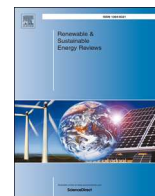




Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

System complexity and policy integration challenges: The Brazilian Energy-Water-Food Nexus

J.-F. Mercure^{a,b,c,d,*}, M.A. Paim^c, P. Bocquillon^{c,e}, S. Lindner^{a,b,c}, P. Salas^c, P. Martinelli^b, I.I. Berchin^f, J.B.S.O de Andrade Guerra^{c,f}, C. Derani^{c,g}, C.L. de Albuquerque Junior^f, J.M.P. Ribeiro^f, F. Knobloch^{b,c}, H. Pollitt^{c,d}, N.R. Edwards^{c,i}, P.B. Holdenⁱ, A. Foley^h, S. Schaphoff^j, R.A. Faraco^f, J.E. Vinuales^c

^a Global Systems Institute, Department of Geography, University of Exeter, Exeter, EX4 4QE, UK

^b Department of Environmental Science, Radboud University, Nijmegen, the Netherlands

^c Cambridge Centre for Environment, Energy and Natural Resource Governance (C-EENRG), University of Cambridge, The David Attenborough Building, Pembroke Street, Cambridge CB2 3QZ, UK

^d Cambridge Econometrics Ltd, Covent Garden, Cambridge CB1 2HT, UK

^e School of Politics, Philosophy, Language and Communication, University of East Anglia, Norwich Research Park, Norwich, Norfolk NR4 7TJ, UK

^f Centre for Sustainable Development (GREENS) at the Universidade do Sul de Santa Catarina (UNISUL), 219 Trajano Street, Florianópolis 88010-010, Santa Catarina, Brazil

^g Center of Legal Sciences, Federal University of Santa Catarina (UFSC), Campus Universitário Trindade, Florianópolis 88040-900, Santa Catarina, Brazil

^h Department of Geography, Birkbeck, University of London, 32 Tavistock Square, London WC1h 9EZ, UK

ⁱ Environment, Earth and Ecosystems, The Open University, Milton Keynes, UK

^j Potsdam Institute for Climate Impact Research, Telegrafenberg, P.O. Box 601203, D-14412 Potsdam, Germany

ARTICLE INFO

Keywords:

Science-based policy
Energy-water-food nexus
Water scarcity
Climate change
Land-use change
Biofuels
Food security

ABSTRACT

The Energy-Water-Food Nexus is one of the most complex sustainability challenges faced by the world. This is particularly true in Brazil, where insufficiently understood interactions within the Nexus are contributing to large-scale deforestation and land-use change, water and energy scarcity, and increased vulnerability to climate change. The reason is a combination of global environmental change and global economic change, putting unprecedented pressures on the Brazilian environment and ecosystems. In this paper, we identify and discuss the main Nexus challenges faced by Brazil across sectors (e.g. energy, agriculture, water) and scales (e.g. federal, state, municipal). We use four case studies to explore all nodes of the Nexus. For each, we analyse data from economic and biophysical modelling sources in combination with an overview of the legislative and policy landscape, in order to identify governance shortcomings in the context of growing challenges. We analyse the complex interdependence of developments at the global and local (Brazilian) levels, highlighting the impact of global environmental and economic change on Brazil and, conversely, that of developments in Brazil for other countries and the world. We conclude that there is a need to adjust the scientific approach to these challenges as an enabling condition for stronger science-policy bridges for sustainability policy-making.

1. Introduction

Income growth, industrialisation, economic change and globalisation are bringing global demand for energy, water and food to a point increasingly beyond the Earth's carrying capacity [1–3]. This, in turn, is causing environmental degradation in many tropical natural resource exporting countries such as Brazil. Such degradation could be seen as a simple management problem but, on closer examination, it results from far more complex interconnections between energy, water and food

[1,4–6]. Efforts to provide integrative policy lenses with which to look at these interconnections have been referred to as the Energy-Water-Food Nexus approach (Nexus henceforth, see [7–11]). However, what this approach exactly entails in practice remains unclear. We use the term 'complex' for nexus governance to highlight that the problem displays, in particular, four key characteristics typical of so-called 'wicked' problems [12,13]: firstly, the pervasive nature of uncertainty in every aspect of the problem, notably both climate and socio-economic change; secondly, the existence of many different stakeholders with

* Corresponding author at: Global Systems Institute, Department of Geography, University of Exeter, Exeter, EX4 4QE, UK.
E-mail address: j.mercure@exeter.ac.uk (J.-F. Mercure).

<https://doi.org/10.1016/j.rser.2019.01.045>

Received 10 March 2018; Received in revised form 16 January 2019; Accepted 17 January 2019

1364-0321/© 2019 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

distinct and potentially conflicting values and views; thirdly, the interdependence of all aspects; and finally the limited success of existing governance structures in implementing proposed solutions. Nexus governance is a true ‘wicked problem’, in which “the process of solving the problem is identical with the process of understanding its nature” [12], and intervention changes the nature of the problem and course of events.

Brazil provides a textbook example of the challenges arising from the Nexus. On one hand, it is one of the regions of the planet that will be most affected by climate change [14]. On the other, it is an economy highly driven by and tied to global economic change, through exports of agricultural and energy commodities. Both climate and economic change drive environmental degradation and social challenges, at all scales of analysis, which are allowed or amplified by the shortcomings of the governance system. Moreover, the situation of Brazil is also a relevant comparator for other countries that face Nexus-related challenges (e.g. large-scale land-use change, water scarcity, energy crises) or may face them in the future. Furthermore, it is very likely that tipping points in Brazil could have far-reaching consequences across the world: for the global climate system [15,16], food supplies [17] and land-use change emissions [18].

Nexus governance can be supported by robust science, but robust science does not automatically lead to effective policy implementation [9]. Engineering-oriented views [5,7,19,20] focus on searching for optimal policy solutions in order to internalise system-wide externalities, maximise system efficiency and minimize waste. The application of such an approach requires the existence of sufficiently good models to optimise Nexus governance choices [10]. But complexity science warns of the dangers in such assumptions. Indeed, complex interactions may lead to new and unpredictable phenomena [6,21]. Human knowledge and predictive power over a complex system is always limited, while decisions must be taken using available resources. It is unrealistic to assume the existence, even theoretically, of an ultimate Nexus planner that could optimise such a complex system. Moreover, overreliance on optimisation has the effect of downplaying path-dependent phenomena, such as behavioural feedbacks on technology uptake and social influence, despite their practical importance [21]. Furthermore, path-dependence (representing the influence of developmental, technological and socio-political histories) is not limited to what has happened in Brazil. The range of realistic options is highly dependent upon paths taken elsewhere. The global-local interaction is therefore a necessary component of the analysis, which tends to be overlooked by a focus on a hypothetical social planner optimizing conditions in one country.

