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WORKING PAPER

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# Livestock intensification and the role of finance in the Food System Transformation in Brazil

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## Abstract

The potential for the Brazilian cattle sector to increase production while concurrently reducing pressure for land expansion is widely recognized. With mounting evidence that land use change amplifies the impacts from global climate change, a transition to climate resilient and low-carbon agriculture becomes imperative and unavoidable. This analysis explores possible contributions of the Brazilian beef cattle sector can make to a Food System Transition (FST). The results of this analysis show a large potential to increase productivity and spare land for other uses, but several socioeconomic and political economy challenges will need to be overcome, such as increasing access to finance and technical assistance as well as a tightening of environmental governance across the country. Adopting intensification practices can increase farm profitability and have payback periods of months to a couple of years but require up-front investments that pose challenges for farmers with low access to finance. While results indicate that realizing the land-sparing potential of the cattle sector is not free from macroeconomic frictions, there are also socioeconomic opportunities for the country in a global FST trajectory. However, capturing the opportunities will require well-designed policies that can link multiple objectives and maximize the synergies across the environmental, health, and inclusion domains.

## Introduction

A transformation to sustainable food systems needs to align with positive social welfare related outcomes along the three dimensions of public health, social inclusivity and environment [1]. Food systems should provide nutritious and affordable diets that enable the elimination of malnutrition globally and create good livelihoods while reducing the environmental footprint of food production to keep it within planetary boundaries. About three-quarters of global agricultural land is pastures mostly inhabited by ruminants which produce methane from enteric fermentation, a major driver of anthropogenic climate change responsible for 5% of anthropogenic global greenhouse gas (GHG) emissions [2]. Livestock are an important component of human welfare, providing food, income, nutrients, employment, insurance, traction, clothing and other benefits [3] while also using a significant amount of land, nutrients, feed, water and other resources [4]. Balancing livelihoods, livestock production and environmental protection is a key challenge in addressing the twin climate and biodiversity crises. Reducing overconsumption of livestock products can contribute to balancing the multiple trade-offs between health, inclusion and environmental outcome indicators [5–7].

Brazil is the second largest beef producing country globally and is a major global provider of meat (especially beef) through exports of 20% of its production. Main destinations of Brazilian beef exports are China, Egypt, and Russia [8]. The sector is the primary driver of deforestation in the country, especially illegal deforestation used for land grabbing practices [9]. Although the role of export markets on Brazilian deforestation has received much attention recently, the domestic supply chain has a higher deforestation risk [9]. The Brazilian domestic market is fuelled by a meat-intensive national diet that in 2019 included 25 kg of beef, 40 kg of chicken meat and 12 kg of pork per capita per year [1].

While over 200 million heads of cattle roam on about 200 million hectares (Mha) of managed pastures and rangelands, the Brazilian livestock sector operates at a chronically low efficiency, evidenced by the low stocking rates, high share of degraded pastures, and substantial pasture yield gaps [10–12]. There are some 60 Mha of pastures in advanced stages of degradation [13] that can be recovered to increase yields and reduce the footprint of beef production both in terms of GHG emissions and other environmental indicators [10–12,14,15], while building resilience and enhancing farm financial performance [15–17]. In line with these opportunities, the 2015 Brazilian nationally determined contributions to the Paris Agreement pledge (NDC) relied heavily on improvements to livestock production to deliver stated GHG reduction targets [18–20]. It also furthered the objectives of the ongoing Low-Carbon Agriculture Plan, or *Plano ABC* for its Brazilian acronym, to deliver financing for the measures outlined in the NDC [21]. The Plan had mixed success in its first phase ending in 2020, but did manage to support the adoption of better management practices in livestock production in the end [22], and is now in its second phase. Early barriers to adoption of low-carbon livestock management practices like integrated livestock-crop-forestry (iCLF) systems [23] have not been completely overcome. Importantly, intensification requires upfront investments so access to finance is crucial. This constitutes a major barrier to four fifths of the farms in Brazil [24] and this finance gap needs to be addressed to ensure an equitable and inclusive sustainable transformation for Brazilian agriculture in general, including the livestock sector.

While the cattle sector has made efforts to improve its environmental credentials, it still faces considerable challenges to dissociate itself from ongoing deforestation and land use change in the country. The continuing association of cattle rearing (*pecuária bovina* in Portuguese) with deforestation, especially when it involves the Amazon forests, has given rise to risks for the sector,

[1] https://data.oecd.org/agroutput/meat-consumption.htm

including market loss and regulatory risks. Market loss is a very material risk for the sector as the European Union (EU) recently enacted legislation banning deforestation-linked commodities from being imported into the bloc. Although the EU is a relatively small importer on a weight basis, China is also considering similar regulation, and this would be a major shock to Brazilian cattle producers. Regulatory risks are associated with non-compliance with Brazilian regulation, especially the 2012 Forest Code [25,26].

On the other hand, improving the resource efficiency of cattle production in Brazil also presents opportunities in a fast-changing world. Climate change and deforestation negatively impact productivity by raising temperatures and altering rainfall patterns, especially in the *Cerrado* biome where most of the livestock herd is located. Opportunities for closing the pasture-to-carcass yield gaps are also associated with improved production and economic resilience of not only the cattle sector, but the agricultural sector in general.

At a global level, the Food System Transformation pathway (FST) assessed by the Food System Economics Commission (FSEC) captures a more sustainable future, implying huge benefits for people and planet. However, at national and sub-national levels, there may be trade-offs and barriers relating to governance, financial and political economy constraints that could hinder the implementation of needed policies. This report examines what the global FST may mean for Brazilian agriculture, especially its cattle sector. The pathway is implemented via bundles of measures to reduce trade-offs that would emerge if individual measures were to be introduced by themselves. It includes several technical interventions in how food is produced as well as a full shift to the EAT-Lancet healthy reference diet by 2050. These pathways are assessed with the Model of Agricultural Production and its Impact on the Environment (MAgPIE) (see Appendix). The report then examines the outcomes of implementation of the FST packages of measures, each in turn separately focusing on climate, health, inclusion and environment outcomes. Finally, accounting for the recalcitrance of the sector to discussions on diet change, scenarios are produced with diet change that falls short of a full shift to the EAT-Lancet diet central to the full FST.

## Results

Figure 1 shows a heat map summarising the main results of the study with resulting outcome indicators for a business-as-usual (BAU) scenario based on the Shared Socio-economic Pathway 2 (SSP2) in 2050 and the changes relative to it from the packages of measures and the full FST pathways, with columns categorized outcomes into Health, Environment, Inclusivity and Economic domains. The distribution of green and red colours highlights that the mostly beneficial health and environmental outcomes are accompanied by mostly trade-offs in both inclusivity and economic outcomes.

Relative change: best, better, none, worse, worst

| | Health | | | Environment | | | | | | | | | | Inclusion | | | Economy | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Underweight Mio people | Obesity Mio people | Premature Mortality Mio years of life lost | All Land Types Cropland Area | All Land Types Pasture & Rangeland Area | All Land Types Other Land Area | All Land Types Forest Area | Cropland Landscapes Biodiv. Intactness Index | Hotspot Landscapes Biodiv. Intactness Index | Croparea Diversity Shannon Index | Nitrogen Surplus Mt N/yr | AFOLU GHG Emissions GtCO2eq/yr | Global Surface Warming Degree Celsius | Expenditure on Ag. Products USD/person/yr | Food Expenditure Index Index2020 | Ag. Employment Mio people | Agriculture GVA Billion US$05/yr | Bioeconomy Supply Billion US$05/yr | Production Costs Billion US$05/yr | Investment R&D Million US$05/yr |
| BASE_SSP2 | 3 | 51 | 11 | 98 | 157 | 50 | 530 | 78.7 | 193.6 | 0.75 | 19 | 0 | | 602 | 82 | 8 | 259 | 118 | 273 | 580 |
| **Packages** | | | | | | | | | | | | | | | | | | | | |
| AllClimate | | | | 88 | 158 | 53 | 536 | 79.3 | 192.3 | 0.74 | 15 | -0.8 | | 664 | 91 | 9 | 287 | 118 | 305 | 1443 |
| AllHealth | 0 | 25 | | 99 | 152 | 57 | 528 | 79 | 217.1 | 0.75 | 17 | -0.5 | | 345 | 65 | 5 | 131 | 120 | 197 | 0 |
| AllInclusion | 2 | 56 | | 98 | 157 | 49 | 531 | 78.7 | 192.3 | 0.74 | 18 | -0.1 | | 586 | 81 | 7 | 259 | 117 | 277 | 36 |
| AllEnvironment | | | | 65 | 96 | 55 | 619 | 82.5 | 185.7 | 0.71 | 20 | -1 | | 665 | 91 | 8 | 270 | 118 | 345 | 3189 |
| FST_SDP | 0 | 28 | 3 | 76 | 36 | 56 | 667 | 83.3 | 229.3 | 0.72 | 14 | -1.6 | | 359 | 97 | 7 | 189 | 134 | 340 | 0 |

*Figure 1* ***- A heat map showing each outcome indicator reductions/increases in FST-SDP scenario compared to BAU in 2050 for Brazil.***

## Environmental outcomes of FST implementation in Brazil

Full FST implementation in Brazil leads to positive outcomes in all but one of the examined indicators. Most importantly, the intensification of agricultural production reduces land demand relative to BAU, meaning that natural vegetation areas are larger for forests and other land, which in Brazil is mostly the savannas of the Cerrado biome in Central Brazil. Because both these land cover types in Brazil are rich in biodiversity and high in carbon stock, their reduced loss leads to an increase in biodiversity outcomes and reduction of GHG emissions.

