ranching and its stability is at risk. On top of this, the introduction of a carbon price will likely increase the cost of emission-intensive feed production and ultimately drive up farm gate prices of ruminant meat. The following paragraphs will discuss the risks and opportunities arising in the beef sector, focusing on actions that investors and firms could take to avoid significant transition costs.

The exposure of the beef sector to policy risk has drawn comparisons to fossil fuels, with analysts drawing comparisons between the overvaluation of beef and that of coal (Terazono et al., 2019)**.** Beef production is currently the primary driver of tropical deforestation worldwide (Henders et al., 2015; Sy et al., 2015), generating approximately 10% of global emissions (Union of Concerned Scientists, 2013). In South America, between 1990 and 2005 beef production was responsible for 71% of total deforestation. Following this period of high forest loss, deforestation due to beef production slowed after an historic agreement was signed between Brazil's four largest meatpackers and state governments began to take strong legislative action (Union of Concerned Scientists, 2016). Often referred to as the Cattle Agreement, it requires the meatpackers to monitor, verify and report that the beef they receive from supplying ranches is not linked to deforestation. However, recent years have again seen an increase in deforestation in the Brazilian Amazon, largely due to the expansion of cattle ranching (Londono & Casado, 2019). This reversal in trends have prompted a group of scientists to call for meat demand to peak in 2030 in order to avoid further losses of forest to livestock expansion (Carrington, 2019; Harwatt et al., 2020). Further, due to the high rates of deforestation coupled with slow action from meatpackers, recent market research finds that beef production assets are currently at risk of becoming stranded due to climate policy (FAIRR, 2020; Scott, 2019).

Existing systems of cattle production do not use land efficiently and emit particularly damaging emissions. Beef production in the Amazon is characterized by low levels of investment per hectare, frequent abandonment of cleared land and low levels of productivity (Boucher et al., 2011). Rather than invest in improving pasture lands by planting legumes and fertilizing them, it has historically been more profitable for farmers to abandon old pastures and instead clear more forest for new pastures (Boucher et al., 2011). Low productivity is largely caused by cattle ranchers keeping low numbers of cattle per hectare, growth rates of cattle being low and infrequent supplemental feeding with energy-rich grains (Boucher et al., 2011; McAlpine et al., 2009). These inefficiencies contribute to higher emissions from cattle, a high proportion of which come in the form of methane and nitrous oxide, greenhouse gases which have global warming potentials 28 and 298 times that of carbon dioxide (FAO, 2020; IPCC, 2015). The

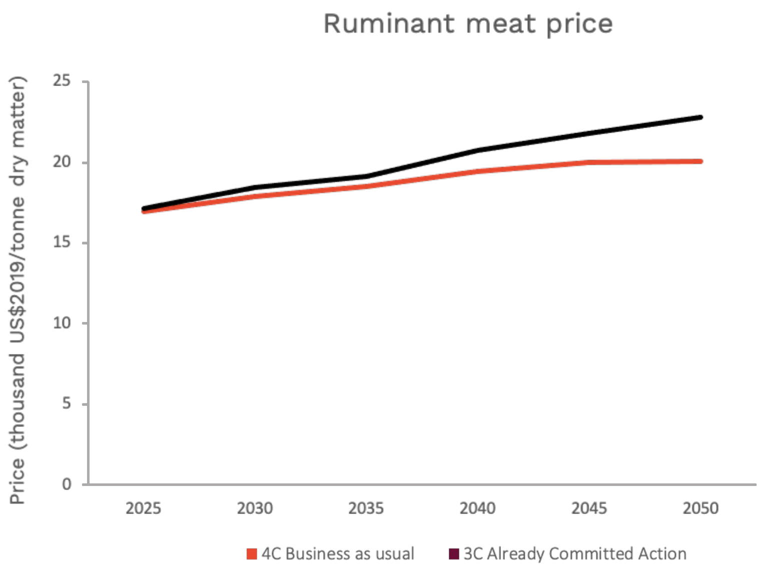
FAO identifies improving feeds and feeding techniques as having the greatest potential to reduce emissions of these potent greenhouse gases from cattle (FAO, 2020).