Here, we identify and discuss the main Nexus challenges faced by Brazil. We map the existing policy landscape addressing the Nexus and assess its performance and shortcomings. Brazil is envisaged as an indicative example of what other countries in analogous positions may face in future. The analysis of its specific challenges suggests the need for change in how science approaches the understanding of Nexus challenges in general. We highlight the need for more complexity-based Nexus research, stronger integration across sectors, scales, stakeholders and disciplines (spanning not only the natural sciences and economics, but also law and social sciences, see [10]), and more attention paid to the interactions between the global and the local levels. We see this change in the scientific approach to Nexus challenges as an enabler for stronger science-policy bridges or, in other words, for better integration of scientific insight into policy-making.

We propose a new approach for Nexus analysis and for formulating integrated Nexus policy strategies in the presence of partial knowledge and understanding, and substantial uncertainty. This includes integrating science deeply in the process of policy-making, i.e. developing a science-policy-law interface, taking inspiration from European impact assessment procedures to identify Nexus-resilient public policy solutions. Other non-optimisation approaches have been discussed in the wider literature (e.g. [6,10,22,23], see [8] for a review of other

framings); however, none emphasise simultaneously the development of a multi-scale complexity-based approach embedded within a deep understanding of the science-policy-law interface, as we advocate here.

The article first summarises the general context of global environmental and economic change as drivers of the Nexus challenges faced by Brazil. This is followed by four case studies that combine economic, scientific, legal and policy data to illustrate the intricate environmental and social interconnections between each node of the Nexus in Brazil: energy-water, food-energy, water-food and energy-water-food. Significantly, the four case studies highlight the role of complexity in Nexus challenges. We review laws and policies in place to address these challenges and their performance. The details for each policy or law, referred to as [SI.1 to SI.25](#), and the online location of the associated documents, are given in the [Supplementary Information \(SI\)](#). We conclude with a statement on how a change in the scientific approach to the Nexus could contribute to a more functional science-policy bridge, and how this bridge could enable the design and implementation of Nexus-resilient public policies.

2. Review of the general context

2.1. Methodology

The methodology of this paper is organised as follows. We carry out a review of the literature and of policy and law documents relevant for each node of the Brazilian Nexus. We do not claim to cover the literature exhaustively for all three sectors and their linkages, as the limits are not clearly delineated from other fields of research, and the full literature covering all three nodes of the Nexus is too large, while most studies do not in fact cover the full Nexus.¹ Our methodology involves explicitly reviewing each vertex of the Nexus linkages using four case studies that cover the most important Nexus relationships. We use these case studies to uncover structural commonalities, and build a case for why and how complex intersectoral interactions must be seriously taken into account when developing strategies for policy-making in all three sectors. These case studies illustrate areas displaying clear challenges that require immediate intervention, and we use them to develop a Nexus framework that demands a deep understanding of the science-policy-law interface.

Building on the complexity approach of Liu et al. [6], we adopt the philosophy of analysis of Rittel & Weber in their description of the ‘wicked problem’ [12], in which it is recognised that the process of solving policy issues is identical with the process of understanding the underlying drivers. This assumes incomplete information and understanding, and by definition sub-optimal policy-making that improves incrementally as knowledge and understanding improves. Since for wicked problems such as the Nexus, policy-makers typically only have limited opportunities to act, and each policy action changes the problem itself, we argue for closer interaction between science and policy and a recognition that the impacts of policy strategies are only ever partially understood and require continual reassessment as more information becomes available.

2.2. Global and local environmental change

Current trajectories of greenhouse gas (GHG) emissions are leading the planet towards somewhere between 3 and 6 °C of warming, unless stringent mitigation policies are adopted worldwide [24]. These emission trajectories imply changes in average temperatures and rainfall that are unevenly distributed, with severe variations (e.g. enhanced floods and droughts) and increased frequency of extreme events. Brazil is likely to experience amongst the most pronounced of these effects.

¹ The Nexus literature that explicitly covers interactions between the three sectors is in fact relatively limited, and is mostly covered in this article.