Cross examining Figure 2 and Figure 3 shows the relationship between agricultural intensification, land sparing and GHG emission reductions. The steep reductions in pasture area are linked to the diet shift away from livestock products which leads to reductions in methane ($CH_4$) emissions from enteric fermentation. Reductions in nitrous oxide ($N_2O$) emissions are associated with agricultural management changes, including improved nitrogen use efficiency (NUE), better manure management practices and lower synthetic fertilizer applications, the latter driven mainly by the lower demand for soy and maize for feed production. These reductions in cropland and pastureland open space for afforestation, delivering an increase in forest area in Brazil, with accompanying $CO_2$ emission reductions which turn deeply net-negative before 2030 (Figure 2).

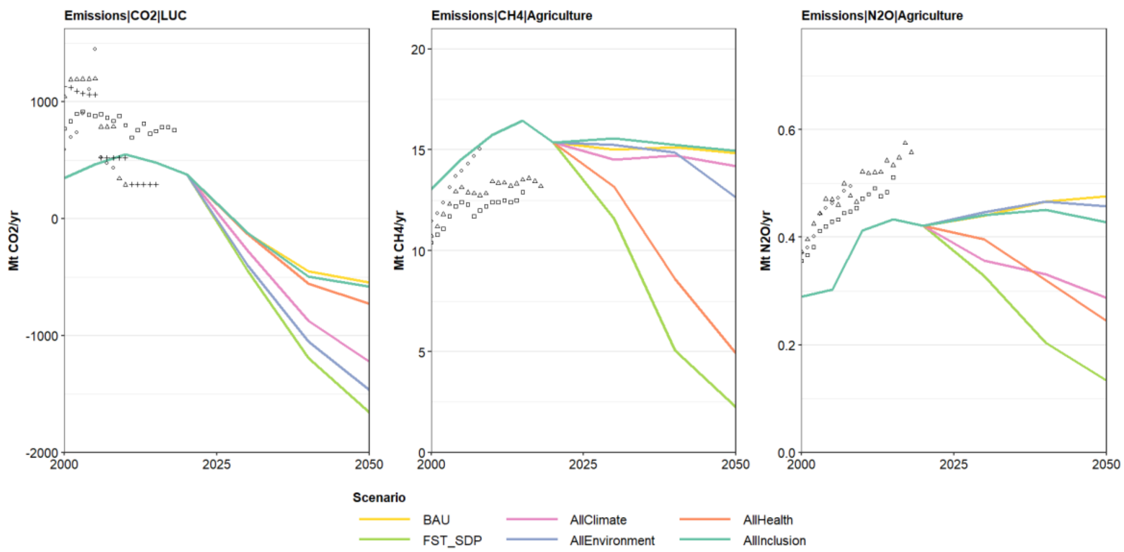


*Figure 2 - Greenhouse gas emissions across scenarios in Brazil*

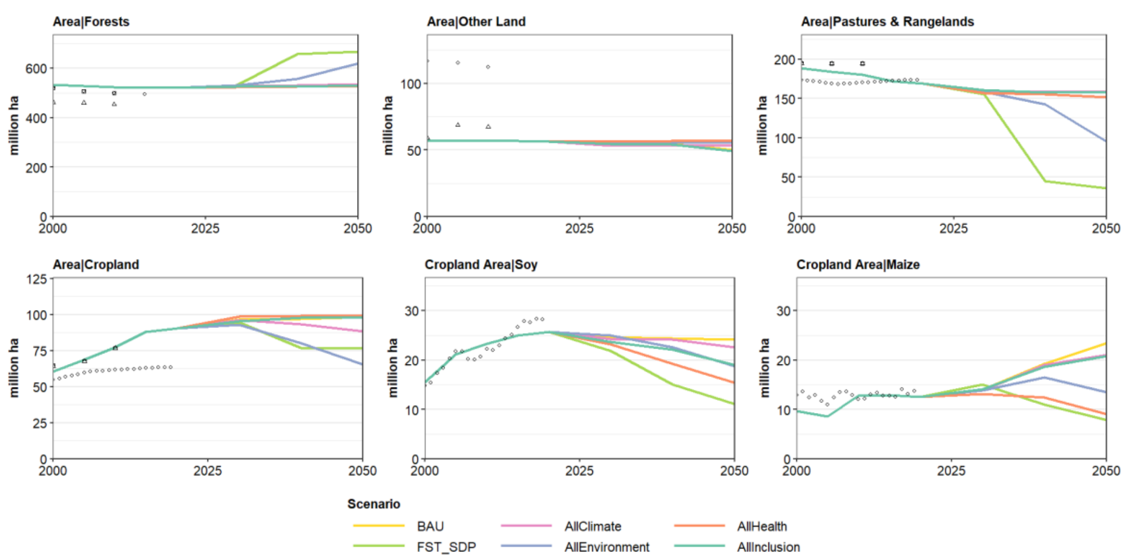


*Figure 3 - Land cover across scenarios in Brazil*

Land sparing opens space for alternative land uses which signal opportunities in a pathway transitioning to a low-carbon and nature-positive future (Figure 4). In such a pathway, carbon pricing would provide incentives for renewable energy sources including second generation bioenergy which sees increasing demand and expansion of the area planted with bioenergy crops (like Miscanthus). Carbon markets would also thrive in this transformed world, creating potential rewards for afforestation through land-based carbon sequestration. If the FST is accompanied by a broader, cross-sector sustainable transformation and liberal trade policies, opportunities with bioenergy and afforestation will benefit Brazil's bioeconomy sector. If implemented alongside stringent biosphere protection, this sector can capitalise on sustainable forestry and bioenergy demand to achieve economic revenues of 134 billion US$05/yr (Figure 1).

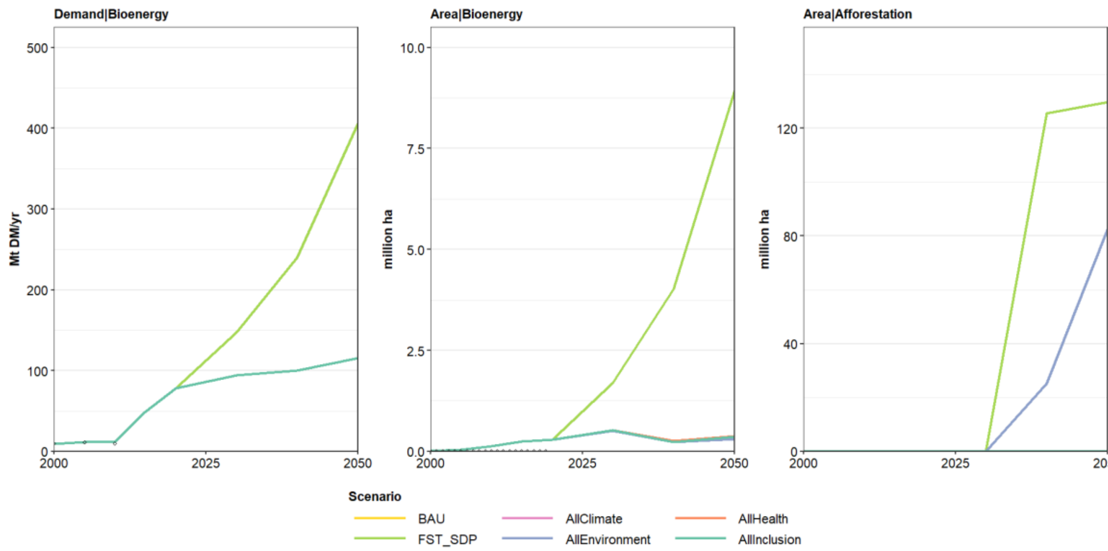


*Figure 4 - Bioenergy demand and planted area, and afforestation area across scenarios in Brazil in 2050.*

Realizing these opportunities would require increased investments into technology and process innovation (Figure 5). A global health-conscious diet shift on its own would lead to reduced net trade and agricultural gross value-added (GVA) for Brazil but if it happens alongside climate and nature positive policies worldwide, Brazil's favourable soil and climate conditions means it can produce agricultural commodities that meet the specifications of these polices and the country is able to maintain its volume of trade, although with some reduction in agricultural GVA compared to BAU.

