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Pathways to sustainability in Brazilian agriculture: technological drivers, governance, and policy linkages

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The rapid expansion of Brazilian agriculture, although centered on productivity gains, has brought challenges to the forefront, influencing food systems at national, regional, and global scales. Looming threats such as climate change, deforestation, and land degradation cast shadows of uncertainty over the sustainability and resilience of Brazilian agriculture. This paper explores how technological and non-technological drivers can further strengthen sustainability pathways in Brazilian agriculture. Achieving the vision of strengthened sustainability pathways necessitates a reevaluation of the multifaceted governance measures that harmonize technological advancements with environmental and social responsibilities. The integration of science, innovation, and governance is essential, but it additionally requires novel approaches, such as interdisciplinary dialogue, public–private partnerships, and international collaboration to effectively move towards meaningful sustainability outcomes at multiple levels.

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Introduction

The growth of Brazilian agricultural production from the late twentieth to early twenty-first centuries is one of the most expansive and rapid agricultural transformations throughout history, with direct impacts on national, regional, and global food systems [1]. Globally, for millennia, agricultural development has involved the substitution of forests and other forms of native vegetation to establish food, feed, and fiber crops, as well as pastures. While this was the case for most of Brazil's history as well, the country has, to a certain extent, been able to decouple this long-standing 'deforestation–agriculture' model. Over the past decades, the predominant strategy to expand agricultural output in Brazilian agriculture, centered on productivity gains [2,3], has been fundamental to minimizing the negative impacts of production on the environment. Much of the natural resource base in Brazil has benefited from the sizable land-saving effects over the past 70 years [3], and as of 2023, 65% of the enormous Brazilian territory, with 850.7 million hectares, is still covered with native vegetation [4].

However, a past of achievements and contributions to the multiple dimensions of sustainability does not guarantee, per se, a successful future for Brazilian agriculture. Indeed, beneath Brazilian agriculture's success lies a complex web of challenges that may threaten its long-term sustainability and resilience. Climate change, characterized by erratic weather patterns and more frequent extreme events, is a key factor that casts a shadow of uncertainty over the country's future agricultural production [5,6]. In 2022, Brazil's total greenhouse gases (GHG) emissions reached 2331.5 million metric tons, with land use change and forestry contributing 48%, and with the agriculture and livestock sector accounting for 26% [7]. Significant land-use change has taken place over the past decades, and as of 2023, nearly half of the Cerrado biome and about 20% of the Amazon biome are already cleared [4], even though these changes are not solely attributable to agriculture [8].

Thus, deforestation and land degradation still persist in certain spots, and if not adequately solved, may compromise the very foundations of the agricultural sector, jeopardizing the future potential of Brazilian agriculture [9]. The stakes could not be higher. Brazilian agriculture does not merely provide sustenance for its population. Brazil's agricultural prowess is strategic to global food security. As the world population swells and urbanizes, with increased per capita incomes, the demand for food is likely to continue to increase [10]. Given its comparative advantages in land and renewable resources, Brazil can contribute to global supply through relatively efficient, land-saving production systems, which, if governed sustainably, may help reduce pressure on more fragile ecosystems elsewhere.

Yet, this role of Brazilian agriculture comes with immense responsibilities. The environmental consequences of unsustainable practices, from deforestation affecting biodiversity to greenhouse gas emissions exacerbating climate change, reverberate from local to global scales [6,9,11–13]. These challenges are not isolated; they are deeply interconnected and demand holistic solutions [14]. For example, the socioeconomic fabric of Brazil is deeply intertwined with agriculture. The agricultural sector fosters important spillover effects on the industry and service sectors. As of 2022, agricultural value chains — for example, the economic sectors linked to agriculture and livestock production, involving inputs, on-farm, industrial production, and distribution, and associated services — accounted for 24.8% of Brazil's gross domestic product (GDP) [15] and for 26.3% of total employment [16].

Hence, the resilience and sustainability of Brazilian agriculture hold the keys not only to food security but also to economic stability and environmental conservation [1,6,17]. In this context, it is necessary to recognize that despite the success of Brazilian agriculture over the past decades, there are localized problems between agricultural production and the environmental and social dimensions that need to be appropriately identified, understood, and solved in the next years [6,17,18]. While these challenges are impressive, the potential benefits of forging an increasingly sustainable and resilient agricultural sector are equally compelling. In this vision of the future, not only is food security bolstered, but ecosystems are preserved [12,13,17], protecting the rich biodiversity of the Amazon and other vital Brazilian biomes. Moreover, such a path of transformation can fuel economic growth, additionally creating new opportunities for innovation and, ultimately, for improving the population's well-being and prosperity [11,12,17,19].