Protein-rich feed and fertilizer use is increasing in beef production, having implications for emissions, and eventually costs in the sector. The global consumption of livestock products has increased dramatically over recent decades, leading to a significant increase in feed required by livestock production systems (Lassaletta et al., 2016). The majority of the growth in livestock feed has been met by crop production, rather than grasses (Lassaletta et al., 2016). Today, approximately 75% of global soy and maize production is used in livestock feed, resulting in soy-related deforestation over recent decades having been largely driven by increased usage of soy in feed (World Wildlife Fund, 2017). Consequently, the feed supply chain now accounts for approximately 10% of beef emissions, and produced approximately 290 MtCO2e in 2013 (Gerber et al., 2013). Sustained increases in livestock product consumption and the use of on-farm mixing of feeds will lead to a continued increase in soy use in feed (FAO, 2017c; Mordor Intelligence, 2019), resulting in higher emissions from the feed supply chain. Increases in feed demand result in increases in fertilizer use. Global cattle manure left on pastures has increased substantially over the past 20 years, as has the use of manure and synthetic fertilizers for crops (FAO, 2018). In 2013, applied and deposited manure on pastures in beef production accounted for 520 MtCO2e of emissions, about 18% of total emissions from beef production (Gerber et al., 2013). Since then, emissions from manure left on pasture have grown by over 5% (FAO, 2018, 2019c). The eventual phasing in of carbon prices to cover agricultural emissions coupled with projections that feed prices will increase quicker than meat prices (Thornton, 2010), will likely lead to higher feed and feed production costs for beef producers.

Global beef consumption has steadily risen over the past five years, with increases seen in both developed and developing regions. Since 2014, beef and veal consumption has grown by 5% to over 69 million tonnes, with consumption in both the OECD and BRICS regions growing by greater than the world average at a 6% increase over this period (OECD, 2018). While the growth in consumption in the European Union has been slower than the OECD average at 4% over the past five years, beef and veal consumption in the United States has grown significantly more quickly with a 9% increase (OECD, 2018). However, global aggregates hide upward trends in demand for alternative and plant-based proteins, particularly in the United States and Western Europe where beef and red meat are increasingly associated with carbon emissions and adverse health effects (Terazono et al., 2019).

Although trends in beef consumption are expected to continue in the near term, implementation of a carbon price leads to increased farm-gate prices for ruminant meat. Emissions costs incurred along the supply chain for ruminant meat are reflected in the farm-gate price, as illustrated in Figure 14, which shows the difference in price trajectory between carbon-priced and un-priced scenarios. The carbon price here is relatively weak and stabilizes rather than reduces emissions. However, even this small price difference relative to business as usual is reflected in 14% higher farm-gate prices by 2050. The increase in farm-gate price is likely to be passed through to the retail price, where it will affect demand for beef and other ruminant products. Previous studies have found demand for beef and similar meat products to highly elastic (Okrent & Alston, 2012).

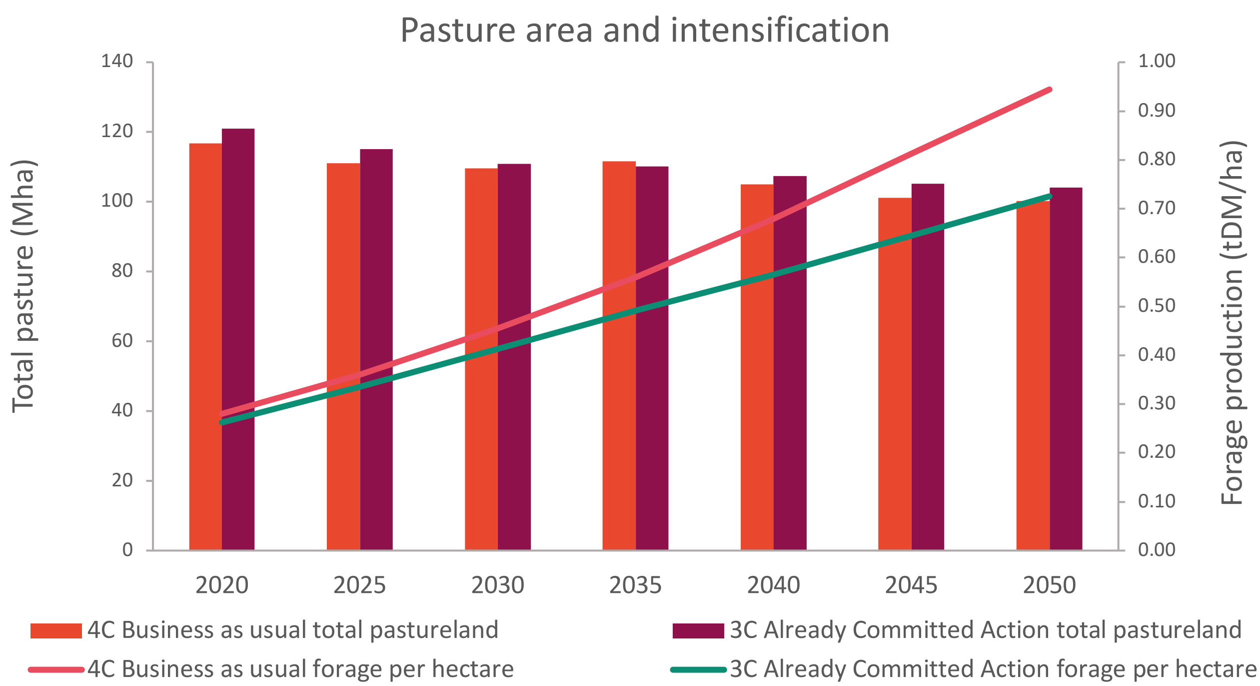
Figure 14 Difference in ruminant meat price driven by emissions price