The increase in investments and costs associated with the transformation cause agricultural commodity prices to increase, and this can lead to increased food insecurity. The intensification of agricultural production in general leads to a drop in agricultural employment relative to BAU in 2050, deepening this secular trend caused by increased mechanization.

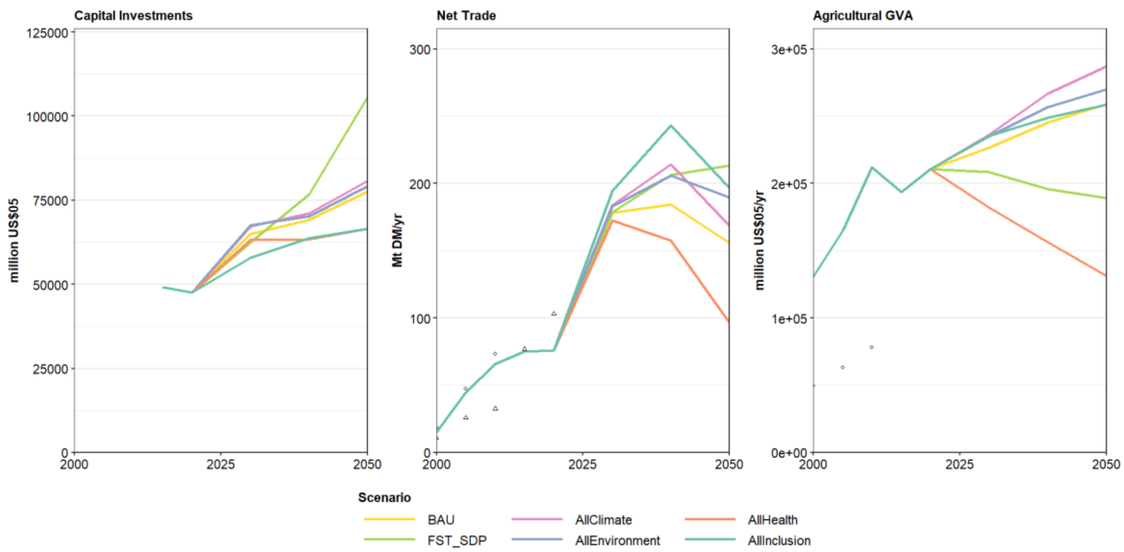


*Figure 5 - Investments, trade and agricultural gross value added (GVA) across scenarios in Brazil.*

Quantitative transformation pathways based on the MAgPIE model or other integrated assessment models (IAM) produce indicative trajectories for key outcome indicators related to measures driving the transformation. Realising these transformation pathways for each indicator requires the introduction of targeted measures [1]. For Brazil, ending illegal deforestation, providing incentives for sustainable resource use, and increasing access to finance are three key policy recommendations to steer the agricultural sector towards more environmentally friendly and inclusive practices [24].

## The financial sector and the Food System Transformation in Brazil

The increased investments imply increased financial flows to sustainable agricultural practices. A just transformation in the agricultural sector would require targeted policies to ensure that no one is left behind due to lack of access to finance for the investments needed.

Diet change is a chronic (relatively slow moving) process, which the financial system has some time and flexibility to adapt to in terms of risk management. However, divestment is an acute risk, which will have an immediate effect on the financing opportunities and cost of capital for the industry.

Large meat producers are exposed to divestment risk. In relation to the Brazilian livestock sector, divestment risk is linked to perceptions and concerns around deforestation (risk). The livestock value chain as a whole is exposed to transition risk (diet change) and liability risk (if land grabbing is practiced or otherwise practices do not adhere to regulations). The ultimate expression of these risks is the risk of stranded assets. Ranchers could be left with stranded assets if downstream purchasers/producers/traders drop them from their supplier list over sustainability/legality concerns. As opposed to other sectors, however, these assets are recoverable in that they can be upgraded through investments to meet new requirements (which is not possible for fossil-fuel installations)

Current discussions in Europe about banning deforestation-linked commodities and the pricing of nature-related risk by the financial sector are indications that such pressures are real and already beginning to manifest.

On the other hand, there could be significant advantages to pro-actively shifting Brazil's livestock sector to sustainable practices, in terms of risk mitigation and positioning the industry for an FST-aligned future. For financial institutions and the Government of Brazil, it offers an opportunity to be industry leaders and capture market shares ahead of what is likely to be an inevitable transformation[24]. But this involves redirecting the flow of capital in a sustainable direction. For such a transformation to take place, the shift to more sustainable cattle production will require investments in genetics, degraded soil recuperation, fencing and water supply. Working capital will be required to purchase cattle and for maintenance of soil fertility. The finance can come from government programmes or from private sources. Both government programmes and private instruments can be used to redirect the flow of capital. It can take place through access to cheaper or new financing sources – e.g. tapping into international capital markets by issuing green bonds or sustainability-linked bonds (SLBs), concessional/subsidised credit from public sources for investments with positive environmental externalities, and possibly funding from international financial institutions (IFIs) and philanthropic sources.

However, lack of access to rural credit is associated with lower investments in intensification of cattle operations[27,28]. Conversely, Carrer et al.[29] find that access to rural credit spurs the adoption of integrated crop livestock systems (ICLS) in the state of São Paulo. Improving access to credit with environmental covenants in a way that facilitates sustainable cattle production therefore is a low-hanging fruit for transforming the livestock industry in the country[24].

## Challenges and opportunities for financing the transformation

While opportunities for action exist, there are also challenges, with many recognised problems with rural credit to ranchers in Brazil. For example, a 2020 World Bank policy note reported that most rural financing goes to a small number of large farms, while over four-fifths of Brazilian farms have no access to credit. It also reported that most of the credit that does exist is for short-term working capital with low probability of going towards needed types of sustainable agriculture investments[30]. Greater efforts must be made to reach small producers.

Brazil's agricultural financing landscape is complex with a number of funding programmes and distribution channels (Feltran-Barbieri & Feres [27] identify 11 different sources and 13 credit programmes for soil management and restoration for ranchers between 2013-21). This complexity means that even programmes which are designed with a particular motive in mind – e.g. environmental benefits – may not reach the intended recipient because the banks channelling the credit has – in many cases – discretion to set its own terms and conditions[27].

Despite the large number of participants, the vast majority of the credit lines to the livestock sector from the official Rural Credit programme is channelled through a small number of institutions, with Banco do Brasil as the dominant lender. It has also been established that there is little competition between financial institutions in some cattle-producing regions, such as the Amazon[28]. The lack of competition could present an obstacle to innovative thinking and lending practices as banks can maintain the status quo and may be dissuaded from offering new credit products.

The last point suggests a more active role should be played by the ultimate funder of the credit programme in setting sustainability and other conditions for lending products, and for ensuring they are implemented. Indeed, programmes for redirecting credit seem to be effective, as indicated by some success (higher productivity, lower deforestation) of conditioning lending to Amazon-based farmers since 2008[27]. However, financial leakage – that is the move from a funder with sustainability requirements to another with no such requirements - is a challenge which can reduce the effectiveness of sustainability-led financing initiatives. This has already been seen in the energy sector, where divestments or increasing demands by institutional investors on fossil-fuel based producers have led to these players seeking alternative financing routes via e.g. private equity.

Finance alone cannot solve all the problems. Technical assistance (extension services) must be offered jointly with access to credit, as studies have shown the latter to be ineffective without the former[29,31]. More broadly, three constraints on rural credit can be identified: i) quantity/supply constraint; (ii) transaction costs constraint and (iii) risk aversion constraint[29]. Extension services could aid in lowering (iii).

The following is likely to be a relatively accurate description of the financing structure of the Brazilian livestock sector[2]. In terms of fixed and working capital requirements, large companies like meat producers and slaughterhouses tend to be well capitalized and will typically have access to own funds. Thus, they can make some investments via self-financing, or capital can be raised via the issuance of shares or bonds. These large players may in turn provide supply chain finance (debt or equity) to their suppliers. Medium sized companies are more likely to rely on bank loans (from state and national development banks/programmes predominantly) and (some) private equity. Small producers/farmers rely almost exclusively on state and national banks (primarily Banco do Brasil) through rural credit lines (NRCS) or through commercial credit (from equipment and input suppliers e.g.). The latter group suffers from under-financing due to 1) a lack of

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[2] Based on a review of commodity financing broadly speaking - source: WEF/TFA, 2017: The Role of the Financial Sector in Deforestation-free Supply Chains

collateral and other perceived risks and 2) a lack of opportunities/ programmes offered due to fiscal constraints.

There is a divide between a minority of well-capitalized farms and a vast majority of farmers with no access to basic finance like credit lines. Improving access to finance is key, and the rural credit currently requires no sustainability criteria, and this provides a good opportunity for engaging currently disenfranchised farmers into a sustainability agenda.