In this paper, we examine how Brazil can navigate climate change, deforestation, and land degradation to ensure a sustainable and resilient future for its agriculture. We first assess key technological drivers — such as advanced biology, digital transformation, climate risk management, and sustainable intensification — and their potential contributions. Next, we explore their integration with non-technological and policy drivers, drawing attention to governance challenges and opportunities. The distinction between technological and non-technological drivers is employed to clarify the dual nature of the factors shaping sustainability pathways in Brazilian agriculture. This analytical separation helps highlight the specific roles of these drivers in the innovation flow, without implying a rigid divide, as their interplay is explicitly addressed. We also outline actionable steps to strengthen science–policy interfaces and collaborative efforts, including international cooperation, for advancing sustainability in Brazilian agriculture. Finally, we present our concluding remarks.

Technological drivers for advancing sustainability and resilience in Brazilian agriculture

Technological pathways to sustainability in Brazilian agriculture can be meaningfully grouped into four interrelated domains: (i) advanced biology and genetics, (ii) digital agriculture and cyberinfrastructure, (iii) climate risk management tools, and (iv) sustainable intensification and novel food systems. This categorization helps clarify how different technological advances align with sustainability goals and interact with governance and policy mechanisms addressed later in this paper.

Advanced biology and genetics

The rapid evolution of technology, encompassing areas such as genetic editing, synthetic biology, high-throughput phenotyping, and precision breeding, is revolutionizing access to genetic variability to address agricultural challenges [20–23]. Advances in gene editing, such as CRISPR (short for clustered regularly interspaced short palindromic repeats), also offer potential to reduce input dependence — for example, by developing varieties less reliant on herbicides like glyphosate — and to broaden the use of new genetic variability in crop improvement. These advancements offer unprecedented capabilities to accelerate the development of desirable traits, understand the complex interactions between genes and the environment, and enhance the efficiency and precision of crop improvement [24]. Leveraging these tools effectively is crucial in an era characterized by dynamic climatic patterns, evolving consumer preferences, and emerging plant diseases and pests [21,22,25]. Climate, population, and per capita income expansion, as well as preference changes, increase pressures on agricultural production and natural capital from both the supply and demand side, and thus, sustainably achieving food security presents complex interactions and effects that necessitate a paradigm shift away from more traditional views of agriculture [10,12,14]. Plant breeders and seed producers play a pivotal role in addressing these challenges, as they are responsible for developing resilient, high-yielding, and climate-smart crop varieties with new traits and characteristics.

Digital agriculture and cyberinfrastructure

In parallel with advanced biology achievements, the rapid development of digital technologies has led to tremendous advancements in processes, competencies, and business models, with further leaps anticipated as artificial intelligence (AI) and quantum computing emerge [26,27]. This ongoing digital transformation is giving rise to solutions that operate in synergy, facilitating 'cross-fertilization' and accelerating technological leaps we have been witnessing in social media, e-commerce, the Internet of Things, AI, robotics, and more [28].

Digital transformation in agriculture involves the integration of cutting-edge technologies such as precision agriculture, smart farming systems, and data-driven decision-making [11,27] and, of course, adequate digital infrastructure for the necessary improved connectivity [29]. In Brazil, many of these digital solutions have been pioneered by national research institutions and Ag-Tech startups, with growing adoption by farmers across different regions and production systems.

These technologies allow farmers to optimize resource management, including water, nutrients, and energy, potentially resulting in more efficient and sustainable farming practices [11,27,30]. Precision agriculture, for example, enables accurate and precise application of inputs based on real-time data, reducing waste and negative environmental impacts [27,31]. Smart-farming systems utilize sensors and automation to monitor and manage farm operations efficiently, while data-driven decision-making empowers farmers to make informed choices regarding crop rotation, pest control, and resource allocation [11,27,30]. More broadly, data, software, analytics, modeling, AI, systems, and people — the components of cyberinfrastructure ecosystems — also need to be integrated and accessible to meet the challenges presented to sustainability [27,29].

Therefore, embracing digital transformation can potentially enhance resource efficiency, reduce environmental impact, and improve the overall resilience of Brazilian agriculture in face of changing conditions [17,27,30]. Given the benefits and growing availability of digital solutions in the market, it is perhaps surprising that there has not been a more widespread adoption of such technologies by farmers, even in countries with a science-based agriculture approach [31]. Lack of high-quality access to communication networks and services, at affordable prices, plays an important role [32]. However, these digital innovations are poised to amplify their reach and impact the impending explosion of connectivity [17,32].