Note: Neither of these scenarios include a ruminant fadeout.
Source: Vivid Economics

Carbon pricing drives a shift toward mixed-use management and agroforestry. Pasture intensification is a no-regret management strategy and a source of low-cost efficiency gains. Across scenarios, investments in yield enhancements are associated with steady declines in pastureland. This is illustrated in Figure 15, which shows consistent reductions in pasture and rangeland even under the reference scenario. Because increasing production drives intensification, higher rates of yield growth, as proxied by forage production per hectare of rangeland, are observed under scenarios where production continues to rise. This is illustrated in Figure 15 which shows nearly 60 million *more* hectares of pastureland in 2050 under the 1.5°C Strong Ambition LP compared to the reference scenario. In the 1.5°C Strong Ambition LP, land competition drives yield enhancing investments in crop cultivation, making cropland available for alternative uses. Modelling suggests a cost-effective management option is to use these areas for grazing as forestry stocks mature, as suggested at the end of Section 3. Depending on the type of cropland and substituted livestock, such an approach mitigates large land conversion costs by providing an income stream during the low-carbon transition.

Figure 15 Trends in pasture and rangelands



Source: Vivid Economics

A.3 Soy

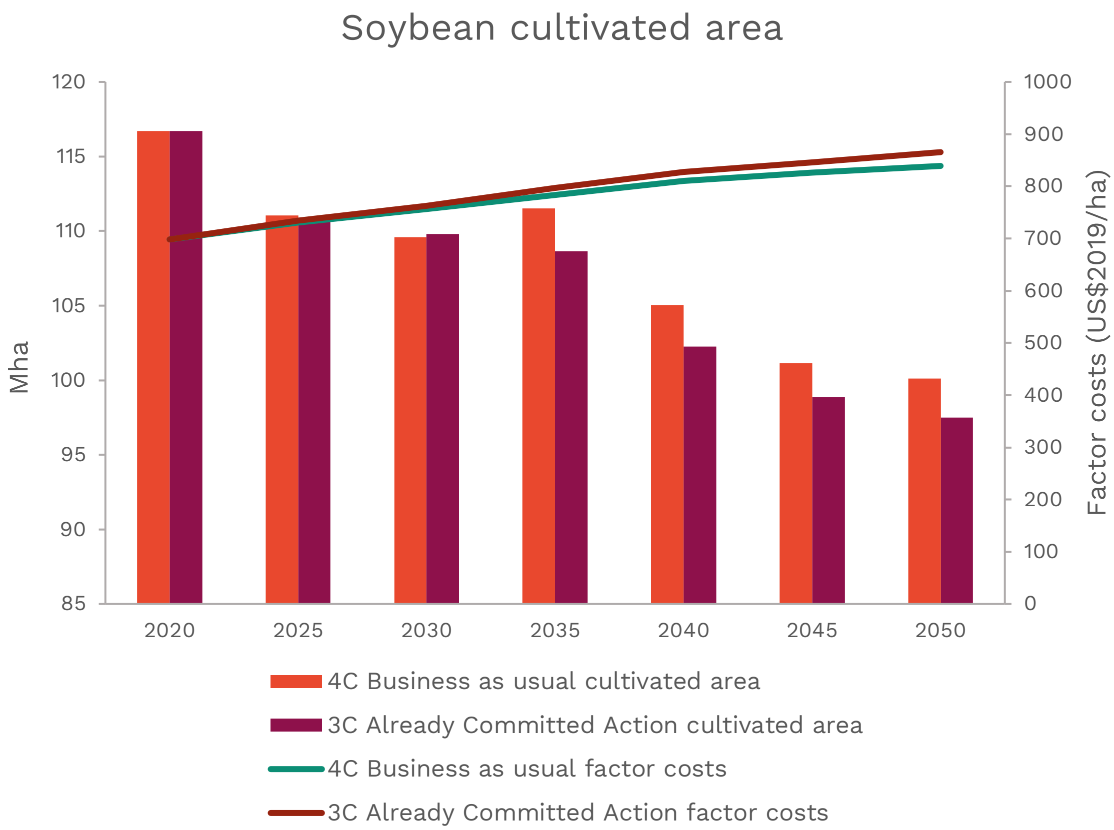
As with palm oil, the expansion of soy production is mainly attributable to its high versatility and productivity, but the commodity's link to deforestation presents risks and opportunities for the entire supply chain at risk. First, the introduction of a carbon price could help accelerate the decoupling of soy production and deforestation which has been a priority for many organizations over the past decade. Additionally, a shift away from ruminant meat consumption could lead to a decline in use of soy for feed, but an increase in production due the higher demand for meat substitutes. The overall effect on soy demand will depend on the strength of substitution between beef and soy and the capacity of firms to shift to more sustainable production systems.