Several incentive structures have been proposed and approved recently, both from government and civil society. For example, the Green Beef Stamp (*Selo do Boi Verde,* Rainforest Alliance Certified) creates a price premium for "sustainably produced" beef. Payment for ecosystem services (PES) schemes can provide further revenue streams to incentivize sustainable livestock production practices, especially following the introduction of the PES Law in 2021, although the rules governing it still need to be implemented.

## Conclusion

Increasing beef cattle productivity is already widely recognized in Brazil as having great potential for the sector to increase production while concurrently reducing pressure for land expansion [32]. With mounting evidence that land use change amplifies the impacts from global climate change [33–35], increasing signs of resilience loss in the Amazon [36] and decreasing agricultural productivity in the Cerrado [37], a transition to climate resilient and low-carbon agriculture becomes imperative and unavoidable. Our results show that he Brazilian beef cattle sector can make substantial contributions to such a transition by harnessing its large unrealized environmental potential to increase productivity and spare land for other uses [10], but several socioeconomic and political economy challenges will need to be overcome. Key among these are access to finance and technical assistance as well as a tightening of environmental governance across the country.

Adopting intensification practices such as crop-livestock integration and degraded pasture recuperation can increase farm profitability and have payback periods of months to a couple of years [13,15,38], but they require up-front investments that pose challenges for farmers with low access to conventional finance and in a country with chronically high interest rates. While our results indicate that realizing the land-sparing potential of the cattle sector is not free from macroeconomic frictions, there are also socioeconomic opportunities for the country in a global FST trajectory. In a transitioning world, Brazilian agricultural production competitiveness means net-trade value can be maintained, and the bioeconomy offers the possibility of new revenue streams. However, capturing the opportunities will require well-designed policies that can link multiple objectives and maximize the synergies across the environmental, health, inclusion and climate domains.

# References

1. Gaupp, F. *et al.* Food system development pathways for healthy, nature-positive and inclusive food systems. *Nat. Food* **2**, 928–934 (2021).
2. Pathak, M. *et al.* Technical Summary. in *Climate Change 2022 - Mitigation of Climate Change* (eds. Shukla, P. R. et al.) 51–148 (Cambridge University Press, 2023). doi:10.1017/9781009157926.002.
3. Herrero, M., Thornton, P. K., Gerber, P. & Reid, R. S. Livestock, livelihoods and the environment: understanding the trade-offs. *Curr. Opin. Environ. Sustain.* **1**, 111–120 (2009).
4. IPCC. Summary for Policymakers. in *Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* (ed. P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.- O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, J. M.) (2019).
5. Willett, W. *et al.* Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet* **393**, 447–492 (2019).
6. GARNETT, T. *et al. What is a sustainable healthy diet? A Discussion Paper.* (2014).
7. Hedenus, F., Wirsenius, S. & Johansson, D. J. A. The importance of reduced meat and dairy consumption for meeting stringent climate change targets. *Clim. Change* **124**, 79–91 (2014).
8. Trase. *Mapping the deforestation risk of Brazilian beef exports*. https://resources.trase.earth/documents/infobriefs/TraseInfobrief8En.pdf (2019).
9. zu Ermgassen, E. K., Godar, J., Lathuillière, M. J., Löfgren, P. & Gardner, T. The origin , supply chain , and deforestation risk of Brazil ' s beef exports. *Proc. Natl. Acad. Sci.* **117**, 31770–31779 (2020).
10. Strassburg, B. B. N. *et al.* When enough should be enough: Improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. *Glob. Environ. Chang.* **28**, 84–97 (2014).
11. Cardoso, A. S. *et al.* Impact of the intensification of beef production in Brazil on greenhouse gas emissions and land use. *Agric. Syst.* **143**, 86–96 (2016).
12. De Oliveira Silva, R. *et al.* Increasing beef production could lower greenhouse gas emissions in Brazil if decoupled from deforestation. *Nat. Clim. Chang.* **6**, 493–497 (2016).
13. Assad, E., Pavão, E., Jesus, M. de & Martins, S. C. *Invertendo o sinal de carbono da agropecuária brasileira. Uma estimativa do potencial de mitigação de tecnologias do Plano ABC de 2012 a 2023*. http://www.observatorioabc.com.br/relatorio-5-invertendo-o-sinal-de-carbono-da-agropecuaria-brasileira?locale=pt-br (2015).
14. Oliveira, P. De *et al. Evolução de Sistemas de Integração Lavoura-Pecuária-Floresta (iLPF): estudo de caso da Fazenda Santa Brígida, Ipameri, GO.* http://ainfo.cnptia.embrapa.br/digital/bitstream/item/109764/1/doc-318.pdf (2013).
15. Silva, R. de O. *et al.* Sustainable intensification of Brazilian livestock production through optimized pasture restoration. *Agric. Syst.* **153**, 201–211 (2017).
16. Gil, J. D. B. *et al.* Tradeoffs in the quest for climate smart agricultural intensification in Mato Grosso , Brazil. *Environ. Res. Lett* **13**, (2018).
17. Molossi, L., Hoshide, A. K., Pedrosa, L. M., Oliveira, S. De & Abreu, D. C. De. Emissions , Profitability , and Resource Use for Nelore Beef Cattle in Brazil's Cerrado and Amazon Biomes. *Animals* **10**, 1386 (2020).

18. GofB. *Intended Nationally Determined Contribution (INDC) towards achieving the objective of the UNFCCC*. http://www4.unfccc.int/submissions/INDC/Published Documents/Brazil/1/BRAZIL iNDC english FINAL.pdf (2015).

19. Köberle, A. *et al.* Brazil Chapter. in *Beyond the Numbers: Understanding the Transformation Induced by INDCs. A Report of the MILES Project Consortium* (eds. Spencer, T. & Pierfedericci, R.) 34–45 (2015).

20. Oliveira, R. De, Gustavo, L., Queiroz, G. & Moran, D. The role of agricultural intensification in Brazil's Nationally Determined Contribution on emissions mitigation. *Agric. Syst.* **161**, 102–112 (2018).

21. MAPA. *Plano Setorial de Mitigação e Adaptação às Mudanças Climáticas para Consolidação da Economia de Baixa Emissão de Carbono na Agricultura – PLANO ABC*. vol. 4 http://www.agricultura.gov.br/desenvolvimento-sustentavel/plano-abc (2012).

22. Köberle, A. C., Tagomori, I. S., Portugal-Pereira, J. & Schaeffer, R. *Policy Case Study: Evaluation of the Plano ABC in Brazil*. (2017).

23. Gil, J., Siebold, M. & Berger, T. Adoption and development of integrated crop-livestock-forestry systems in Mato Grosso, Brazil. *Agric. Ecosyst. Environ.* **199**, 394–406 (2015).

24. Köberle, A. C., Gurgel, A., Pinto, T. P., Lima, C. Z. de & Suassuna, K. R. *Finance, Nature and Food Systems – Opportunities for the Brazilian agri-food system*. https://www.naturefinance.net/resources-tools/financas-natureza-e-transicoes-alimentares/ (2022).

25. Rochedo, P. R. R. *et al.* The threat of political bargaining to climate mitigation in Brazil. *Nat. Clim. Chang.* (2018) doi:10.1038%2Fs41558-018-0213-y.ris.

26. Rajão, R. *et al.* The rotten apples of Brazil's agribusiness. *Science (80-. ).* **369**, 246–248 (2020).

27. Feltran-Barbieri, R. & Féres, J. G. Degraded pastures in Brazil: improving livestock production and forest restoration. *R. Soc. Open Sci.* **8**, 201854 (2021).

28. Souza, P. Z., Campos, G., Herschmann, S., Vogt, P. & Assunção, J. J. *6 Peculiarities of Rural Credit in the Amazon: New Research Shows Credit Restrictions and Extensive Land Use in Agriculture*. https://www.climatepolicyinitiative.org/publication/6-peculiarities-of-rural-credit-in-the-amazon-new-research-shows-credit-restrictions-and-extensive-land-use-in-agriculture/#Nota1 (2021).

29. Carrer, M. J., Maia, A. G., de Mello Brandão Vinholis, M. & de Souza Filho, H. M. Assessing the effectiveness of rural credit policy on the adoption of integrated crop-livestock systems in Brazil. *Land use policy* **92**, 104468 (2020).

30. World Bank. *Mobilizing Private Finance for Nature*. https://thedocs.worldbank.org/en/doc/916781601304630850-0120022020/original/FinanceforNature28Sepwebversion.pdf (2020).

31. Bragança, A. *et al.* Extension services can promote pasture restoration: Evidence from Brazil's low carbon agriculture plan. *Proc. Natl. Acad. Sci.* **119**, (2022).

32. Assunção, J. J. & Bragança, A. *Pecuária mais produtiva para o Brasil.* https://www.climatepolicyinitiative.org/wp-content/uploads/2020/05/WhitePaper_Pecuaria_PT_112019_final-2.pdf (2019).