Climate risk management tools

Massive data analysis (soil, crop, management), coupled with agrometeorological data and projections, offers key insights to improve agricultural climate risk management approaches, which could be particularly useful for improving yields and agricultural output resilience in the tropics [5,33]. In Brazil, a tool called ZARC (an acronym for 'Agricultural Climate Risk Zoning') helps farmers and policymakers make climate-resilient decisions by delineating suitable areas and planting times [34,35]. As ZARC continues to develop and mature, it holds the promise of becoming an even more powerful tool for enhancing the resilience and sustainability of Brazilian agriculture. With ongoing advancements in data analytics, precision agriculture technologies, and climate modeling [27,36], ZARC could evolve to offer increasingly accurate and personalized insights to farmers, allowing them to make timely decisions based on specific local conditions, relative prices, and changing climate patterns. Moreover, as international collaboration and knowledge sharing grow, ZARC could serve as a valuable blueprint for similar initiatives in other regions of the world, fostering a global network of climate-resilient agriculture practices and contributing to a more sustainable and food-secure future worldwide.

Sustainable intensification and novel food systems

Decisions on suitable areas and planting times are boosted by improved management strategies. Sustainable agriculture intensification (SAI) is a holistic approach to agriculture [37–40] that can help Brazil to increase agricultural productivity while reducing negative environmental impacts and avoiding pressures for more deforestation [1,17]. SAI is sometimes also referenced as regenerative agriculture, climate-smart agriculture, etc., as conceptually these terms aim to express a very similar idea [40]. SAI integrates a range of practices, such as crop rotation, cover cropping and no-till planting, integrated pest management, precision agriculture, crop-livestock-forest systems, and precision management, that can help to improve soil health, reduce water pollution, increase biodiversity, and mitigate and adapt to climate change [37–41]. By increasing the efficiency of the land already allocated to agriculture, SAI can help Brazil meet its food security needs without the need to expand agriculture into new areas, thereby minimizing impacts to forests and other natural ecosystems [17,42,43]. Importantly, both SAI and digital tools hold significant potential to support small- and medium-sized producers by improving productivity, optimizing resource use, and facilitating access to technical information and markets.

Novel food systems are also at the forefront of reshaping how we produce and consume food, driven by evolving consumer demands and demographic shifts [10,11]. These transformations are not merely about changing what we eat but represent a profound shift in our perception of food systems and their far-reaching impacts on nutrition, health, and sustainability [44,45]. One of the key elements of these innovations is the emergence of alternative protein sources, such as plant-based proteins mimicking meat's protein, cultured proteins, and insect-based foods that, in some circumstances, can provide protein-rich food and feed with a lower environmental footprint [46,47].

However, several challenges still exist beyond consumers' preferences. For example, plant-based meat may contain high amounts of sodium and additives, lower amounts of B12, zinc, and iron (if not added), and, additionally, is highly processed. Other alternative protein sources may be associated with allergies, and there are cases in which little is known about their costs of production, nutritional composition, and overall health effects [48]. Nevertheless, as societies become more health-conscious and environmentally aware, dietary choices are undergoing a transformation [46,49]. Consumers, particularly in high-income countries, are already seeking foods that not only nourish but also align with their ethical and ecological values. Despite major short to medium-run barriers, this shift goes beyond individual diets; it reflects concerns on the interconnectedness of our food choices with broader issues like climate change and biodiversity loss [10,11,46,47].

Non-technological and policy drivers for advancing sustainability governance in Brazilian agriculture

Governance plays a critical role not only in setting enabling conditions for the adoption of technologies, but also in guiding their integration into socially and environmentally responsible agricultural systems. We organize the governance discussion into: (i) key legal and policy frameworks, (ii) enabling conditions and institutional challenges, and (iii) strategic governance innovations to support sustainability outcomes.

Key legal and policy frameworks

Brazil has made significant strides in sustainability governance, particularly in the realm of policies and regulations [1]. Brazil's Forest Code [50] stands out as the most significant public environmental governance framework for the regulation of agricultural production. In addition to establishing the rules determining the conservation and restoration of native vegetation within private lands, the implementation of the law provides incentives to prioritize the intensive margin, for example, agricultural productivity gains [51], thus creating stimuli for rural producers to invest in technologies promoting intensification and land-saving results [17,45]. Protected areas [52], moratoriums on deforestation [53], and ongoing efforts to define due diligence regulations, to ensure that the goods other countries import from Brazil are legally sourced and produced [54], are also key advances in the sustainability governance realm. The implementation of regulatory measures often depends on complex political dynamics, and alignment among key stakeholders is not always straightforward. In some cases, this has limited the adoption of potentially beneficial governance solutions, even when technically feasible.