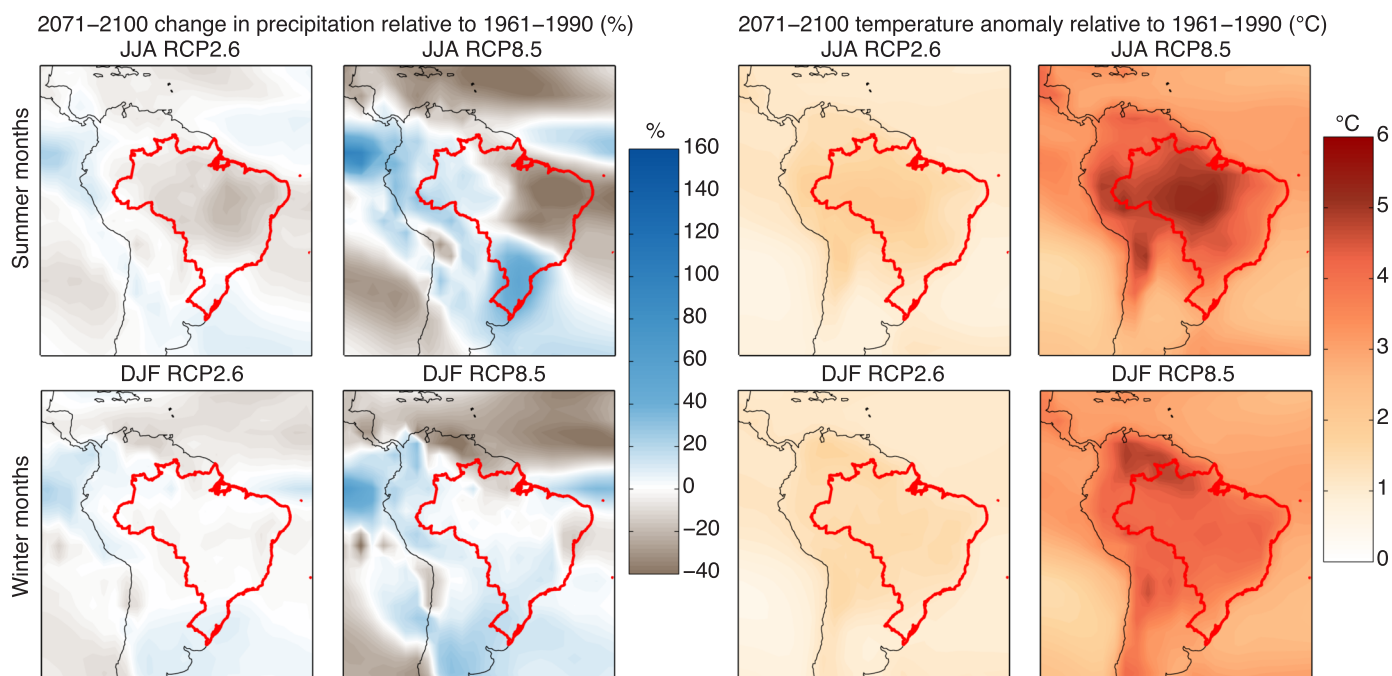


Fig. 1. Changes in annual average rainfall (as a % change to annual averages) and mean temperature, in the summer (top panels) and the winter (bottom panels), for low cumulative global GHG emissions (left panels) and high cumulative emissions (right panels). In scenarios of high emissions, temperature changes of up to 6 °C are expected over the Amazonian region, and rainfall changes of +60% and –40% are expected in North-Eastern and Southern Brazil, respectively. These changes are likely to lead to radical changes in vegetation and land cover, including desertification. CMIP5 data obtained through the KNMI Climate Explorer. More information on models and methodology can be found on the website (<https://climexp.knmi.nl/start.cgi>).

Fig. 1 shows maps of changes in mean temperatures and rainfall in Brazil for low and high emissions scenarios (RCPs 2.6 and 8.5). In a scenario of continued high global emissions, temperature changes of up to 3–6 °C could occur over the Amazonian region, potentially severely degrading vegetation and ecosystems. Meanwhile, in such a scenario, rainfall could be significantly disturbed, increasing by 60% in the southern regions while it could decrease by 40% in arid regions of the north. These changes would have serious impacts on agriculture and food production in Brazil. However, these projections also rank amongst the least certain globally, partly because the Amazon rainforest is intimately connected with the local and global climate, and land use, making it complex to predict [25,26]. These patterns of climate change and warming are uncertain but well studied [27,28]. Brazil has recently faced several droughts, with evidence suggesting that changing rainfall patterns will lead to reduced river flows in several catchment areas [29–32]. The Brazilian rainforest is particularly sensitive to drought events [28]. A self-reinforcing interaction exists between temperature change, drying, forest fires, deforestation and a collapse of the Amazonian rainforest [33,34]. In particular, drought-fire interactions generate one of the possible tipping points [15,16]. However, here tipping points come about through a combination of direct (e.g. LUC) and indirect (e.g. climate change) anthropogenic factors [34].

In recent years, Brazil's Cerrado biome and the Amazon have both been exposed to increased rainfall intensity during the wet season followed by longer-than-usual dry seasons [35]. In 2014–2015, the state of São Paulo experienced a severe water crisis driven by below-average rainfall. Water in this region is supplied by moisture from the Amazon and the South Atlantic through low-level easterly jets [36,37]. During the drought period, the regional atmospheric circulation was blocked by a high-pressure system in the mid-troposphere [38,39]. This barrier changed moisture transport from the Amazon to South-Eastern Brazil. These changes were unpredictable, but most likely have anthropogenic roots, and could become recurrent.

A changing climate leads plant and animal species to migrate [40] and/or evolve [41]. In Brazil, this phenomenon affects agricultural

activities, as land productivity changes with the climate [42], primarily as a result of rainfall changes and water availability. Under severe climate change, this could involve large-scale land-use change, which would mean significant biodiversity loss. As agricultural activities re-organise themselves, Brazilian society itself is affected. Thus, climate change would result in pronounced pressures on Brazilian food production, itself accounting for a large component of economic activities in Brazil, and of the world's food supply sources.

2.3. Global economic change driving environmental degradation

The Brazilian economy benefits from lucrative exports of agricultural and food products. These account for around one third of total Brazilian exports making Brazil one of the countries with highest export shares in that sector (Fig. 2a). These goods have traditionally accounted for a major component of Brazilian exports (Fig. 2b) and their production employs a significant portion of the entire Brazilian labour force (Fig. 2c). These figures place Brazil in a context of growing wealth associated to exports of natural resources, driven by growing purchasing power worldwide.

However, these data also signal the significant vulnerability of the Brazilian economy. Voluminous exports of natural resources are made lucrative by international prices, supported by high demand in many other nations around the world (particularly Chinese imports of soybeans), and export growth is thus strongly driven by economic growth in other large emerging economies [43]. This economic pressure is well known to strain the Brazilian environment through man-made deforestation and land-use change that creates space to expand agriculture (e.g. see [34]), a phenomenon often involving indirect land-use change (ILUC).

ILUC refers to the phenomenon in which an event of land-use change in one place induces another event of land-use change elsewhere, mediated by commodity and land prices [44,45]. In Brazil, this typically involves a hierarchy of production associated to land productivity, where the most productive land is converted to produce new

