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Discussion

Getting pastoral systems productivity right

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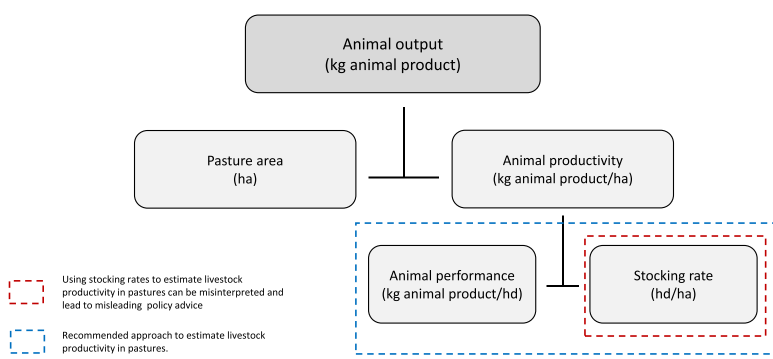
HIGHLIGHTS

- Land-productivity levels have agronomic, economic and environmental implications.
- Yield gap analysis reveals agronomic, economic, and policy challenges.
- Both, stocking rates and animal performance levels, modulate systems' productivity.
- To capture synergies and trade-offs novel modeling methods and approaches are needed.

GRAPHICAL ABSTRACT



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ABSTRACT

Beef production in pasture-based systems is increasingly contested due to related biophysical and environmental challenges. Addressing these requires rigorous science-based evidence to inform private decisions and public policies. Increasing yields and simultaneously reducing the negative environmental impacts of agricultural and livestock production are central to sustainable intensification approaches. Yet, stocking rate, the commonly used metric for animal productivity in pastures, or more broadly, of sustainable intensification in pastoral production systems, warrants scrutiny to signpost successful transformative change of food systems and to avoid provision of misleading policy advice. Here we discuss why future studies would benefit of considering the two constituent elements of productivity in pastoral systems – animal performance (kg of animal product/head) and stocking rates (heads/ha) –, rather than stocking rates alone.

Our food systems are increasingly central to sustainability debates and the need to reduce greenhouse gas (GHG) emissions in particular.

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Livestock are highly implicated, and while food producing animals afford undoubted economic and social benefits, their associated direct and indirect environmental footprints in terms of land use change and GHG emissions have come under increasing scrutiny (Godde et al., 2021; Henchion et al., 2021; Moran and Blair, 2021).

One sector's response to this challenge is through sustainable intensification, which integrates a range of practices that can help to improve soil health, reduce water pollution, mitigate and adapt to climate change, and increase biodiversity (Cassman and Grassini, 2020; Giller et al., 2021a, 2021b). Reducing the emissions-intensity (GHG per unit of product) is an increasingly important focus for livestock science (Godde et al., 2021; Moran and Blair, 2021), as well as the goal of expanding (land) productivity, i.e. the output per unit area, with associated land-saving effects (Martha Jr et al., 2012; Villoria, 2019). Increasing yields and simultaneously reducing the negative environmental impacts of agricultural and livestock production are, thus, central to sustainable intensification approaches.

In pastoral systems, stocking rates have been used as a proxy for land productivity (Marin et al., 2022; Monteiro et al., 2020; Stocco et al., 2020). However, stocking rate, as a metric of productivity or, more broadly, of sustainable intensification in production systems warrants scrutiny to signpost successful transformative change of food systems and to avoid provision of misleading policy advice. Here we discuss why future studies would benefit of considering the two constituent elements of productivity in pastoral systems – animal performance (kg of animal product/head) and stocking rates (heads/ha) –, rather than stocking rates alone.