Enabling conditions and institutional challenges

The greatest sustainability governance challenge for Brazil still centers around the critical issue of deforestation and its impact on the environment and international perception [55,56]. Balancing the need for agricultural expansion with environmental preservation, mitigating climate change, and promoting biodiversity conservation are pressing concerns [1,6,12]. Addressing this requires clearer coordination mechanisms, stronger incentives for compliance across the entire sector, and inclusive dialogue that builds legitimacy among diverse stakeholders. Achieving sustainable agricultural models [17,44,45], adopting land-saving and greenhouse gas emission-reducing technologies [5,10,11,42,45], and integrating carbon markets into agriculture [57] all pose governance challenges. Social inclusion in agriculture, effective environmental governance in the digital age, and the stability of policies in face of changing political dynamics are also significant issues [58,59]. Greater attention is needed to the social pillar of sustainability, particularly the challenges of improving smallholder livelihoods, promoting rural inclusion, and advancing human development in agricultural regions.

Brazil's role in the global environmental agenda and trade relations [18,60] adds even more complexity to governance efforts, requiring a delicate balance between international demands and domestic needs for robust sustainability outcomes. To ensure the effectiveness of these policies is not diminished and to minimize their vulnerability to short-term political influences, it is crucial to consistently emphasize the importance of ongoing public engagement and scientific research in advancing sustainable outcomes. Nonetheless, despite the well-known strategic role of agricultural research and development (R&D) to advancing agricultural competitiveness, sustainability, and resilience, the decreasing R&D expenditures over the past decade, especially in the Global South, warrant urgent attention [2,17,61,62].

Strategic governance innovations to support sustainability outcomes

Realizing the potential of technological drivers depends heavily on effective governance, including regulatory stability, policy alignment, public–private coordination, and long-term investment in R&D, which are explored in the next section. Nature-based sectors, such as agriculture and forestry, have strong links with the rest of the economy with backward and forward multipliers [12,15]. By recognizing the critical role of natural capital, which encompasses the world's resources and services provided by nature, in underpinning economic progress and societal development, we acknowledge the foundation upon which sustainable agriculture rests [5,12,13,63,64]. Innovative science and cutting-edge models highlight the efficiency gap — where current resource utilization falls short of what could be achieved sustainably. Closing these gaps, especially in biodiversity, carbon storage, agriculture, grazing, timber, and economic returns, can address pressing global challenges like health, food security, water security, climate change, and economic productivity [12]. As we grapple with the intricate challenges of sustainability governance in agriculture, recognizing the value of natural capital and harnessing nature-based solutions emerge as pivotal strategies [12,13,19,63,64]. These approaches not only contribute to meeting climate and economic objectives but also serve as crucial tools for securing a more resilient and prosperous future [5].

Synergies and holistic integration of drivers

As we contemplate the path forward for Brazilian agriculture, it becomes evident that the pursuit of sustainability, innovation, and governance must not operate in isolation but must be tightly woven together to address the multifaceted challenges at hand. The advances in science and innovation, as discussed in this review and elsewhere [10,11,17,27,35,45], hold immense potential to transform Brazilian agriculture, making it more resilient, efficient, and environmentally friendly. However, realizing such potential necessitates a parallel advancement in sustainability governance that aligns with these technological innovations.

The challenges are formidable. The complexities of climate change, deforestation, and biodiversity loss demand comprehensive solutions that go beyond the capabilities of any single organization or sector [65]. Cooperation and alignment of purposes are paramount, but the current landscape to advance on that path presents challenges. Firstly, existing organizations and institutions may not be adequately equipped to address the intricate interplay of these drivers effectively. Many traditional structures were not designed to adapt to the rapid pace of technological and environmental changes we are witnessing today. New models of collaboration and governance are required to bridge the gap between scientific progress and effective technological and knowledge implementation [11,14,28]. Secondly, the integration of advanced knowledge and technologies into sustainable practices and associated governance measures is not a straightforward task. It requires breaking down silos and fostering interdisciplinary collaboration among researchers, policymakers, industry stakeholders, and local communities. Achieving this level of cooperation can be hindered by bureaucratic processes and conflicting interests.

To overcome these challenges, it is essential to explore novel approaches for cooperation and alignment of purposes [11]. One promising avenue is the creation of multidisciplinary task forces or consortia that could bring together experts from various fields, including (but not limited to) agronomy, biology, economics, data science, and environmental governance. These task forces need to work in synergy to develop integrated, multiscale analyses and solutions that leverage the full potential of technological drivers — advanced biology, digital transformation, climate risk management tools, and SAI — while adhering to robust environmental, social, and governance principles.