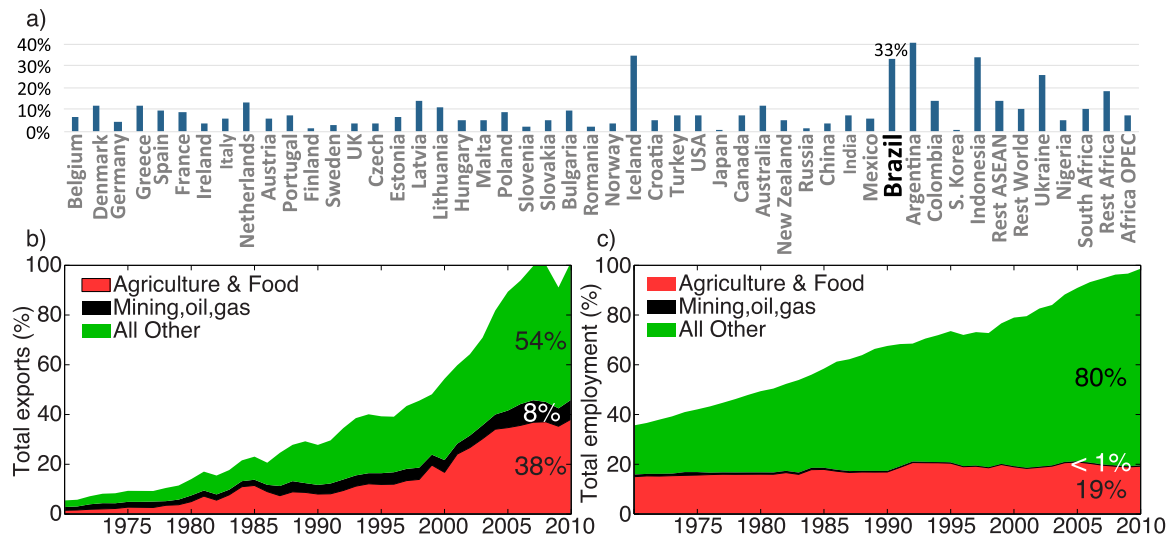


Fig. 2. (a) Current share of total exports consisting of agricultural products and food by country (33% for Brazil). (b) Total exports, normalised to 2010. (c) corresponding shares of employment, normalised to 2010. Data from Eurostat, OECD, national statistics, Asian Dev. Bank, UN prodcom. Differences between panels (a) and (b) stem from whether exports are accounted for in constant or current prices.

lucrative crops for exports (e.g. soybeans, sugar cane), displacing cattle farming, which itself moves to occupy other areas which are deforested before use [45–47]. Deforestation in the Amazon has declined from 2004 to 2014 as authorities have managed to regulate farmers’ behaviour partly by law enforcement and partly by economic measures [48]. Intensification and commoditisation of agriculture also contributed to reduced rates of deforestation [48]. However, the deforestation in the Amazon has increased again from August 2015 to July 2016. Over the last 30 years the Cerrado has lost 50% of its native vegetation cover. Deforestation is likely to continue mostly because it is linked to global markets growth for agricultural commodities, mediated by prices, and made possible by globalisation, giving rise to powerful incentives for agribusiness to acquire new land in Brazil [43].

Agricultural products, grown either as feedstock for biofuel production or to feed animals, contribute to this phenomenon [34,46,49,50]. Under climate change mitigation policy following the Paris Agreement, global markets for biofuels are virtually unbounded [51]. Meanwhile, under growing affluence and increasingly meat-intense diets in middle-income countries, global markets for soy as animal feed can become very large (see Section 3.5). Concerns over the sustainability of biofuel mandates have raised sufficient concern in Europe to revise this policy trajectory (see e.g. [52]), but this may not necessarily deter policy-makers in other large economies. Indeed, despite sustainability concerns [46,50,53], biofuels remain a key component of the national strategy of many countries to mitigate climate change [52,54]. Thus a large global market for liquid biofuels for transport could be expected to emerge by 2050 [55].

Estimates of the world’s carrying capacity for biofuel production [56–59] consider only land left over after global food demand has been supplied. However, no evidence exists to suggest that food demand will be supplied before energy demand, since biofuel consumers in some regions can easily, and inadvertently, outbid food consumers in others [43]. Brazil will very likely face this intricate problem.

2.4. Overview of the domestic policy landscape addressing the Nexus in Brazil

Climate change impacts combined with increasing global demands for food and energy commodities expose vulnerabilities in Brazil’s water, energy and food systems, as a result of their complex interconnections. The government has recently acknowledged the need to adapt existing regulation and to create new policies to manage these

challenges. Although Brazil has comprehensive water, energy and food governance frameworks, each sector has evolved separately and is organised independently from the other two. The law and policy pertaining to each sector only occasionally and marginally refer to issues arising in other sectors. Such fragmentation is what makes Nexus challenges so pressing.

The climate change framework in Brazil includes some integrative guidance and instruments to deal with the Nexus. Since the 2000s, Brazil has adopted climate change legislation and policies, including the 2008 National Plan on Climate Change (SI.1) and the 2009 National Policy on Climate Change (“NPCC” – SI.2), which establish the country’s voluntary emissions reduction target and incorporate laws and policies relating to climate change.

As part of the NPCC, the 2016 National Adaptation Plan to Climate Change (“NAP” – SI.3) refers to goals, thematic and sectoral adaptation strategies and guidelines, to be implemented within the timeframe of four-year cycles. The NAP mentions explicitly the need to promote interactions and synergies amongst sectors for broadening the coherence of adaptation strategies in the context of climate change. For instance, the NAP provides as intersectoral goals: (i) in the agriculture sector, encouraging farmers to adopt renewable energy sources and to promote sustainable and efficient water use; (ii) in the energy sector, to assess interactions between adaptive measures for water, energy and land use; and (iii) in the water sector, to integrate water resources planning with that of other sectors, replace current irrigation methods with more efficient ones, and promote better management of multiple-use reservoirs. The development of new and existing legal and policy instruments will require capacity building, intergovernmental coordination, monitoring systems, and the improvement of the climate change projections to be reflected in public policies (SI.4).

Under the 2015 Paris Agreement on Climate Change,² Brazil has developed its Nationally Determined Contributions (“NDC” – SI.5) comprising the reduced emissions targets of 1.3 GtCO₂e per year by 2025 and 1.2 GtCO₂e by 2030, equivalent to 37% and 43% below the 2005 level. Amongst the mitigation measures, the NDC includes: (i) increasing biofuels to approximately 18%; (ii) implementing the Forest Code, particularly to achieve zero illegal deforestation in the Amazon; (iii) achieving 45% of renewables in the energy mix, amongst which non-hydro renewable energy between 28% and 33%, and non-fossil fuel

² Adoption of the Paris Agreement, Decision 1/CP.21, 12 December 2015, FCCC/CP/2015/L.9, Annex.

energy sources at least 23%, by raising the share of wind, biomass and solar; and (iv) restoring degraded pasturelands and enhancing integrated cropland-livestock-forestry systems. The following issues linked to the NDCs, however, relate to more than one sector: (i) the land use effects on the conservation of forests; (ii) the expansion of non-hydro energy sources and cropland-livestock forestry. At the moment the Ministry of the Environment coordinates the development of a National Strategy for the Implementation and Financing of the Brazilian NDC to the Paris Agreement (SI.5).