1. Productivity in pasture-based systems

Many studies have successfully applied yield gap modeling and analysis to assess local and global opportunities for increasing yields in several crops (Cassman and Grassini, 2020; Giller et al., 2021a, 2021b; Marin et al., 2022; van Dijk et al., 2017). Recent yield gap studies have extended the focus to livestock productivity in pastoral systems. Some of these studies have considered stocking rates, observed and potential (i.e. carrying capacity), as a proxy for animal productivity in pasture-based livestock systems (Marin et al., 2022; Monteiro et al., 2020; Stocco et al., 2020). However, the analysis of land productivity in pasture-based systems is more complex. Forage production may be the major determinant of potential stocking rates (heads/ha), but two other partial efficiencies are relevant to grazing systems: the grazing efficiency (i.e., the proportion of herbage dry mass produced that is ingested by the grazing animals), and the conversion efficiency (i.e. the ratio between consumed herbage dry mass and animal product). In pasture-based systems, productivity (kg of animal product/ha) derives from the product of animal performance (kg of animal product/head) and stocking rates. Animal output is, thus, the product of area and productivity (Martha Jr et al., 2012). Accordingly, using stocking rates as a proxy for productivity in pasture-based systems can be misleading for both private decision making and public policy.

Firstly, stocking rates explain only a fraction of observed productivities in reality. For example, used as a proxy for productivity, stocking rates would have captured only one-third of the actual productivity gains registered in Brazilian beef production in 1996–2006 (Martha Jr et al., 2012). Were a similar analysis performed for the period 2006–2017, stocking rates would indicate that “productivity” had only slightly decreased (from 1.10 head/ha to 1.09 head/ha). However, gains in animal performance contributed for an overall 13 % increase in beef productivity in the period (from 43 to 48 kg carcass weight-equivalent/ha).

Secondly, a focus solely on stocking-rates may be misleading in terms of environmental impacts of livestock production. This is due to the inaccurate description of variations in emissions-intensity associated with animal performance (i.e., kg methane emitted per unit of carcass weight-equivalent).

Thirdly, stocking rates inadequately capture the price signals associated with changes in demand and supply that ultimately provide incentives (disincentives) to expand (contract) production, because it is not directly linked to the value of commercialized beef.

In practical terms, if stocking rates increase without matching forage availability, they may reduce animal performance, animal productivity and, therefore, jeopardize economic performance. A lower animal performance increases methane emission-intensity (McAuliffe et al., 2018). Furthermore, attaining higher stocking rates, especially in environments with weathered tropical soils, would likely require increased use of fertilizers, supplements, and other inputs (Martha Jr et al., 2012), so full impacts should include a production system approach and lifecycle assessment. If a higher level of animal performance is associated with a very low stocking rate, then again productivity and economic performances are compromised.

Note that the concept of a yield gap, per se, is not automatically linked to an economic assessment of agricultural production. To that end, it is necessary to consider the yield that maximizes the net value at a particular condition, which in addition to biophysical criteria will vary according to input/product price ratios (Beddow et al., 2014; van Dijk et al., 2017). Such technological and economic perspectives become more complex when applied to pastoral systems, because considering only one component of productivity (i.e., animal performance or stocking rates) may lead to misleading conclusions.

Furthermore, from both economic and environmental analytical viewpoints, there is no rule of thumb, i.e., increasing stocking rates or animal performance might or might not be profitable and environment-friendly. Each situation must be carefully evaluated, and the efficiency of any pastoral system should consider price and transformation ratios for both productivity components, stocking rates and animal performance, including the possibility of using supplements, such as agricultural co-products, for the grazing animals. Increasingly, key environmental variables should be explicitly considered as part of the farmers' objective function.