33. Rodrigues, A. A. *et al.* Cerrado deforestation threatens regional climate and water availability for agriculture and ecosystems. *Glob. Chang. Biol.* (2022) doi:10.1111/gcb.16386.

34. Hofmann, G. S. & et al. Changes in land cover and atmospheric circulation are reducing rainfall in the Brazilian Cerrado. *Sci. Rep.* **preprint**, (2022).

35. Hofmann, G. S. *et al.* The Brazilian Cerrado is becoming hotter and drier. *Glob. Chang. Biol.*

**27**, 4060–4073 (2021).

36. Lapola, D. M. *et al.* Limiting the high impacts of Amazon forest dieback with no-regrets science and policy action. *Proc. Natl. Acad. Sci. U. S. A.* **115**, 11671–11679 (2018).

37. Rattis, L. *et al.* Climatic limit for agriculture in Brazil. *Nat. Clim. Chang.* (2021) doi:10.1038/s41558-021-01214-3.

38. Embrapa. *Avaliação econômica de sistemas de Integração Lavoura-Pecuária-Floresta: as experiências da Embrapa*. (Embrapa Gado de Corte, 2019).

39. Soergel, B. *et al.* A sustainable development pathway for climate action within the UN 2030 Agenda. *Nat. Clim. Chang.* **11**, 656–664 (2021).

# • Appendix

## Supplementary Material

## Supplementary Material (SM)- An assessment of food system measures for sustainable transformation in Brazil

### Description of the modelling set-up for Brazil

This analysis uses the Model of Agricultural Production and its Impact on the Environment (MAgPIE)[1]as thecentral modelling tool. The model codes are open source (https://github.com/magpiemodel). For this analysis, the extensively documented 4.5 model version documented used (https://rse.pik-potsdam.de/doc/magpie/4.5.0/). The central model is also coupled with several other models. A complete description of MAgPIE and all the coupled models can be found in the global synthesis report[2]. A description of the setting is provided below.

### Representation of pastures management

The FST scenario is characterised by deep structural changes to all sectors of the global economy and achieves targets of the SDGs concurrently. It is based on Soergel et al[3] but includes many new features and developments in the MAgPIE model (see global study). One development that is particularly relevant for the Brazil case study is the separation of the old aggregated pasture land use class into rangelands and managed pastures[4].

**A.2. Detailed scenario description**

| | |
|---|---|
| **BAU** | A Business-as-usual Scenario where no specific policy action is implemented, parametrized under the SSP2 framework, which is also the middle-of-the-road |

| | |
|---|---|
| | trajectory[5]. The scenario helps us project a future based on historical trends under current policies. The SSP2 pathway characterizes with medium growth in economy, population, urbanization, and education level. The population is expected to reach 1.73 billion by 2050 based on our assumption of SSP2 parameterization[6].The projected future, according to this pathway, follows SSP parameterization with regard to food demand and moderate GDP growth. Consistent with the SSP2 framework, dietary patterns tend toward increased consumption of animal proteins[7,8]. |
| **All inclusion** | A bundled scenario where policy measures seek greater socio-economic parity by improved institutional structures with high GDP growth, slower population growth under the SSP1 framework, second-generation bioenergy demand implemented, greater use of timber for construction, and fair trade between countries. The population is expected to reach 1.55 billion by 2050 based on our assumption of SSP1 parameterization. The SSP1 parameterization is in line with more sustainable pathways that assume that investments in health and education will accelerate the demographic transition, leading to a relatively low world population[6]. Research indicates that under the SPP1 scenario for India, female education levels will be higher along with lower assumed education-specific fertility rates, resulting in much lower birth rates. |
| **All environment** | A scenario representing bundles of FSMs that help achieve environmental sustainability. Includes measures that prioritize biodiversity restoration (including reduced degradation and deforestation) and minimize pressures on land, water, soil pollution, and air pollution. Population and GDP growth rates are in line with SSP2 parametrization. |
| **All climate** | A bundled climate scenario where crop production efficiency is targeted, good practices for animal waste management are followed, and emission pricing policies are implemented. Population and GDP growth rates are in line with SSP2 parametrization. |
| **All health** | A scenario where food consumption moves toward healthy diets, i.e., EAT-Lancet dietary for recommendations for most food items (animal products, oils, sugars, fruits, vegetables, nuts, etc.). Population and GDP growth rates are in line with SSP2 parametrization. |
| **WaterSoil** | A scenario that bundles water and soil management measures like protected by environmental flow policy regulations and emission pricing policies targeting soil carbon conservation. Population and GDP growth rates are in line with SSP2 parametrization. |

| | |
|---|---|
| **Efficiency** | A scenario that bundles FSMs enabling overall efficiency. The bundle includes measures like nitrogen use efficiency in crops, reduction in food loss and waste, better animal waste management, and efficient trading based on relative competitiveness. Population and GDP growth rates are in line with SSP2 parametrization. |
| **Food System Development Pathway (FST_SDP)** | A complete food system transition scenario that is a combination of all food system measures (FSMs), including external transformation measures. Population and GDP growth rates are in line with SSP1 parametrization. |

## Description of food system measures

| FSM name | Description | Implementation | Definition |
|---|---|---|---|
| Population | Population growth is reduced, in particular in low-income countries, due to higher education and faster socio-economic development | Switch from SSP2 to SSP1 population projections[6] | No interaction with macroeconomy (GDP per capita stays constant), no interaction with energy system (non-food emissions stay the same for global warming indicator), higher education which is the driver behind reduced population growth has no further implications on the model |

| FSM name | Description | Implementation | Definition |
|---|---|---|---|
| EconDevelop | Economic development is faster, and international catch-up growth is stronger. | Switch from SSP2 to SSP1 projections for per-capita gross domestic product | No interaction with population. |
| EnergyTrans | Sustainable development in other sectors influencing food system, including energy transformation, transport transformation, urbanisation transformation | Bioenergy demand for energy transition increases from X to X, water demand for non-agricultural use changes from X to X, urbanisation scenario changes from SSP2 (X Mio ha) to SSP1 (X mio ha), active transportation changes physical activity levels from sedentary to moderate activity | |
| Timber cities | Wood is increasingly used as construction material for cities | For our “TimberCities” scenario, we assume that X% of future urban dwellers could be housed in buildings made of engineered wood[9] to replace carbon-intensive steel and concrete. This increases future timber demand by X Mt and thereby increases the need for plantations. | No $CO_2$ fertilization; no differentiation between hardwood and softwood: static rotation lengths in forest plantations; does not account for changes in soil carbon; assumes static production technologies and emission factors; does not account for rebuilding existing buildings; no albedo affect accounting due to extensive tree planting; does not account for timber prices |

| FSM name | Description | Implementation | Definition |
|---|---|---|---|
| Bioplastics | Increasing biomass demand as a substrate for bioplastic production | Bioplastics are assumed to replace 30% of estimated total plastic demand by 2050. Total plastic demand is assumed to increase to 675 Mt[10]. | Conversion rates (biomass substrate to bioplastic as well as primary products to starch and cellulose) and the share of each biomass substrate are kept constant over time. Glycerol is assumed to be available in sufficient quantities as it is a byproduct from biodiesel production but not modeled explicitly. Global bioplastic demand is disaggregated to regional level based on population size. |
| No underweight | | Food intake of all people with BMI<20 is increased until they reach a BMI of 20--25. Food composition is kept constant. | |
| No overweight | | Food intake of all people with BMI>25 is reduced until they reach a BMI of 20--25. Food composition is kept constant | Food composition may not be in line with a likely reduction of BMI. |
| LessFoodWaste | Food waste in households and food loss in retail (difference between intake and FAO food supply) is reduced. | Reduction from projected outcome based on GDP regression[11] to 20% of intake where it exceeds 20% of intake. | |

| FSM name | Description | Implementation | Definition |
|---|---|---|---|
| DietVegFruisNutsSeeds | Increase healthy consumption of vegetables, fruits, nuts, and seeds | The aggregate categories "Vegetables, Fruits, Nuts", (unprocessed) "sunflower" and "other oilseeds" (including sesame seed and mustard seed) is increased to the levels recommended by the EAT-Lancet diet. The consumption of staples (cereals, roots, tubers) is reduced to hold total calories constant. For the health model, these categories are further disaggregated based on X | |
| DietRuminants | Decrease of ruminant meat and milk | The intake for the two product categories of "Ruminant meat" and "Dairy products" are reduced to the level suggested by EAT-Lancet[12,13], which is a decrease in high-consuming and an increase in low-consuming countries. The consumption of staples (cereals, roots, tubers) is adjusted to hold total calories constant. | |
| DietMonogastrics | Decrease of poultry meat, monogastric meat, and eggs | The intake for the three product categories of "Non-ruminant meat" and "Poultry meat" and "Eggs" are reduced to the level suggested by EAT-Lancet[12,13] , which is a decrease in high-consuming and an increase in low-consuming countries. The consumption of staples (cereals, roots, tubers) is adjusted to hold total calories constant. | |