Other examples exist of Nexus legislation in Brazil. The 2013 National Policy on Integration of Farming, Livestock and Forestry (Law N. 12.805 – SI.6) is designed to mitigate deforestation, support best practices to develop these sectors in a sustainable manner, and contribute to the recovery of degraded areas. The 2013 National Irrigation Policy (Law N. 12.787 – SI.7) governs the sustainable use of water for irrigation and policy integration for water resources, environment, energy and sanitation, giving priority to projects that allow multiple uses of water. It includes tax incentives, rural credits and insurance, certification of irrigation projects and technical assistance. These examples notwithstanding, Nexus challenges are only partially taken into account in the relevant governing frameworks, if at all.

2.5. International law and policy influencing the Nexus in Brazil

Measures also exist in Brazil at the supply-chain governance level, to improve sustainability in agricultural commodity production. These measures include regulating or incentivising global market access by certain products. This includes certification requirements for producers to respect sustainability standards or the use of specific labels reflecting abidance by such standards. They result from a coordinated effort between local governments, producers, consumer groups, others directly involved in commodity supply-chains and civil society groups [60].

Furthermore, the global finance mechanism REDD+,³ developed under the United Nations Framework Convention on Climate Change (UNFCCC), plays a significant role in preventing deforestation. Brazil has received international finance from REDD+ (SI.8) as a result of its verified emissions reductions, initially prioritizing strategies in the Amazon and most recently organizing data about the Cerrado for further action. REDD+ is considered a valuable instrument in catalysing international support to promote more integrated land-use policies and practices [61].

3. Nexus analysis: four case studies

3.1. Selection of case studies of cross-sectoral interactions

This section discusses four case studies selected to chart the most salient⁴ Nexus interactions relevant for Brazil as well as the shortcomings of the existing governance framework. We look at (1) the water-energy link, focusing on water use for hydroelectricity under increasing climate change constraints, (2) the energy-food link, focusing on the competition for land between energy and food production sparked by biofuels policy, (3) the food-water link, focusing on the impact of climate change on food production in Brazil, and finally, (4) simultaneous water-energy-food links, focusing both on ILUC generated by global demand for agricultural and bio-energy commodities produced in Brazil, and on the scarcity of suitable land resulting from climate change. We define and apply a Nexus lens that combines economic and biophysical modelling data with an overview of the

legislative and policy landscape, to analyse the dynamics of the Nexus in Brazil and derive common patterns. We use these common patterns to formulate more specifically the core components of a Nexus approach to science-informed policy-making. The goal of this paper is to lay down the foundations of a Nexus research agenda,⁵ and improve the effectiveness of existing science-policy bridges in Brazil.

3.2. Water-energy – hydroelectricity and climate change

Climate change is modifying rainfall patterns in Brazil [14,32]. A water crisis has emerged in recent years, which has resulted in record low levels in hydroelectric dam reservoirs [31,33]. Persistent drought has also affected agriculture in the North-East region [29]. In the São Paulo region, where 10% of the Brazilian population live and one third of GDP is produced, water scarcity from 2014 to 2016 generated both electricity blackouts and a drinking water crisis leading to the rationing of both [33]. The water crisis is a problem of water management and efficiency of use, but it is related to local and global environmental change, while it affects and is governed by policy in both the water and energy sectors simultaneously. In particular, electricity policy encouraging the use of water for generation of energy directly affects drinking water availability. According to the water policy (SI.9), the water management must promote multiple uses of water including for the generation of energy and direct human use, except in case of water scarcity, when priority is given to the latter. In practice, the lack of definition of water allocation priorities causes increasing water competition conflicts between the energy and water supply sectors, especially during water shortage periods and before scarcity is reached [62].

The Brazilian electricity system is largely based on hydroelectricity (> 62.6% [63]), making it low-carbon, but also vulnerable to changes in climate and rainfall [64,65]. The Brazilian electricity system features 219 hydroelectric dams (MME, August/2018 – SI.10), one of the largest systems in the world [66]. The vast majority of the large-scale generators (99.5%) are connected by the National Interconnected System (SIN – Sistema Interligado Nacional). Modelling suggests that in most hydrological basins, river flows will decline in all climate change scenarios [64]. These projections place constraints on the future composition of the Brazilian electricity sector, and technological diversification appears inevitable. This is challenging if the objective is to simultaneously maintain low CO₂ emissions, although non-hydro renewables could contribute to alleviate pressure on water resources [67].

The country's overreliance on hydro became conspicuous in 2001, when a combination of below-average rainfall and insufficient investments in new generation capacity culminated in a major electricity supply crisis. In order to avoid blackouts, a 20% demand reduction was required at short notice, and 22 of the 27 Brazilian states were instructed to implement rationing policies (using quotas, financial incentives and information campaigns, see [68]). These measures were in place for less than a year, but had a lasting effect on people's energy-use: 90% of households changed their consumption habits, with a 14% reduction in electricity use that remained 10 years later [69]. This suggests a large potential for efficiency improvements in the Nexus that can be realized by targeted policies. But also, the “energy efficiency gap” unveiled an underlying “water efficiency gap” [70].

Hydropower projects have continued to obtain the go-ahead from authorities until the Plano Decenal de Energia – PDE, Ten Year Plan 2024, released in 2015 (SI.11). Most new dam projects are in the Amazon basin, where most of Brazil's remaining hydroelectric potential

³“Reducing emissions from deforestation and forest degradation in developing countries; and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks in developing countries”.

⁴We note that other Nexus linkages exist and could be covered, but we cannot do so within space constraints.

⁵For instance, as part of the UK research council-funded BRIDGE project (Building Resilience In a Dynamical Global Economy: Complexity across scales in the Food-Water-Energy Nexus). For more information, see <https://www.ceenrg.lanedecon.cam.ac.uk/research/the-bridge-project> and <http://gtr.rcuk.ac.uk/projects?ref=ES/N013174/1>.

lies, demanding comparatively large investments to connect these to the transmission grid, with environmental impacts associated with flooding areas of rich biodiversity and often under indigenous occupation. The implementation of the Belo Monte hydropower plant offers a good illustration of the emerging complexity [71]. Nevertheless, the recent Ten-Year Energy Plan 2026, released in 2017, features less dependency on hydropower, and aims at increasing non-hydro renewables (wind, solar, biomass) to up to 48% by 2026 (SI.11).