Public–private partnerships that involve both governmental bodies and industry players can facilitate the adoption of cutting-edge technologies and sustainable practices on a broader scale. Incentives and regulations can be designed to encourage environmentally responsible behavior and the adoption of innovative solutions [11–13,17]. International collaboration and knowledge sharing should hold a central focus. Brazil's position as a global agricultural powerhouse means that its experiences and solutions for strengthening sustainability can have far-reaching impacts [1]. Establishing partnerships among countries can lead to shared knowledge and the development of novel strategies towards global sustainability and the achievement of the Sustainable Development Goals (SDGs). These efforts should be guided by clear sustainability goals, including those embedded in the SDGs, such as zero hunger, climate action, responsible consumption, and life on land — where agriculture plays a direct and strategic role.

Conclusion

The vision of advancing science and innovation in sync with sustainability governance is not without its hurdles. The stakes are high, and while the potential benefits are immense, achieving them requires overcoming substantial challenges, such as political fragmentation, uneven governance, and ensuring inclusive growth for all stakeholders. Reaching a sustainable and resilient agriculture will not be easy and will demand coordinated, long-term efforts across different sectors. Strengthening such an approach is essential for the future of Brazilian agriculture, global food security, and environmental preservation. To succeed, we must reevaluate some of the current policy and organizational structures, foster collaboration among diverse stakeholders, in Brazil and abroad, and embrace innovative approaches to address the pressing sustainability challenges that lie ahead.

As the world looks on, Brazil stands at a pivotal crossroads, presented with a unique opportunity to set a compelling example. The country has the potential to demonstrate how sustainable and resilient agriculture can thrive in the face of unprecedented challenges. This is a resounding call that requires revitalized collaborative actions, resonating with the global imperative of feeding a growing population while safeguarding the planet. The stakes are high, but the potential benefits are even higher — an agriculture that not only helps feed the world but also nurtures our planet for generations to come.

Author contributions

The two authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Data Availability

No data were used for the research described in the article.

Declaration of Competing Interest

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

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References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. • Søndergaard N, De Sá CD, Platiau AFB: **Introduction: the sustainability challenges of Brazilian agriculture**. In *Sustainability Challenges of Brazilian Agriculture*. Edited by Søndergaard N, De Sá CD, Barros-Platiau AF. Springer International Publishing; 2023:1-16.

The book offers an up to date account of the challenges of reconciling Brazilian agricultural growth with ecological imperatives, discussing perspectives and solutions for improving the sustainability performance of Brazilian agriculture.

2. USDA-ERS: **International Agricultural Productivity**; 2022.

3. Martha GB, Alves E: **Brazil's agricultural modernization and Embrapa**. In *The Oxford Handbook of the Brazilian Economy*. Edited by Amann E, Azzoni CR, Baer W. Oxford University Press; 2018.

4. • Mapbiomas: **MapBiomas Project: Annual Land Use and Land Cover Mapping of Brazil**. *Collection 9*; 2024..

MapBiomas is a collaborative network formed by NGOs, universities, and technology startups, which provides open-access data and insights on land use change dynamics in Brazil. The most recent collection 8, released on August 2023, presents yearly information for the 1985–2022 period.

5. Calvin K, Dasgupta D, Krinner G, Mukherji A, Thorne PW, Trisos C, Romero J, Aldunce P, Barrett K, Blanco G, et al: IPCC, 2023: **Climate change 2023: synthesis report**. *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland*. Intergovernmental Panel on Climate Change (IPCC). Edited by Core Writing Team, Lee H, and J. Romero; 2023.

6. •• Zilli M, Scarabello M, Soterroni AC, Valin H, Mosnier A, Leclère D, Havlík P, Kraxner F, Lopes MA, Ramos FM: **The impact of climate change on Brazil's agriculture**. *Sci Total Environ* 2020, **740**:139384.

The article provides projections of climate change impacts on key agricultural production systems in Brazil, offering insights into the intersection of technological drivers and science-policy challenges to drive sustainability in the face of the climate crisis.

7. SEEG: **SEEG - Sistema de Estimativas de Emissões e Remoções de Gases de Efeito Estufa**; 2024.

8. Mueller B: **Property rights and the evolution of a frontier**. *Land Econ* 1997, **73**:42.

9. Lapola DM, Pinho P, Barlow J, Aragão LEOC, Berenguer E, Carmenta R, Liddy HM, Seixas H, Silva CVJ, Silva-Junior CHL, *et al*.: **The drivers and impacts of Amazon forest degradation**. *Science* 2023, **379**:eabp8622.

10. Springmann M, Clark M, Mason-D′Croz D, Wiebe K, Bodirsky BL, Lassaletta L, De Vries W, Vermeulen SJ, Herrero M, Carlson KM, *et al*.: **Options for keeping the food system within environmental limits**. *Nature* 2018, **562**:519-525.