| FSM name | Description | Implementation | Definition |
|---|---|---|---|
| DietLegumes | Increased consumption of legumes | The intake for three product categories- Pulses, Soybean, and Groundnut- are increased to the level suggested by EAT-Lancet[12,13]. The consumption of staples (cereals, roots, tubers) is adjusted to hold total calories constant. | |
| DietFish | Increase or decrease of fish consumption | The intake for the product category of "Fish" is increased or decreased to the level suggested by EAT-Lancet[12,13]. The consumption of staples (cereals, roots, tubers) is adjusted to hold total calories constant. | Fish is not included in MAgPIE. Effects of aquaculture and capture fishery on inclusion and environmental indicators are not included; only the effect on health is captured. |
| DietEmptyCalories | Decreased consumption of sugar and alcohol | The intake for the product category of 'Fish' is decreased to the level suggested by EAT-Lancet[12,13]. The consumption of staples (cereals, roots, tubers) is adjusted to hold total calories constant. | |
| WaterSparing | The environmental flow requirements cannot be used for irrigation. | Spatially explicit minimum environmental flow requirements (EFR) are derived from LPJmL monthly discharge using the Smakhtin method taking high- and low-flow requirements into account[14]. These volumes are then aggregated to the required spatial (200 simulation clusters) and temporal resolution (yearly values, accounting for growing-period months only). | 1) Water availability and environmental flow requirements, as well as water demands (agricultural and non-agricultural), are aggregated into large spatial clusters based on bio-physical similarity. These may span large |

| FSM name | Description | Implementation | Definition |
| --- | --- | --- | --- |
| | | | distances and cross river basin boundaries or water management boundaries. Tends to over-estimate water availability and under-estimate environmental flow violations that often occur locally. 2) The temporal scales of MAgPIE are yearly time steps. Temporal variability of water availability and demand is accounted for in that only monthly water availability of growing period months are accounted for in the calculation of EFRs. However, further temporal variability (daily variations, mismatches between the beginning and end of the growing period) are not accounted for. We assume that water is made available by storage infrastructure. |
| LandSparing | Following the Half- | In each eco-region, 50% of the | |

| FSM name | Description | Implementation | Definition |
|---|---|---|---|
| | Earth conservation approach, 50% of terrestrial land cannot be used as agricultural land. | terrestrial land is set aside for nature conservation[15,16,17] | |
| LandUseDiversity | The Biodiversity Intactness Index (BII) has to exceed 0.81 in all cells | | |
| PeatlandSparing | Emissions from peatlands are priced with a carbon price (?) | | The GHG price is lower than the one used in the other economic sectors (here, a price of 1000 Mt budget is used), as higher carbon prices in the LU sector have low additional mitigation effects, but create unnecessary trade-offs with other outcome indicators like food expenditure. |
| CropRotatios | Crop rotations are incentivized with payments | Exceeding typical rotation lengths is priced to account for the external costs of less diverse agriculture. For the tax rate of rotation length exceedance, see table SI X). | We do not cover ecosystem service feedbacks (e.g. on yields, pest control intensity) which would cause different systemic effects (e.g. via land scarcity, reduced costs) |
| NitrogenEff | | | |
| CropEffTax | Soil nitrogen uptake efficiency is | | |

| FSM name | Description | Implementation | Definition |
|---|---|---|---|
| | increased exogenously. Will change into: Soil nitrogen uptake efficiency is elastic to pollution pricing. | | |
| RiceMit | | | |
| LivestockMngmt | Livestock systems are intensified in particular in low-income countries, leading to increased feed: product conversion efficiencies and a consistent change in feed baskets towards higher concentrate feed. | We assume improved livestock management based on a shift of livestock productivity and feed baskets from SSP2 to SSP1 parametrization[18,19]. Additionally, we include the full set of technical mitigation measures for reducing methane emissions from enteric fermentation. | The feedback of the technical mitigation measures for livestock productivity is not considered. |
| ManureMngmt | Improved animal waste management reduces losses and emissions during collection and storage of manure using a set of measures at additional costs. | For N2O emissions, the shares of different animal waste management systems are shifted such that 50% of manure is managed in anaerobic digesters, while the remainder is still managed according to the current mix. Anaerobic digesters are assumed to have a 90% recycling rate of manure, accounting for some remaining losses in stables and waste collection. For CH4 emissions, we activate the full set of technical mitigation measures described by Harmsen et al (2019)[20] | CH4 and N2O mitigation is estimated using two distinct approaches, which should, however, be mostly consistent. Cost estimates are only available for the CH4 mitigation. |

| FSM name | Description | Implementation | Definition |
|---|---|---|---|
| AirPollution | Burning of crop residues is faded out quicker (?) | | |
| REDD | A carbon price on C in aboveground vegetation in non-agricultural land incentivizes reduced conversion of forests and other lands into agricultural land. | | The GHG price is lower than the one used in the other economic sectors (here a price of 1000 Mt budget is used), as higher carbon prices in the LU sector have low additional mitigation effects, but create unnecessary trade-offs with other outcome indicators like food expenditure. |
| REDDaff | A carbon price on C in aboveground vegetation in non-agricultural land incentivizes reduced conversion of forests and other lands into agricultural land, and also incentivizes afforestation. | The "REDDaff" scenario, in addition to incentives for reduced deforestation, also provides incentives for afforestation[21]. | The GHG price is lower than the one used in the other economic sectors (here a price of 1000 Mt budget is used), as higher carbon prices in the LU sector have low additional mitigation effects, but create |

| FSM name | Description | Implementation | Definition |
|---|---|---|---|
| | | | unnecessary trade-offs with other outcome indicators like food expenditure. |
| SoilCarbon | A carbon price on C in soil carbon and litter (?) | Based on IPCC ?2019? stock change factors, dependent on climate, irrigation, perennial/annual | The GHG price is lower than the one used in the other economic sectors (here a price of 1000 Mt budget is used), as higher carbon prices in the LU sector have low additional mitigation effects, but create unnecessary trade-offs with other outcome indicators like food expenditure. |
| FairTrade | Trade is less oriented along historical trade patterns and more along relative competitiveness | Two trade pools: Regions must meet a self-sufficiency level in terms of production before exporting goods, based on historical observation. Exported goods, the liberal trade pool, is based on relative cost-competitiveness. In the FairTrade scenario, the self-sufficiency factor is reduced and the quantity of goods freely traded is increased by a factor 2 for livestock and secondary products, and factor 1.5 for crops. | |

| FSM name | Description | Implementation | Definition |
|---|---|---|---|
| MinWage | A global minimum wage increases wages in the lower income countries | A linear term to the baseline hourly labor costs, starting from 0 zero in 2020 and increasing such that resulting hourly labor costs will match the minimum wage of 5 USD/h in 2050. The additional wage increase does not affect labor productivity. Therefore labor costs per production increase proportional to hourly labor costs, leading to a substitution from labor to capital as input to crop production. | There is no regional differentiation in minimum wage. Substitution between labor and capital is only implemented for crop production (not for livestock production) |
| | | | |

Definition of outcome indicators

| Indicator | Definition (right), Limitation (down) | Level of aggregation | Limitations | Description of processes that determine the indicator |
|---|---|---|---|---|
| Population underweight | Defined as the number of adults with a BMI <18.5 (for people older 15 years) and children and adolescents with a BMI that is 2SD below normal (0-14 years). | Country level, by age and sex | | The country-level share of the underweight population is based on age and sex-specific GDP regressions[11] and results in different levels of intake based on metabolic equations that also take into account body height, age, sex, and physical |

| Indicator | Definition (right), Limitation (down) | Level of aggregat ion | Limitations | Description of processes that determine the indicator |
|---|---|---|---|---|
| | | | | activity. As the metabolic link between intake and body weight is fixed, the regressions can also be interpreted more intuitively as an income-elastic intake regression; the direct regression to underweight, however, preserves more of the information in the data and therefore better predictions of anthropometrics. |
| Population obese | Defined as the number of adults with a BMI >30 (for people older than 15 years) and children and adolescents with a BMI that is 2SD above normal (0-14 years). | Country level, by age and sex | | The country-level share of obese population is based on age and sex-specific GDP regressions[11] and results in different levels of intake on the basis of metabolic equations that also take into account body height, age, sex, and physical activity. As the metabolic link between intake and body weight is fixed, the regressions can also be interpreted more intuitively as an income-elastic intake regression; the direct regression to underweight however preserves more of the information in the data and therefore better predictions of anthropometrics. |
| Life years lost | Defined as the life years lost by malnutrition. | Country level, by sex | | |

| Indicator | Definition (right), Limitation (down) | Level of aggregat ion | Limitations | Description of processes that determine the indicator |
|---|---|---|---|---|
| Greenhouse gas emissions | Emissions from land use and land use change in Gt CO2 equivalents using a 100-year global warming potential (GWP100) | 0.5° | Spatial distribution of livestock is very simplified, allocating GHG emissions rather to agricultural areas than livestock production centers | |
| Global warming | Degrees of warming (relative to ?) | Global | | Global warming is estimated using the climate emulator MAGIC-C (). It combines land use and land use change emissions with emissions from other sectors. |
| Nitrogen Surplus | Nitrogen surplus in croplands, pastures, natural vegetation, and animal waste management in Tg Nr | 0.5° | Spatial distribution of livestock is very simplified, allocating GHG emissions rather to agricultural areas than livestock production centers | |
| Biodiversity Intactness Index | | 0.5° | | |