The high protein and energy content and per hectare productivity of soy have made it the dominant vegetable oil and protein crop worldwide. Like oil palm, soy's versatility – as an important component of livestock feeds, processed foods, and biofuels – has contributed to rapid growth in production and area under cultivation. Globally, production volumes have doubled since 2000 and the total planted area has expanded from 74 million hectares in 2000 to nearly 125 million in 2018 (Brack et al., 2016; FAO, 2019a). Like oil palm, a few exporters supply most of the world's demand. Until recently, the United States led the world in the production of soy, but rapid expansion in South America (mainly in Brazil, but also in Argentina, Bolivia, Paraguay, and Uruguay), has made the region the leading exporter of soymeal and oil, together accounting for 57% of global production in 2019 (Kuepper et al., 2019; World Wildlife Fund, 2014). Rapid expansion has come at the expense of tropical Amazonian rainforests which have been converted for soy plantation. Between 1990 and 2010, 14.5 million hectares of soybean production were brought online in Brazil, with more than 85% of forest losses occurring in the “arc of deforestation” in the agricultural frontier, as well as in the *Cerrado* biome, a biodiverse tropical savannah south of the Amazon (Macedo et al., 2012). Like forest conversion for the cultivation of palm oil, emissions-intensive fires are often lit to clear forest stands before soils are tilled.

Over the last decade, important progress has been made in decoupling soy production and deforestation. In 2006, the release of a Greenpeace report linking soy production to tropical deforestation precipitated the adoption of the Soy Moratorium, a voluntary commitment by Brazilian soybean processors and exporters to not buy soybeans produced on Amazon farmland (Boucher et al., 2011). The moratorium is widely regarded as a success with the suggestion that soy cropping has been ‘decoupled’ from Amazonian deforestation (Macedo et al., 2012). Indeed, the decade following was marked by a 70% reduction in deforestation of the Brazilian Amazon. However, Trase calculates that between 2006 and 2017, soy-driven deforestation in the *Cerrado* led to emissions totaling 210 million tonnes of carbon dioxide equivalent. Additionally, Nepstad et al. (2014) suggest that when land already cleared for pasture becomes scarce, soy production will move into unprotected areas of the Amazon or further south to the *Cerrado* biome. Box 4, however, highlights that Brazil’s high international trade exposure may lead it to transition relatively quickly to zero-deforestation soy production.

A carbon price has potential to further decouple soy production from Amazonian deforestation. Figure 16 compares area cultivated for soy under the reference scenario and under a weak carbon price. A differential begins to emerge in 2025 when the carbon price takes effect, and by 2050 even a low carbon price relies on 2.5 million fewer hectares for essentially the same level of production (290.5 million tonnes per year). A carbon price also increases overall production costs, illustrated in Figure 16 by per-hectare factor costs. In addition to being directly affected through the cost of direct emissions, production costs will also be sensitive to changes in fertilizer costs (Cordonnier, 2019), which will likely increase with a carbon price.

Figure 16 *Production figures capture important dynamics between soy and beef production*



Note: Note that factor costs include cost of capital, labor, and energy. They do not include emissions or land costs.
Source: Vivid Economics

A fadeout of ruminant meat consumption leads substitution for soy as a source of protein. Table 9 shows that under the 1.5°C Strong Ambition LP, a reduction in beef production is associated with growth in soy. In fact, the relationship between beef and soy is more complex than one of simple substitutes. Because soy is an important ingredient in livestock feed (see 2. Beef above), and because it is grown very often on abandoned pasture, there are many dynamic linkages between these production systems. For example, replacement of cattle pastures with mechanized crop production (most often soy) is common in many Amazonian soy producing states like Pará (Macedo et al., 2012). It has also been noted that soybean expansion has pushed cattle pastures further north of the *Cerrado* into Mato Grasso (Boucher et al., 2011). However, the strength of these commodities as complements may be limited in this case as the ruminant fadeout is associated with a shift toward agroforestry and mixed-use management and away from single use pasture, feedlots, or stall-fed production that would use soy-based feed.