11. •• Herrero M, Thornton PK, Mason-D′Croz D, Palmer J, Benton TG, Bodirsky BL, Bogard JR, Hall A, Lee B, Nyborg K, *et al*.: **Innovation can accelerate the transition towards a sustainable food system**. *Nat Food* 2020, **1**:266-272.

The authors underscore the pivotal role of technological innovation in conjunction with drivers, such as stakeholder dialogue, transition pathways, social license, and others, for advancing sustainability in the food system.

12. •• Damania R, Polasky S, Ruckelshaus M, Russ J, Amann M, Chaplin-Kramer R, Gerber J, Hawthorne P, Heger MP, Mamun S, *et al*.: **Nature's Frontiers: Achieving Sustainability, Efficiency, and Prosperity with Natural Capital**. The World Bank; 2023.

This report presents a novel methodology combining innovative science, new data sources, and cutting-edge biophysical and economic models, which builds sustainable resource efficiency frontiers to assess how countries can sustainably use their natural capital more efficiently. This approach offers countries a way to design better plans for using their natural capital to simultaneously achieve economic and environmental goals.

13. Johnson JA, Baldos UL, Corong E, Hertel T, Polasky S, Cervigni R, Roxburgh T, Ruta G, Salemi C, Thakrar S: **Investing in nature can improve equity and economic returns**. *Proc Natl Acad Sci USA* 2023, **120**:e2220401120.

14. Liu J, Mooney H, Hull V, Davis SJ, Gaskell J, Hertel T, Lubchenco J, Seto KC, Gleick P, Kremen C, *et al*.: **Systems integration for global sustainability**. *Science* 2015, **347**:1258832.

15. • CEPEA-ESALQ-USP: **PIB do agronegócio brasileiro**; 2024.
.

Gross domestic product estimates for Brazilian agribusiness (agricultural value chains) – national level – since 1996.

16. • CEPEA-ESALQ-USP: **Mercado de trabalho do agronegócio**; 2024.

Labor data for Brazilian agribusiness (agricultural value chains) – national level – since 2012.

17. Martha Júnior GB, Lopes MA: **Charting new sustainable agricultural innovation pathways in Brazil**. *Sci Agric* 2023, **80**:e20230067.

18. Rajão R, Soares-Filho B, Nunes F, Börner J, Machado L, Assis D, Oliveira A, Pinto L, Ribeiro V, Rausch L, *et al*.: **The rotten apples of Brazil's agribusiness**. *Science* 2020, **369**:246-248.

19. Nobre I, Nobre CA: **The Amazonia Third Way Initiative: the role of technology to unveil the potential of a novel tropical biodiversity-based economy**. In *Land Use – Assessing the Past, Envisioning the Future*. Edited by Carlos Loures L. IntechOpen; 2019.

20. Crisp PA, Bhatnagar-Mathur P, Hundleby P, Godwin ID, Waterhouse PM, Hickey LT: **Beyond the gene: epigenetic and cis-regulatory targets offer new breeding potential for the future**. *Curr Opin Biotechnol* 2022, **73**:88-94.

21. Guo T, Lin H-X: **Creating future crops: a revolution for sustainable agriculture**. *J Genet Genom* 2021, **48**:97-101.

22. Roell M-S, Zurbriggen MD: **The impact of synthetic biology for future agriculture and nutrition**. *Curr Opin Biotechnol* 2020, **61**:102-109.

23. Schnurr MA, Rock J, Kingiri A, Lieberman S: **Are genetically modified and genome-edited crops viable strategies for climate-change adaptation among smallholder farmers?** *Curr Opin Environ Sustain* 2022, **58**:101216.

24. Hickey LT, N. Hafeez A, Robinson H, Jackson SA, Leal-Bertioli SCM, Tester M, Gao C, Godwin ID, Hayes BJ, Wulff BBH: **Breeding crops to feed 10 billion**. *Nat Biotechnol* 2019, **37**:744-754.

25. Stetkiewicz S, Menary J, Nair A, Rufino M, Fischer ARH, Cornelissen M, Guichaoua A, Jorasch P, Lemarié S, Nanda AK, *et al*.: **Food system actor perspectives on future-proofing European food systems through plant breeding**. *Sci Rep* 2023, **13**:5444.

26. Ayoade O, Rivas P, Orduz J: **Artificial intelligence computing at the quantum level**. *Data* 2022, **7**:28.

27. In *Digital Agriculture: Research, Development and Innovation in Production Chains*. Edited by Massruhá SMFS, Leite MA de A, Oliveira SR de M, Meira CAA, Luchiari Junior A, Bolfe ÉL. Embrapa; 2023.