In 2002, the two-stage programme PROINFA (Programa de Incentivo às Fontes Alternativas de Energia – Incentive Programme for Alternative Sources of Electric Power – SI.12) was created to encourage power matrix diversification with other energy sources such as wind, solar and biomass. The goal of the first stage was to install 3300 MW of renewable energy, using subsidies and other incentives. The second stage target was to increase the renewable energy generation (excluding hydro) to 10% of annual consumption within 20 years. The second stage did not occur and was later replaced by the regulator ANEEL's energy auctions. The following additional policies were created to grant subsidies schemes for wind, solar, biomass and small hydro plants (up to 30 MW) projects (SI.12): (i) at least 50% discount on tariffs charged by the transmission and distribution systems (Resolution ANEEL 77/2004); and (ii) the requirement that these sources are the only ones available for purchase by Special Consumers (from 500 kW to 3 MW) on the energy Free Trade Environment (ACL) (Law 9427/1996). The reduction in generation costs for wind power, in particular, has led to a significant growth of its share in the electricity mix from almost no production in 2006–10.8%, in 2018, while biomass and solar account for, 7.9% and 0.7%, respectively (MME, 2018).

It is clear that diversification of the power grid could improve water security, by giving hydro dams better flexibility to regulate water supplies. The NAP (SI.3) envisions that the electricity sector planning follows climate-change projections, notably to evaluate the “interactions between adaptive measures for water, energy, land use and biodiversity, as a means for understanding and managing such interactions”. The NAP, however, does not indicate how this goal is to become operative in the context of long-term power plans oriented towards the expansion of hydroelectricity. Aligned with the NDC, the recent Ten-Year Plan for long-term power planning to 2026 reserving a proportionate role for large hydropower systems and taking into account Brazil's vast potential for low-cost solar and wind resources, could be an approach for tackling risks to water availability. This strategy responds to the environmental concerns surrounding backup thermal power plants used during periods of water shortage to secure energy supply in the national grid interconnection. Meanwhile, establishment of water policy priorities or criteria for allocating water amongst different users could ultimately mitigate competition for the water supply, especially coming from the energy sector.

3.3. Food-energy – liquid biofuels and competition for land between food and energy

The global demand for first generation liquid biofuel feedstocks such as sugar cane, maize and soy has grown rapidly in the past decade due to the increasing adoption of policies to decarbonise transport fuels (using lower carbon fuels) and to support local biofuel industries (e.g. in the US; see Fig. 3). This new demand requires a dedicated supply of agricultural products, which has the potential to partially displace existing food production. Brazil produces a substantial share of the global supply for agricultural commodities for biofuels, notably sugar cane and soybeans (see Section 3.5). Prices for internationally traded agricultural commodities can fluctuate widely, in connection to oil and biofuels, leading to complex interdependencies.

Since 2008, a significant body of research has developed issuing a stark warning regarding (i) the carbon sustainability of biofuels and (ii) the competition for land that the development of large biofuel markets could generate, with the potential to price out local agriculture for food

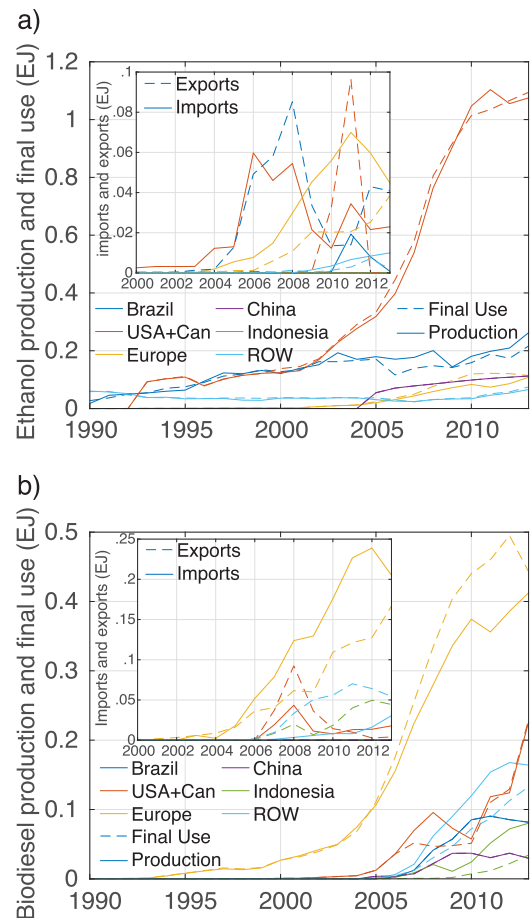


Fig. 3. Biofuel production, final use, imports and exports worldwide. a) Ethanol. b) Biodiesel. The main charts show production and final use, while the insets show imports and exports. Data from IEA World Energy Balances (2017).

and lead to food price volatility as well as restrict access to food [e.g. 6,34,48,50,53]. These studies primarily emphasise the effects of ILUC [44,45] as a driver of linkages across activities, environmental impacts and markets, mediated by commodity and land prices.

The complexity of these linkages is appreciated and debated in both science and policy circles. However, it has not yet been translated into consensus over appropriate policy solutions, which creates uncertainty for the development of the sector. Yet, large-scale biofuel use is considered as a necessary component of climate change mitigation scenarios consistent with the Paris Agreement [e.g. 51,72,73].

For present purposes, we analyse large-scale biofuel use in road transport globally and its impact on Brazil, focusing on hypothetical scenarios in which, by 2050, biofuel mandates are substantially increased worldwide in order to implement the Paris Agreement. Global liquid biofuel use could easily reach 5–10 EJ [73],⁶ which would entail that, given land availability, comparatively low production costs and the current advanced development of the sector, Brazilian agriculture could be incentivised to supply a substantial fraction of these bioenergy feedstocks. This would require large areas of additional land for sugarcane (ethanol) and/or soybeans (biodiesel) [74]. Land areas currently available for biofuels production in Brazil amount to (i) 85.6 Mha (excluding cropland and pastures), (ii) 41.8 Mha (safeguarding protected areas), or (iii) 37.8 Mha (excluding the Amazon) [75]. Land

⁶ Own calculations with the model E3ME-FTT-GENIE. For reference, current global use of transport fuels (petrol, diesel) is 100 EJ. Existing efficiency change and electrification trajectories reduce this quantity over time substantially in most realistic scenarios.

requirements for biofuel feedstocks are of between 20.2 and 2.3 ha/1000 GJ (soybeans and sugarcane) [76]. Thus, between < 37 EJ (sugar cane ethanol) and < 2 EJ (soybean biodiesel) of liquid biofuels can be produced in Brazil depending on the crop used. Several EJ of biofuel demand in Brazil could incentivise farmers to produce beyond current limits, especially if other demands for land are simultaneously growing, causing ILUC cascades (see Section 3.5).