Table 9 Production (MtDM /year) figures capture important dynamics between soy and beef production*

	Soy			Beef		
	BAU	Disorderly	Coordinated	BAU	Disorderly	Coordinated
2020	281	287	294	65	61	58
2025	290	301	311	72	66	59
2030	294	308	315	78	69	60
2035	294	313	325	84	72	59
2040	299	324	342	90	74	58
2045	305	333	361	96	76	56
2050	304	335	374	102	77	53

Note:* MtDM: Million tonnes of Dry Matter
Source: Vivid Economics

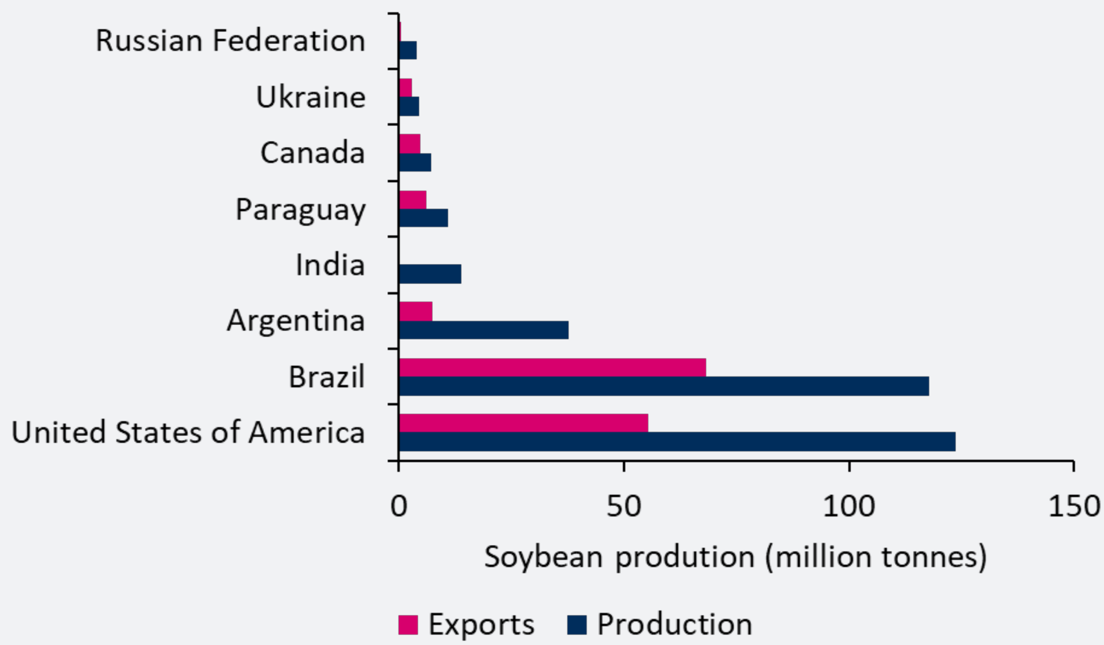
Box 4 Brazilian soy's high international trade exposure gives buying nations greater leverage to demand sustainable growing practices, leading to a more abrupt transition

Brazil is the world's largest exporter of soy, making it especially sensitive to international pressure to stop soy-related deforestation. Figure 17 illustrates that Brazil is currently the world's second largest producer and first largest exporter of soy. Moreover, Brazil is predicted to overtake the United States as the world's largest producer of soy in 2020 and will remain the world's largest exporter of soy, sending over 50% of its 124 million tonnes of production overseas (Anand, 2020). Recent analysis shows that soy was responsible for close to 10% of deforestation in Brazil between 2006 and 2017 (Trase, 2018). With deforestation at risk of increasing with expanding production, Brazil will likely face mounting international demands to halt soy-related deforestation through continued pressure from multinational corporations such as Tesco and Asda (Chain Reaction Research, 2019) and regulatory changes abroad, such as plans by the European Union to implement a border carbon adjustment potentially covering agricultural emissions (Lowe, 2019). High trade exposure gives buying nations leverage over the Brazilian soy industry and so will likely force Brazilian producers to transition to more sustainable practices before producers in markets driven by domestic demand.