2. A real-world perspective on animal productivity in pastures

As indicated by others (Marin et al., 2022; Monteiro et al., 2020; Stocco et al., 2020), stocking rates as a proxy for productivity may be problematic, as this approach is unable to adequately capture key variables associated with decisions in the real-world, and might not provide sufficient guidance for policies focusing on the multiple dimensions of sustainability. Distortions arising from using stocking rates as a productivity proxy may be minimized by estimating animal productivity in pastures as the product between animal performance and stocking rates. A methodological challenge refers to estimating animal productivity at more disaggregated scales, such as the municipality level. Yet, it is possible to adapt available methods (Martha Jr et al., 2012) (for an example, see Supplementary material). A key assumption is that animal performance at aggregate levels (such as state or province) can represent the average animal performance at more disaggregated scales (such as county or municipality levels). Yet, that approach, although offering a better perspective of productivity compared to the stocking rate-only approach, has some limitations. In part, because it is unable to capture the factors influencing animal performance locally and, as such, it is not completely accurate. In addition, this analysis is based on annual proxy variables that only partially capture complex interactions in biophysical, socio-economic, and environmental dimensions affecting productivity. Thus, it is not able to, nor intended to, reflect characteristics of the production systems across seasonal variations such as the dry season impacts and associated coping strategies. Such monthly, weekly, or daily effects are diluted in any annual average. Also, available data for beef output, used as a proxy of animal performance, is based on a complete cattle cycle, i.e., cow-calf, yearling, and finishing phases. More detailed analysis, such as the evaluation of the impacts of improved technical coefficients on bio-economic performance and greenhouse gas emissions, would require additional pre- and post-modeling efforts based on cattle herd structure and selling projections resulting from variations in technical coefficients.

3. Livestock productivity in pasture-based systems: from science into practice

Beef production in pasture-based systems is increasingly contested due to related biophysical and environmental challenges (Giller et al., 2021a, 2021b; Godde et al., 2021; Henchion et al., 2021; Herrero et al., 2020; Moran and Blair, 2021). Addressing these challenges will require rigorous science-based approaches so that private decisions and public policies can be based on the best evidence.

For a given output level, the higher the land productivity (output per unit area) – the intensive margin – the lower is the demand for agricultural land expansion – the extensive margin. The Borlaug hypothesis implies that a focus on the intensive margin allows agricultural output expansion with less pressure on natural resources and biodiversity (Hertel et al., 2014). Such a strategy should be additionally coupled with resource-use efficient approaches to alleviate the demand for human-made inputs such as fertilizers and agrochemicals and, thus, minimize their associated impacts on the environment (Beddow et al., 2014; Martha Jr et al., 2012). However, it must be recognized that a rebound effect ("Jevons' paradox"), i.e. land expansion despite yield gains, may occur when global food demand is price responsive and yields in an innovative region are relatively low compared to the global average (Hertel et al., 2014).

Furthermore, sustainable intensification goals and achievements require animal productivity in pastures to be adequately estimated. "Productivity" can be easily estimated by using available cattle herd population and pasture area data (e.g. stocking rate). However, this "standard" approach fails to reflect accurately livestock productivity in pastoral systems. By minimizing such measurement distortions – e.g. by estimating animal productivity in pastures as the product of animal performance and stocking rate – it is possible to refine the insights presented to decision-makers and, consequently, to improve the basis in which policies and programs are designed, implemented, and monitored. From a policy perspective, for instance, the knowledge of current productivity and its potential (and associated gap) may indicate opportunities for simultaneously expanding agricultural output and the provision of environmental services through land-sparing effects. In addition, a more accurate knowledge of animal productivity in pastures could guide the design of improved research and development (R&D) targets, tailored rural extension approaches and agricultural risk management recommendations, and the need for improving market functioning through credit, fertilizer and other inputs (Beddow et al., 2014; Cassman and Grassini, 2020; van Dijk et al., 2017).

Novel modeling methods and approaches to simultaneously evaluate biophysical, environmental, and economic synergies and trade-offs are needed to support better private and public planning and policy design. Correctly estimated livestock productivities in pastures can greatly contribute to that analytical framework, as they can be plugged into available biophysical (Hoogenboom et al., 2019; van Dijk et al., 2017; Wu et al., 2022) and economic-environmental models (Wang et al., 2022; Zilli et al., 2020) to spatially simulate multi-scale socioeconomic and environmental impacts of technological gaps and/or policy shocks.

Innovative farmers are already intensifying their production systems, driven by market requirements, economic pressures, and environmental objectives (Giller et al., 2021a, 2021b; Herrero et al., 2020). However, pursuing sustainable intensification approaches in agricultural systems is not a simple or risk-free task. Despite the urgent need for food systems transformation it must be recognized that transformative pathways are usually vulnerable to a combination of structural challenges such as fragmented decision-making, vested interests, and power imbalances in the climate policy and food communities (Zurek et al., 2022).