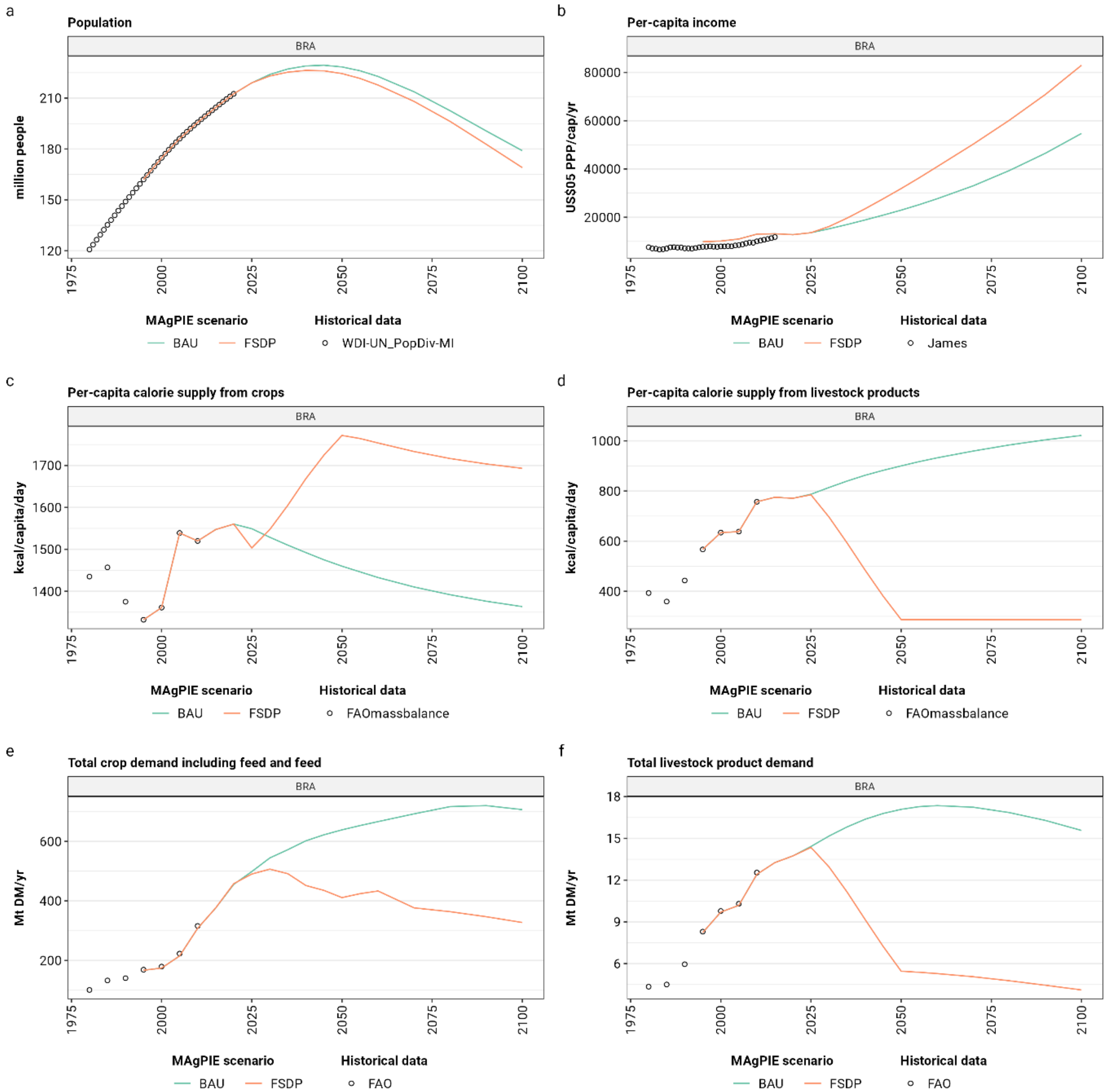
| Indicator | Definition (right), Limitation (down) | Level of aggregat ion | Limitations | Description of processes that determine the indicator |
|---|---|---|---|---|
| Shannon crop diversity index | | 0.5° | | |
| Water environmental flow violations | Water withdrawals exceeding the Environmental Flow requirements of natural ecosystems, in $km^3$ | 0.5° | | |
| Expenditure for agricultural products | | Country-level | Agricultural products are only a fraction of actual food expenditures due to lack of representation of value-added in food supply chain | |
| People living below X $ | | Country-level | | |
| Employment | People working in agriculture, in million people | World region level | | |
| Agricultural wages | | World region level | | |
| Bioeconomy supply | Value stream from food and land system to other economic sectors, including the value of bioenergy, bioplastics, timber and material use of products at fixed prices of 2010. Food demand is considered internal to | World region level | | |

| Indicator | Definition (right), Limitation (down) | Level of aggregation | Limitations | Description of processes that determine the indicator |
|---|---|---|---|---|
| | the food system. | | | |
| Costs | Value stream from other economic sectors to food and land system, including labor and capital for agricultural production, R&D expenditures, land expansion expenditures, transport costs, in USD05MER/year. | World region level | | |

### A.3. Supplementary plots

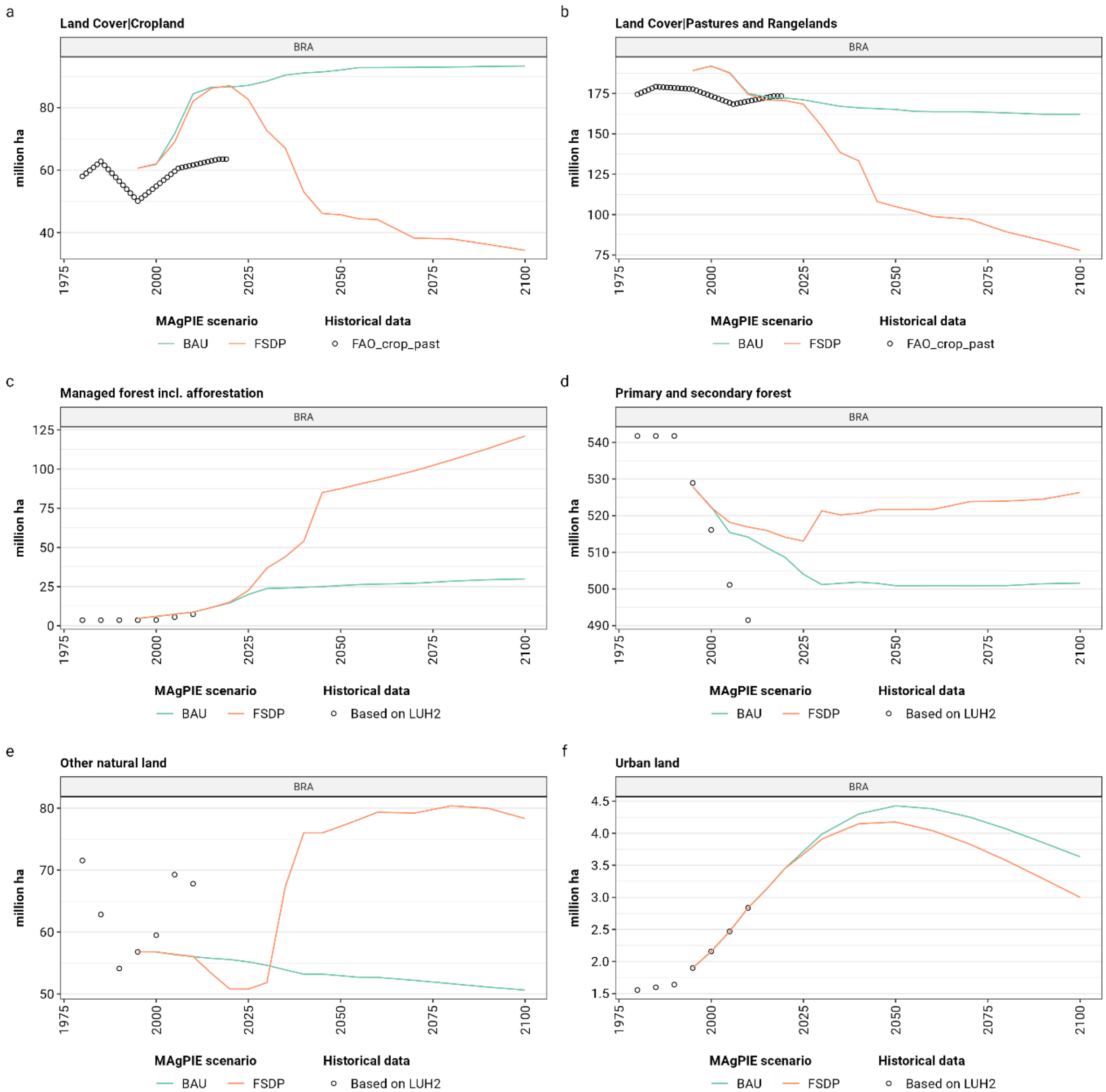
### A.4. Validation plots of key indicators