Many of Brazil's large soy producers will face additional market pressure from consumers with zero-deforestation policies due to the sector's high trade exposure. SLC Agricola is Brazil's largest listed soybean producer and sells 63% of its product to three companies, Cargill Agricola S.A., Amaggi LD Commodities and Bunge Alimentos S.A., all of which have zero-deforestation policies (Chain Reaction Research, 2020). Currently, SLC Agricola continues to allow deforestation in its soy plantations, most recently clearing 5,200 hectares of native vegetation in the Cerrado (Chain Reaction Research, 2020). However, SLC Agricola's exposure to three large multinational firms will likely compel the company to act quickly if and when its main buyers begin to enforce their zero-deforestation policies. SLC Agricola's high exposure to a handful multinational firms is standard for producers in Brazil, where the seven largest firms account for over 90% of exports (Gomes & Mano, 2019).

High international exposure has already led to significant pressure from downstream companies calling for regulatory changes to end soy-related deforestation in Brazil. In response to the risk of deforestation increasing with increased production, at the end of 2019, 84 companies, including Tesco, Mars, Carrefour and Robeco penned a letter urging the Brazilian government to take action on soy-related deforestation (Chain Reaction Research, 2019). The companies called for the continued implementation of the soy production moratorium in the Amazon, which is under threat of being removed by the current administration. Simultaneously, others called to expand this moratorium to the Cerrado region (Soterroni et al., 2019), where over 90% of soy-related deforestation in Brazil currently occurs (Trase, 2018).

Figure 17 Soybean exports and production of the world's 8 top soybean producers.



Note: This is figure was made from 2017 data. Brazil is expected to surpass the United States in production in 2020 (S&P Global, 2020).

Source: Figure from Vivid Economics, data from FAO (2017a).

Growth in Brazil's bioenergy output coupled with the soy sector's high trade exposure will likely add to producers' sensitivity to international demands for zero-deforestation soy. Recent studies suggest that bioenergy production in Brazil is expected to at least double by 2050 (Lap et al., 2019; Winchester & Reilly, 2015). While the exact land required to meet this supply depends on the crops grown, this is certain to lead to a rise in competition for land, resulting in higher farmland prices. In fact, increases in farmland prices have already been observed due to the rise in bioethanol production in Brazil in recent decades. Higher farmland prices increase the cost of production for soy producers, which threatens Brazilian soy farmers' international competitiveness. With rising costs of production, Brazilian soy producers will have to ensure they obtain the highest price for their crop, which is unlikely to occur if buyers are not guaranteed production is deforestation-free.

Appendix B: Modeling methodology

This annex describes scenario development and input assumptions for the global report. It details modeling inputs and assumptions and provides context for the interpretation of global results.

B.1 Model overview

The land use modeling for the global report was undertaken using the Model of Agricultural Production and its Impact on the Environment (MAgPIE). Developed by the Potsdam Institute for Climate Impact Research, MAgPIE is a spatially explicit, partial equilibrium model that solves for the least-cost way to meet future demand for food. The model accounts for climate policy, socio-economic variables (GDP, income and population) and physical inputs (biophysical constraints on water and yields) and determines land use costs and patterns of future land use change. Five are the considered categories of land use:

- **Cropland**, irrigated or rainfed, produces food crops (cassava, cotton, fodder, groundnut, maize, others, potato, pulses, rapeseed, rice, soybean, sugar beet, sunflower, temperate cereals, tropical cereals), energy crops (first and second generation[6])
- **Pastureland** can be used to farm three different categories of livestock: ruminants, pigs or poultry;
- **Forestland** includes primary and secondary forest (natural forest) and managed forest (plantations);
- **Other** marginal land refers to young secondary and primary (non-forested biomes) vegetation;
- **Urban** areas.

A short general description of the model can be found on the MAgPIE home page on PIK's website as well as in Dietrich et al. (2019).

MAgPIE is an established modeling framework that has been regularly utilized by the international community to inform our understanding of the impacts associated with climate change and policies, including in IPCC reports. MAgPIE has been under development since 2008, but the latest version was recently released open source (Dietrich 2019). Vivid Economics has brought this model in-house and used it to understand land use change dynamics in past projects.

B.2 Model assumptions

MAgPIE includes a set of assumptions which can be modified by the user to obtain the desired scenario (see Table 10 for a summary)**.** This analysis considers five transition pathways for the agricultural sector that cover a range of mitigation targets and policy levers. The modelling examines societal shifts that will have impacts material to investors with exposure in agricultural commodity supply chains.

- **Population & GDP -** Across scenarios, we assume moderate income and population growth in line with historic trends. Modelled trends follow the “Middle of the Road” shared socioeconomic pathway (SSP2),

[6] First generation crops include oil palm, sugar cane and all those crops that can be used for both food and energy production. Second generation crops include grasses and trees (switchgrasses, miscanthus, etc…) that can only be used for energy production.

which describes a world with intermediate challenges for adaptation and mitigation. Under SSP2, global population peaks at about 9.4 billion and levels off in the second part of the century. Income growth and economic development proceed unequally, with some countries and regions experiencing strong growth and others falling short of targets. The Shared Socioeconomic Pathways include well-developed narratives that trends in other socioeconomic indicators, like education and urbanization, as well as implications for energy and land use systems. However, in this modelling exercise we simply use the population and GDP growth trajectories as a basis for all scenarios.