CRediT authorship contribution statement

Geraldo B. Martha: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Luis Gustavo Barioni:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. **Patrícia M. Santos:** Funding acquisition, Writing – original draft, Writing – review & editing. **Rodrigo Fernando Maule:** Data curation, Writing – original draft, Writing – review & editing. **Dominic Moran:** Funding acquisition, Writing – original draft, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.170268.

References

Beddow, J.M., Hurley, T.M., Pardey, P.G., Alston, J.M., 2014. Food security: yield gap. In: Encyclopedia of Agriculture and Food Systems. Elsevier, pp. 352–365. https://doi.org/10.1016/B978-0-444-52512-3.00037-1.

Cassman, K.G., Grassini, P., 2020. A global perspective on sustainable intensification research. Nat Sustain 3, 262–268. https://doi.org/10.1038/s41893-020-0507-8.

van Dijk, M., Morley, T., Jongeneel, R., van Ittersum, M., Reidsma, P., Ruben, R., 2017. Disentangling agronomic and economic yield gaps: an integrated framework and application. Agric. Syst. 154, 90–99. https://doi.org/10.1016/j.agsy.2017.03.004.

Giller, Ken E., Delaune, T., Silva, J.V., Descheemaeker, K., Van De Ven, G., Schut, A.G.T., Van Wijk, M., Hammond, J., Hochman, Z., Taulya, G., Chikowo, R., Narayanan, S., Kishore, A., Bresciani, F., Teixeira, H.M., Andersson, J.A., Van Ittersum, M.K., 2021a. The future of farming: who will produce our food? Food Sec. 13, 1073–1099. https://doi.org/10.1007/s12571-021-01184-6.

Giller, Ken E., Hijbeek, R., Andersson, J.A., Sumberg, J., 2021b. Regenerative agriculture: an agronomic perspective. Outlook Agric 50, 13–25. https://doi.org/10.1177/0030727021998063.

Godde, C.M., Mason-D'Croz, D., Mayberry, D.E., Thornton, P.K., Herrero, M., 2021. Impacts of climate change on the livestock food supply chain; a review of the evidence. Glob. Food Sec. 28, 100488 https://doi.org/10.1016/j.gfs.2020.100488.

Henchion, M., Moloney, A.P., Hyland, J., Zimmermann, J., McCarthy, S., 2021. Review: trends for meat, milk and egg consumption for the next decades and the role played by livestock systems in the global production of proteins. Animal 15, 100287. https://doi.org/10.1016/j.animal.2021.100287.

Herrero, M., Thornton, P.K., Mason-D'Croz, D., Palmer, J., Benton, T.G., Bodirsky, B.L., Bogard, J.R., Hall, A., Lee, B., Nyborg, K., Pradhan, P., Bonnett, G.D., Bryan, B.A., Campbell, B.M., Christensen, S., Clark, M., Cook, M.T., de Boer, I.J.M., Downs, C., Dizyee, K., Folberth, C., Godde, C.M., Gerber, J.S., Grundy, M., Havlik, P., Jarvis, A., King, R., Loboguerrero, A.M., Lopes, M.A., McIntyre, C.L., Naylor, R., Navarro, J., Obersteiner, M., Parodi, A., Peoples, M.B., Pikaar, I., Popp, A., Rockström, J., Robertson, M.J., Smith, P., Stehfest, E., Swain, S.M., Valin, H., van Wijk, M., van Zanten, H.H.E., Vermeulen, S., Vervoort, J., West, P.C., 2020. Innovation can accelerate the transition towards a sustainable food system. Nat Food 1, 266–272. https://doi.org/10.1038/s43016-020-0074-1.

Hertel, T.W., Ramankutty, N., Baldos, U.L.C., 2014. Global market integration increases likelihood that a future African Green Revolution could increase crop land use and

CO_2 emissions. Proc. Natl. Acad. Sci. U. S. A. 111, 13799–13804. https://doi.org/10.1073/pnas.1403543111.