I. **Economic and food demand indicators**

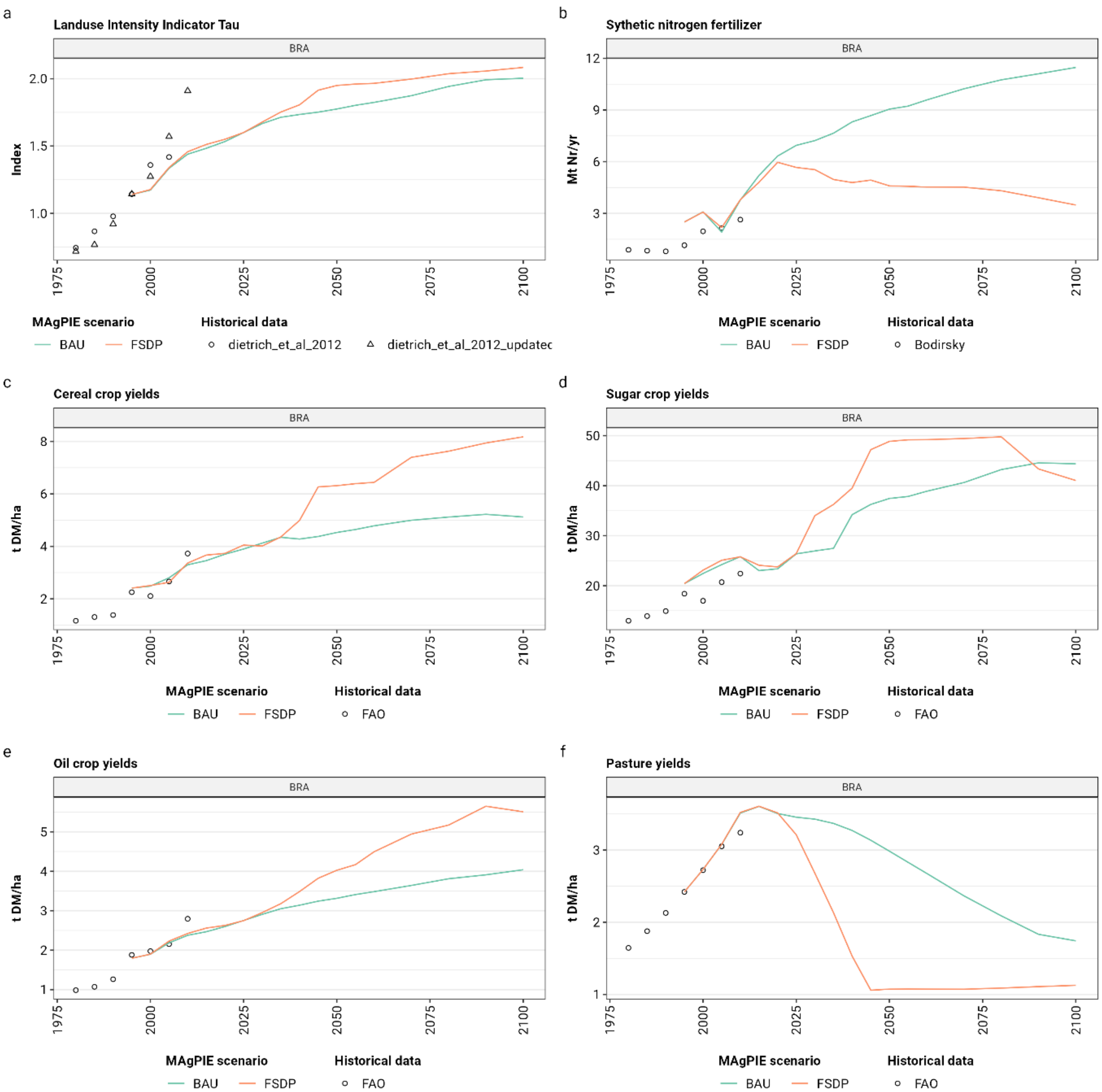


a
Population
BRA
million people
120
150
180
210
1975
2000
2025
2050
2075
2100
MAgPIE scenario
BAU
FSDP
Historical data
WDI-UN_PopDiv-MI
b
Per-capita income
BRA
US$05 PPP/cap/yr
20000
40000
60000
80000
MAgPIE scenario
BAU
FSDP
Historical data
James
c
Per-capita calorie supply from crops
BRA
kcal/capita/day
1400
1500
1600
1700
MAgPIE scenario
BAU
FSDP
Historical data
FAOmassbalance
d
Per-capita calorie supply from livestock products
BRA
kcal/capita/day
400
600
800
1000
MAgPIE scenario
BAU
FSDP
Historical data
FAOmassbalance
e
Total crop demand including feed and feed
BRA
Mt DM/yr
200
400
600
MAgPIE scenario
BAU
FSDP
Historical data
FAO
f
Total livestock product demand
BRA
Mt DM/yr
6
9
12
15
18
MAgPIE scenario
BAU
FSDP
Historical data
FAO

## II. Land Indicators



## III. Yields




References Appendix

1. Dietrich, Jan Philipp, et al. "MAgPIE 4–a modular open-source framework for modeling global land systems." *Geoscientific Model Development* 12.4, 1299-1317 (2019).
2. Bodirsky, B. et al. "A food system transformation can enhance global health, environmental conditions and social inclusion. " *Forthcoming* (2023).
3. Soergel, B. et al. "A sustainable development pathway for climate action within the UN 2030 Agenda." *Nat. Clim. Change* 11.8, 656-664 (2021).
4. Pedrosa, M. et al. *Global assessment of the impacts of grassland management on modeled soil organic carbon.* **[Manuscript in preparation]** (2024)
5. O'Neill, B. et al. "A new scenario framework for climate change research: the concept of shared socioeconomic pathways." *Climatic change* 122, 387-400 (2014).
6. KC & Lutz. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Global Environmental Change 42, 181-192 (2017), DOI: 10.1016/j.gloenvcha.2014.06.004
7. O'Neill, B. et al. "The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century." *Global environmental change* 42, 169-180 (2017).
8. Fricko, O. et al. "The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century." *Global Environmental Change* 42, 251-267 (2017).
9. Mishra, A. et al. Land use change and carbon emissions of a transformation to timber cities. Nat. Commun. 13, 4889 (2022).
10. OECD/FAO (2022), OECD-FAO Agricultural Outlook 2022-2031, OECD Publishing, Paris, https://doi.org/10.1787/f1b0b29c-en.
11. Bodirsky, B. L. et al. The ongoing nutrition transition thwarts long-term targets for food security, public health and environmental protection. Sci. Rep. 10, 19778 (2020).
12. Willett, W. et al. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. The Lancet (2019).
13. Springmann, M. et al. Options for keeping the food system within environmental limits. Nature (2018).
14. Smakhtin, V., Revenga, C. & Döll, P. A Pilot Global Assessment of Environmental Water Requirements and Scarcity. Water Int. 29, 307–317 (2004).
15. Dinerstein, Eric, et al. "An ecoregion-based approach to protecting half the terrestrial realm." *BioScience* 67.6, 534-545 (2017).
16. Dinerstein, Eric, et al. "A global deal for nature: guiding principles, milestones, and targets." *Science advances* 5.4, eaaw2869 (2019).
17. Immovilli & Kok. Narratives for the "Half Earth" and "Sharing The Planet" scenarios. PBL Netherlands Environmental Assessment Agency. (2020)
18. Weindl, I. et al. Livestock production and the water challenge of future food supply: Implications of agricultural management and dietary choices. Glob. Environ. Change 47, 121–132 (2017).
19. Weindl, I. et al. Livestock and human use of land: Productivity trends and dietary choices as drivers of future land and carbon dynamics. Glob. Planet. Change 159, 1–10 (2017).
20. Harmsen, J. H. M., et al. "Long-term marginal abatement cost curves of non-CO2 greenhouse gases." *Environmental Science & Policy* 99, 136-149 (2019).
21. Humpenöder, F. et al. Investigating afforestation and bioenergy CCS as climate change mitigation strategies. Environ. Res. Lett. 9, 064029 (2014).