28. Schwab K: **The Fourth Industrial Revolution**. Crown Business; 2016.

29. Song CX, Merwade V, Wang S, Witt M, Kumar V, Irwin E, Zhao L, Walton A: **Cyberinfrastructure for sustainability sciences**. *Environ Res Lett* 2023, **18**:075002.

30. Fabregas R, Kremer M, Schilbach F: **Realizing the potential of digital development: the case of agricultural advice**. *Science* 2019, **366**:eaay3038.

31. Lowenberg-DeBoer L: **The economics of precision agriculture**. Precision Agriculture for Sustainability. Burleigh Dodds Science Publishing; 2019:461-481.

32. OECD: **Enhancing Access and Connectivity to Harness Digital Transformation (OECD Going Digital Policy Note)**; 2019.

33. Parker L, Bourgoin C, Martinez-Valle A, Läderach P: **Vulnerability of the agricultural sector to climate change: the development of a pan-tropical Climate Risk Vulnerability Assessment to inform sub-national decision making**. *PLoS One* 2019, **14**:e0213641.

34. Santos WG, Martins JIF: **O Zoneamento Agrícola de Risco Climático e sua contribuição à agricultura brasileira**. *Rev De Política Agric* 2016, **25**:73-94.

35. Monteiro JDA, Costa FDS, Bezerra M, Comunello E, Zolin C, Pereira JR, Melém Junior NJ, Antônio IC, Santiago AV, Silva SC, *et al.*: **Zoneamento Agrícola de Risco Climático (ZARC)**. Estratégias de Adaptação às Mudanças do Clima dos Sistemas Agropecuários Brasileiros. MAPA; 2021:102-103.

36. Westerveld JJL, Van Den Homberg MJC, Nobre GG, Van Den Berg DLJ, Teklesadik AD, Stuit SM: **Forecasting transitions in the state of food security with machine learning using transferable features**. *Sci Total Environ* 2021, **786**:147366.

37. Godfray HCJ: **The debate over sustainable intensification**. *Food Sec* 2015, **7**:199-208.

38. Garnett T, Appleby MC, Balmford A, Bateman IJ, Benton TG, Bloomer P, Burlingame B, Dawkins M, Dolan L, Fraser D, *et al.*: **Sustainable intensification in agriculture: premises and policies**. *Science* 2013, **341**:33-34.

39. Campbell BM, Thornton P, Zougmoré R, Van Asten P, Lipper L: **Sustainable intensification: what is its role in climate smart agriculture?** *Curr Opin Environ Sustain* 2014, **8**:39-43.

40. Giller KE, Hijbeek R, Andersson JA, Sumberg J: **Regenerative agriculture: an agronomic perspective**. *Outlook Agric* 2021, **50**:13-25.

41. • Cassman KG, Grassini P: **A global perspective on sustainable intensification research**. *Nat Sustain* 2020, **3**:262-268.
One of the key features of sustainable intensification approaches is to efficiently increase yields. Under Borlaug hypothesis, a land-saving effect would be observed, allowing agricultural output to increase with lower pressure on land resources. The yield gap concept represents the difference between attainable yields (or yield potential) and average farmer yields over some specified spatial and temporal scale of interest. Thus, from a biophysical perspective, the yield gap concept indicates the opportunities to expand output through the intensive margin (i.e. land productivity gains).

42. • Martha GB, Alves E, Contini E: **Land-saving approaches and beef production growth in Brazil**. *Agric Syst* 2012, **110**:173-177.
The analysis of land productivity in pasture-based systems is more complex. In pasture-based systems, productivity (kg of animal product/ha) derives from the product of animal performance (kg of animal product/ha) and stocking rates (animals/ha). Additionally, the authors highlight the pivotal role of technological advances and land-saving gains in steering Brazil's beef production sector towards more sustainable practices.

43. Baker E, Bezner Kerr R, Deryng D, Farrell A, Gurney-Smith H, Thornton P: **Mixed farming systems: potentials and barriers for climate change adaptation in food systems**. *Curr Opin Environ Sustain* 2023, **62**:101270.

44. von Braun J, Afsana K, Fresco LO, Hassan M, Torero M: **Food system concepts and definitions for science and political action**. *Nat Food* 2021, **2**:748-750.

45. Giller KE, Delaune T, Silva JV, Descheemaeker K, Van De Ven G, Schut AGT, Van Wijk M, Hammond J, Hochman Z, Taulya G, *et al.*: **The future of farming: who will produce our food?** *Food Sec* 2021, **13**:1073-1099.

46. Thornton P, Gurney-Smith H, Wollenberg E: **Alternative sources of protein for food and feed**. *Curr Opin Environ Sustain* 2023, **62**:101277.

47. Frezal C, Nenert C, Gay H: **Meat protein alternatives: opportunities and challenges for food systems' transformation**. *OECD Food Agric Fish Pap* 2022, **182**:51.