Hoogenboom, G., Porter, C.H., Boote, K.J., Shelia, V., Wilkens, P.W., Singh, U., White, J. W., Asseng, S., Lizaso, J.I., Moreno, L.P., Pavan, W., Ogoshi, R., Hunt, L.A., Tsuji, G. Y., Jones, J.W., 2019. The DSSAT crop modeling ecosystem. In: Burleigh Dodds Series in Agricultural Science. Burleigh Dodds Science Publishing, pp. 173–216. https://doi.org/10.19103/AS.2019.0061.10.

Marin, F.R., Zanon, A.J., Monzon, J.P., Andrade, J.F., Silva, E.H.F.M., Richter, G.L., Antolin, L.A.S., Ribeiro, B.S.M.R., Ribas, G.G., Battisti, R., Heinemann, A.B., Grassini, P., 2022. Protecting the Amazon forest and reducing global warming via agricultural intensification. Nat Sustain. https://doi.org/10.1038/s41893-022-00968-8.

Martha Jr., G.B., Alves, E., Contini, E., 2012. Land-saving approaches and beef production growth in Brazil. Agric. Syst. 110, 173–177.

McAuliffe, G.A., Takahashi, T., Orr, R.J., Harris, P., Lee, M.R.F., 2018. Distributions of emissions intensity for individual beef cattle reared on pasture-based production systems. J. Clean. Prod. 171, 1672–1680. https://doi.org/10.1016/j.jclepro.2017.10.113.

Monteiro, L.A., Allee, A.M., Campbell, E.E., Lynd, L.R., Soares, J.R., Jaiswal, D., Castro Oliveira, J., Santos Vianna, M., Morishige, A.E., Figueiredo, G.K.D.A., Lamparelli, R. A.C., Mueller, N.D., Gerber, J., Cortez, L.A.B., Sheehan, J.J., 2020. Assessment of yield gaps on global grazed-only permanent pasture using climate binning. Glob. Chang. Biol. 26, 1820–1832. https://doi.org/10.1111/gcb.14925.

Moran, D., Blair, K.J., 2021. Review: sustainable livestock systems: anticipating demand-side challenges. Animal 15, 100288. https://doi.org/10.1016/j.animal.2021.100288.

Stocco, L., de Souza Ferreira Filho, J.B., Horridge, M., 2020. Closing the yield gap in livestock production in Brazil: new results and emissions insights. In: Madden, J.R., Shibusawa, H., Higano, Y. (Eds.), Environmental Economics and Computable General Equilibrium Analysis, New Frontiers in Regional Science: Asian Perspectives. Springer Singapore, Singapore, pp. 153–170. https://doi.org/10.1007/978-981-15-3970-1_7.

Villoria, N.B., 2019. Technology spillovers and land use change: empirical evidence from global agriculture. Am. J. Agric. Econ. 101, 870–893. https://doi.org/10.1093/ajae/aay088.

Wang, Z., Martha, G., Liu, J., Lima, C.Z., Hertel, T., 2022. Transportation cost, agricultural production and cropland expansion in Brazil: a multi-scale analysis. In: Presented at the GTAP 25th Annual Conference on Global Economic Analysis, GTAP, Pudue University, Virtual Conference.

Wu, L., Harris, P., Misselbrook, T.H., Lee, M.R.F., 2022. Simulating grazing beef and sheep systems. Agric. Syst. 195, 103307 https://doi.org/10.1016/j.agsy.2021.103307.

Zilli, M., Scarabello, M., Soterroni, A.C., Valin, H., Mosnier, A., Leclère, D., Havlík, P., Kraxner, F., Lopes, M.A., Ramos, F.M., 2020. The impact of climate change on Brazil's agriculture. Sci. Total Environ. 740, 139384 https://doi.org/10.1016/j.scitotenv.2020.139384.

Zurek, M., Hebinck, A., Selomane, O., 2022. Climate change and the urgency to transform food systems. Science 376, 1416–1421. https://doi.org/10.1126/science.abo2364.