- **Global trade patterns -** A continuation of current global trade patterns is adopted for the full set of scenarios. The trade module balances self-sufficiency and comparative advantages in production to manage crop balances and satisfy regional demand. Trade margins and tariffs are included in the optimization processes that determine trade balances. Patterns of trade liberalization are extrapolated from recent historical trends.

- **Mitigation policies -**

  ◊ **Carbon price level and pass-through -** Carbon price level and pass-through to the land use sector are varied across scenarios to explore the impacts of pollutant pricing on land use allocation. The model incorporates a carbon price by multiplying the pollutant price by cellular emissions. This policy lever increases the competitiveness of mitigation activities, which are only undertaken if they become the highest value of land in a particular grid cell. One-off emissions (e.g., from deforestation) are discounted using an infinite time horizon to level them with yearly continuous management emissions (e.g., from fertilizer application). Carbon price levels are set to align with temperature targets set out in the development of the scenarios. The scenarios also consider the extent to which the AFOLU sector is included in a carbon pricing policy. Political sensitivities surrounding increasing the cost of production for farmers has meant that most carbon pricing schemes to date have not included coverage of the agricultural sector. In this scenario analysis, hesitance to regulate agricultural firms is captured by limiting the rate of pass-through to the sector by applying a carbon price reduction factor to cellular emissions costs.

  ◊ **Forestry policy and area protection - Protection policies are modelled as land set asides by removing national parks, heritage sites, and other conservation areas from the optimization procedure.** MAgPIE uses spatially explicit files (see, for example, IUCN's World Protected Areas Database) to remove grid cells from optimization, effectively locking protected land to remain unchanged during the modelling as it solves for the least-cost way to meet exogenous food demand.[7] Land protection policies also include nationally implemented policies and nationally determined contributions to the Paris Agreement, both of which are taken from individual country reports. These ramp up until 2030 and then are assumed to be constant thereafter. **Afforestation is incentivized through the greenhouse gas emissions price.** The carbon pricing policy is used to calculate a reward for afforestation, which enters the objective function as a negative cost. The reward is calculated as the annualized present value of expected carbon dioxide removal multiplied by the corresponding carbon price. Carbon dioxide removal is based on vegetation age classes to capture sequestration potential and saturation. Afforestation is then modeled endogenously given the calculated reward.

- **Energy system - Bioenergy demand pathways are set by assumption.** First-generation bioenergy demand is assumed to increase until 2020 and then remain constant thereafter. Because first-generation bioenergy crops compete with food crops, it is expected that population pressure will stabilize demand for first-generation crops and shift demand toward second generation bioenergy crops, including

[7] Barring these set asides, all land in the model is eligible to be changed to another land use, subject to biophysical constraints like soil and water input into MAgPIE from LPJmL. Land use conversions incur both an initial conversion cost and an ongoing management cost that depends on the land use, its region, and in some cases the biophysical constraints.

dedicated bioenergy grasses and trees and agricultural, forest, and municipal wastes and residues. These demand pathways are also set by assumption and to align with global technical potential, which is estimated at about 100-400 EJ. There is wide variation in estimates of economic potential, but Popp et al. (2011) estimated the economic potential to be 100 EJ by 2050.[8]

- **Crop productivity - The acquisition of yield-enhancing technologies is modelled endogenously.** While the unit cost of making yield improvements is set by model assumption, acquisition of new technologies is triggered endogenously either through better cost-effectiveness compared to other investments or as a response to resource constraints. Investments are made at the region level, and yield enhancements accrue over a 30-year timespan but with diminishing marginal returns. The model is agnostic to the technology itself – i.e., uptake of genetically modified seeds is modeled in the same way as increased use of yield-enhancing equipment. The exception is irrigation, which is modeled separately. Irrigation cost pathways are set exogenously by region, and irrigation efficiency increases with GDP, representing better efficiency associated with advanced irrigation systems. Pasture yields are set exogenously according to a pasture management factor.

- **Ruminant fadeout - The ruminant fadeout imposes a dietary shift on the food bundles that satisfy caloric budgets**. MAgPIE is a partial equilibrium model, in which food demand is estimated using population, GDP per capita trajectories, and caloric budgets. MAgPIE then finds the least-cost way to meet that food demand. Fadeout scenarios replace ruminant meat with less carbon intensive protein sources, including poultry, fish, eggs, and alternative meats. The modeling presented in this report is agnostic to the nature of this substitution (i.e., does not consider shifts to a particular non-ruminant protein source).