48. Food Forum, Food and Nutrition Board, Health and Medicine Division, National Academies of Sciences, Engineering, Medicine: **Alternative Protein Sources: Balancing Food Innovation, Sustainability, Nutrition, and Health: Proceedings of a Workshop**. National Academies Press; 2023.

49. • Gouel C, Guimbard H: **Nutrition transition and the structure of global food demand**. *Am J Agric Econ* 2019, **101**:383-403.
The authors analyze expected nutrition transitions and their impact on global food demand, offering insights into the changing dietary patterns and consumption trends that are key to inform technological drivers and science-policy synergies for sustainable agriculture in Brazil.

50. Soares-Filho B, Rajão R, Macedo M, Carneiro A, Costa W, Coe M, Rodrigues H, Alencar A: **Cracking Brazil's Forest Code**. *Science* 2014, **344**:363-364.

51. Chiavari J, Lopes CL, De Alcantara Machado L: **The Brazilian Forest Code: the challenges of legal implementation**. In *Sustainability Challenges of Brazilian Agriculture*. Edited by Søndergaard N, De Sá CD, Barros-Platiau AF. Springer International Publishing; 2023:295-314.

52. Gonçalves-Souza D, Vilela B, Phalan B, Dobrovolski R: **The role of protected areas in maintaining natural vegetation in Brazil**. *Sci Adv* 2021, **7**:eabh2932.

53. Guimarães AL, De Castro Chaves Stabile M, Moutinho P: **Private governance: multistakeholder initiatives and moratoriums**. In *Sustainability Challenges of Brazilian Agriculture*. Edited by Søndergaard N, De Sá CD, Barros-Platiau AF. Springer International Publishing; 2023:427-444.

54. Bosselmann AS, Dolmer SEN: **Sustainability governance of soybean trade between Brazil and Europe: the road travelled and the challenges ahead**. In *Sustainability Challenges of Brazilian Agriculture*. Edited by Søndergaard N, De Sá CD, Barros-Platiau AF. Springer International Publishing; 2023:45-65.

55. Seymour F, Harris NL: **Reducing tropical deforestation**. *Science* 2019, **365**:756-757.

56. Zu Ermgassen EKHJ, Godar J, Lathuillière MJ, Löfgren P, Gardner T, Vasconcelos A, Meyfroidt P: **The origin, supply chain, and deforestation risk of Brazil's beef exports**. *Proc Natl Acad Sci USA* 2020, **117**:31770-31779.

57. Liu Z, Lang L, Hu B, Shi L, Huang B, Zhao Y: **Emission reduction decision of agricultural supply chain considering carbon tax and investment cooperation**. *J Clean Prod* 2021, **294**:126305.

58. German LA, Bonanno AM, Foster LC, Cotula L: **"Inclusive business" in agriculture: evidence from the evolution of agricultural value chains**. *World Dev* 2020, **134**:105018.

59. Roberts C, Geels FW: **Conditions for politically accelerated transitions: historical institutionalism, the multi-level perspective, and two historical case studies in transport and agriculture**. *Technol Forecast Soc Change* 2019, **140**:221-240.

60. Soterroni AC, Ramos FM, Mosnier A, Fargione J, Andrade PR, Baumgarten L, Pirker J, Obersteiner M, Kraxner F, Câmara G, *et al.*: **Expanding the Soy Moratorium to Brazil's Cerrado**. *Sci Adv* 2019, **5**:eaav7336.

61. Pardey PG, Chan-Kang C, Dehmer SP, Beddow JM: **Agricultural R&D is on the move**. *Nature* 2016, **537**:301-303.

62. • Prasad PVV, Bhatnagar N, Bhandari V, Jacob G, Narayan K, Echeverría R, Beintema N, Farah Cox P, Compton J: **Patterns of investment in agricultural research and innovation for the Global South, with a focus on sustainable agricultural intensification**. *Front Sustain Food Syst* 2023, **7**:1108949.
The authors examine global investment patterns in agricultural research and innovation, shedding light on the sources of funding, their allocation, and the need to align these investments with sustainability goals and technological drivers for sustainable agricultural intensification.

63. Bateman IJ, Mace GM: **The natural capital framework for sustainably efficient and equitable decision making**. *Nat Sustain* 2020, **3**:776-783.

64. Barbier EB, Burgess JC: **Natural capital, institutional quality and SDG progress in emerging market and developing economies**. *Sustainability* 2023, **15**:3055.

65. Talukder B, Blay-Palmer A, vanLoon GW, Hipel KW: **Towards complexity of agricultural sustainability assessment: main issues and concerns**. *Environ Sustain Indic* 2020, **6**:100038.