Brazil's biofuel policies date back to the oil shock of 1973, and have been historically geared towards energy security and rural development, with limited concerns for their ecological impact and potential competition with food production [77–80]. It was only with the commodity and biofuels boom of the mid-2000s that increased production and exports raised questions of competition with food production and of deforestation in the Cerrado and the Amazon [50,53].

In this context, Brazilian authorities took some measures to ensure the sustainable development of biofuels. At the federal level, the main framework regulating sugarcane expansion is the Agro-Environmental Zoning (Zoneamento Agro-Ecológico da Cana-de-açúcar, or ZAE Cana – SI.13). This is a planning instrument developed by the Brazilian Agricultural Research Corporation (EMBRAPA) in collaboration with other institutions, adopted by Decree in 2009 (Decree 6961/2009). Based on agricultural potential, land vulnerability, climate risks and environmental regulations, it defines suitable areas for the expansion of sugarcane. ZAE Cana excludes cultivation in areas with original vegetation cover or highly bio-diverse regions, including the Amazon and Pantanal biomes; and others (e.g. indigenous land, conservation areas). It prioritizes expansion in under-used areas, areas occupied by livestock and degraded pastures [81]. However, one major limitation of the zoning is that it does not consider potential competition between sugarcane and food production within those areas. It does not address issues relating to water availability, energy planning or socio-economic aspects (e.g. land prices). It remains a technical instrument of a merely indicative nature, which aims to orientate credit allocation and investment decisions but has never been translated into binding law as originally planned.

The state of São Paulo represents over 60% of Brazil's sugarcane production and about 50% of ethanol production. In 2008, driven by concerns about urban air pollution, the São Paulo state government adopted the 'Etanol Verde' programme and its associated agro-environmental protocol (SI.14). Developed by the state in collaboration with powerful sugarcane producer union UNICA, it sets guidelines to phase out sugarcane burning for manual harvesting to replace it with mechanical harvesting [82].⁷ The protocol also aims to favour water conservation, protect biodiversity, ensure fair labour practices, and develop environmental awareness. Based on voluntary certification by the State, the agro-environmental protocol has benefited from UNICA's support and has performed well. Indeed, in 2016 over 90% of the sugarcane harvest was conducted without burning, significantly reducing emissions of particles with harmful impacts on health, GHG emissions, and water consumption.

In December 2017, Brazil has approved the National Biofuels Policy, known as *RenovaBio*, to expand low-carbon fuels such as ethanol, biomass and biodiesel, within its Paris Agreement NDC's commitments (SI.15). Inspired by California's Low Carbon Fuel Standards (LCFS), *RenovaBio* includes the following mechanisms: (i) targets for the GHG emissions reduction in the fuel mix, including individual targets to fuel distributors (ii) decarbonisation credits, (iii) biofuel certification, (iv) addition of biofuels to fossil fuels, (v) incentives on tax, finances and credits.

In addition to federal- and state-level legislation, some certification schemes have emerged, driven by the adoption of sustainability requirements and criteria (GHG emission reductions, biodiversity protection) in importing jurisdictions, notably the EU and US. A number of

multi-stakeholder supply-chain sustainability schemes with different requirements have been developed [82,83]. The interest of producers and public authorities for these schemes has been motivated by a desire to access foreign markets. These schemes notably include *Bonsucro* for ethanol (SI.16), and the Round Table on Responsible Soy (RTRS – SI.17). However, uptake has been uneven [84] and it has waned as the debates on ILUC and 'food vs fuel' intensified in major export markets such as the EU, limiting the appetite for biofuels for decarbonising transport. However, the attraction to low-carbon fuels may not be limited by sustainability concerns in other emerging economies such as China and India, and thus this may change again. Although the current policy framework goes some way towards addressing environmental issues, it has serious limitations and does not adequately address the potential displacement of food production by energy crops. ILUC cascades are likely to result from further biofuel expansion and affect deforestation (see Section 3.5). Precisely, *RenovaBio* aims to guarantee a sustainable production of biofuels, but its environmental efficiency methodology, under development, will most likely take into account direct LUC but not indirect (SI.15).

3.4. Water-food – climate change impacts on food and water

In future climate change scenarios up to 2100, large areas of land may be at risk of degradation as a result of more frequent drought in the North and North-East of Brazil [29,85], while lands in the South are likely to suffer from more frequent flooding and erosion [86]. A tipping point involving the collapse of the Amazon through droughts and fires may also be on the horizon [27,32,87]. Inhabitants of the North-East of Brazil (the Caatinga) traditionally cope with frequent droughts [29], but this area could undergo desertification as a result of climate change. Under scenarios of productivity collapse, people migrate [88], and thus agricultural activities also effectively migrate, as some farmers abandon their land to find work in cities while other farmers plant crops that used to be grown elsewhere [89]. Climate change will lead to substantial regional economic losses for the North-East and other areas [90].

The effects of climate change will likely push maize, soybeans and sugarcane grown over much of the territory to migrate, as land productivity evolves (Fig. 4). Scenarios of land productivity changes and yield of crop types in Brazil captured in Fig. 4 have been derived with the latest version of the Lund-Potsdam-Jena model with managed land (LPJmL4), a global dynamic vegetation model [92]. LPJmL is a process-based ecosystem model that simulates the growth, production and phenology of 13 crop functional types and managed grass (rain-fed and irrigated). All processes are modelled at a daily resolution and on a global $0.5^\circ \times 0.5^\circ$ grid. LPJmL4 simulates the transient changes in carbon and water cycles due to land use, specific phenology and seasonal CO_2 fluxes in carbon and water cycles of agricultural-dominated areas, as well as the production of crops and grazing lands. Effectively, the model allows for assessing a broad range of feedbacks within the terrestrial biosphere as increasingly shaped by human activities such as climate change and land use. It allows for simulating the management of crops (irrigation, intercropping, treatment of residues), which leads to different maximum levels for leave areas [91,92]. For agricultural crops, assimilated biomass from photosynthesis is allocated at daily steps to four carbon pools: leaves, roots, harvestable storage organs, and a pool representing stems and mobile reserves. We ran two different scenarios (RCP 2.6 and 8.5) for atmospheric CO_2 between 2000 and 2100 using data from the Hadley centre's climate model (HAD-GCM) as inputs to LPJmL4.