Table 10 Relevant model assumptions and sources

Variable	Description	Source	Link to scenario analysis
Population	Sets trajectories based on SSPs (Shared Socioeconomic Pathways)	SSP database	SSP2 – 'Middle of the road' consistent pathways
GDP	Sets trajectories based on SSPs (Shared Socioeconomic Pathways)	SSP database	
Trade liberalization	Defines change in current trade patterns	(Schmitz et al., 2012)	Current trade patterns and trend in trade liberalization
Mitigation policy	Defines global price trajectories for CO_2, N_2O, CH_4.	IIASA Database and PIK integrated assessment modelling exercise	Changes across scenarios (see Mitigation Policy, Table 2)
Annual bioenergy demand	Defines demand for second generation bioenergy crops (only used for fuel production, not for food)	IIASA Database and PIK integrated assessment modelling exercise	Changes across scenarios (see Annual bioenergy demand, Table 2)

8 Lotze-Campen, H., Popp, A., Beringer, T., Müller, C., Bondeau, A., Rost, S., Lucht, W. (2010): Scenarios of global bioenergy production: The trade-offs between agricultural expansion, intensification and trade. Ecological Modelling 221: 2188-2196. https://sci-hub.tw/https://onlinelibrary.wiley.com/doi/full/10.1111/agec.12092#support-information-section (Accessed 05/06/20)

Area protection	WDPA categories plus all proposed areas and key biodiversity hotspots	(Leclère et al., 2018)*	Changes across scenarios (see Area protection, Table 2)
Ruminant meat fadeout	Defines decline in proportion of calories from ruminant meat in total meat demand relative to baseline scenario where it is treated as constant	(Bodirsky *et al.*, no date)	Changes across scenarios (see Ruminant meat fadeout, Table 2)
Future costs of investment	Selected options for the expected costs of future productivity improvement.	(Dietrich et al., 2014)	It results in the different levels of productivity reported in Table 2

Note: * The default protection in MAgPIE is defined by the WDPA protected areas. It includes IUCN WDPA categories I and II. The WDPA protection covers approximately 400 Mha of the terrestrial land surface. For a world with increased protection, this work creates a 'potential protected area layer' - i.e. areas of the world that should be a priority to protect. Two criteria served for selection - (i) expansion of the WDPA protection from Cat I and II to cover all categories, and inclusion of proposed PAs (areas which are not protected, but deemed by WDPA to be prioritized for protection in near or distant future, using a variety of local factors). (ii) Inclusion of key biodiversity hotspots. The resulting potential protection layer comes to around 2700 Mha, or ~21-24% of the terrestrial land surface.

Source: Vivid Economics

B.3 Model selection

MAgPIE was selected to support this engagement as the most fit-for-purpose tool given the project aims. Broadly, the objectives of the global modeling were to explore the impacts of climate change mitigation policies and transition risk on land use and food production systems, and specifically on tropical soft commodity supply chains. Table 1 lays out how MAgPIE capabilities supports delivery of these objectives.

Table 1 MAgPIE capabilities support project objectives

Modelling objectives	MAgPIE capabilities	MAgPIE limitations
Examine the implications of land-based carbon mitigation policies and other societal shifts on the AFOLU sector.	Mitigation policies can be implemented and tested straightforwardly in MAgPIE.	Global cost minimization does not account for local policies and considerations. Threshold effects can cause abruptness in model outputs.
Assess price, production, and land use impacts on tropical soft commodities.	MAgPIE covers most of the key deforestation-linked commodities, including ruminant meat, oil palm, and soybeans.	The model is set up to satisfy caloric demand, meaning it models staple crops. It does not include commodities that are not calorically important, such as coffee or cocoa. MAgPIE groups beef, lamb, mutton, and goat together, implying we cannot

		separate these activities from one another within the modelling framework.
Disaggregate outputs spatially to obtain results at the regional or country level.	MAgPIE is connected to the dynamic vegetation model LPJmL, which uses a grid with a spatial resolution of 0.5°x0.5°. Outputs are aggregated at the regional and global levels.	Cells are assigned to one of 15 economic regions, and grid cells are clustered to make global computation tractable. This makes raw results unsuitable for localized estimation.
Provide estimates of the change in costs of agricultural inputs for regional analyses conducted by other workstreams.	MAgPIE produces estimates of the change in cost of water, fertilizer and energy to agricultural production.	Factor costs are based on area harvested, land use intensity, and a crop- and water-specific regional factor requirement meaning cellular factor costs are identical across cells within a region.

Source: Vivid Economics

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