Simulations of crop yields show that under a high emissions scenario (RCP 8.5), land productivity for all four commodities decreases substantially, except for sugarcane, which may find more suitable conditions in the South. Productivity loss under a low emissions scenario (RCP 2.6) is less pronounced but still likely to occur. Maize declines steeply in the North and North-East, which could induce

⁷ The targets are 2014 for declivity < 12%; and 2017 for declivity > 12%.

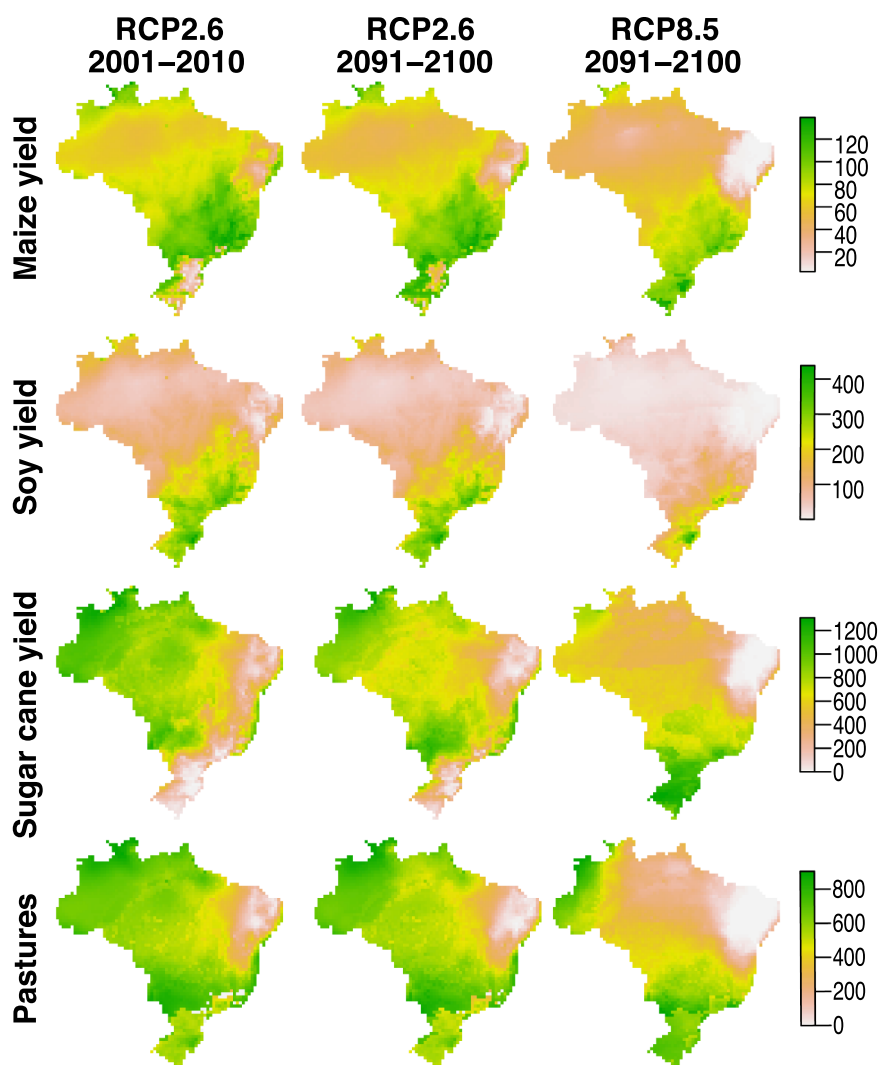


Fig. 4. Simulated future productivity across Brazil under climate change for various land-uses in comparison to the 2001–2010 decade. Colour bar units are in units of gC/m^2 , where high productivity is represented by dark green colours and low productivity grey-white. The data were generated by the LPJm4 model ([91,92]) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

substantial socio-economic changes. Soybeans, grown in the South and in the Cerrado, could be constrained to the South, with substantial impacts on exports (see Section 3.5). The cane industry, traditionally rain-fed and situated in the São Paulo area, is currently expanding to drier areas in the North where irrigation is required [93,94]. Finally, pastures could also be displaced from their traditional southern heartland.

Brazil has experience in designing policies to deal with the effects of climate variability on the farming sector. In 1996, the Agricultural Climate-Risk Zoning (ZARC – Zoneamento Agrícola de Risco Climático – SI.18) was implemented to minimize risks from adverse climate events on crops. At that time, the ZARC was designed to reduce the large number of payment claims faced by the rural public insurance as a result of crop losses caused by either floods or droughts [95]. The ZARC comprises a crop year calendar with the zoning of the most suitable crops for each region and the best period for planting, considering the soil conditions and the crop cycling capacities. Although not originally developed with climate change in mind, the ZARC was incorporated to the NAP, subject to some adjustments to include the long-term effects of climate change on the crops. Similarly, the Agricultural Activity Guarantee Programme (PROAGRO – SI.19) and the Family Agricultural Activity Guarantee Programme (PROAGRO-Mais – SI.19), which insure farmers against the commodity price variations and harvest failures

caused by climate events, have been integrated through the NAP with other official insurance programmes previously in force to minimize risks associated with agricultural production.

The Low-Carbon (ABC) Plan (SI.20) was created in 2011 to reduce agricultural GHG emissions, and it includes the provision of low-interest loans for farmers who implement low-carbon agricultural practices. The ABC Plan provides for climate change adaptation measures to ensure food security, including the development of projects, research, and the transfer of technologies (i) to increase efficiency and resilience of agro-ecosystems, (ii) to maintain productivity under biotic and abiotic climate change pressures, (iii) to foster sustainable and integrated uses of water and soil, and (iv) to consider the climate modelling of different agricultural systems. Although several years have elapsed since its creation, the ABC Plan is not yet fully implemented, mostly due to lack of awareness by farmers, lack of skilled technical assistance amongst farmers to implement new technologies, insufficient technical support from public or private agencies, regional disparities in the allocation of credits,⁸ and lack of monitoring to ensure compliance [35,96]. Projected climate variations call for further agricultural risk-management policies. Some steps have been taken to integrate climate

⁸ A substantial fraction of the funding is allocated to farmers from the Centre-West, Southeast and South, in detriment to the North and Northeast regions.

change scenarios when amending existing public policies that address climate risks in agriculture. However, implementation challenges remain, mainly as regards the ability of the public sector to put in practice the required policy adjustments and to address social and regional economic disparities. Meanwhile, more sound water and electricity policy could contribute in alleviating risks of food availability crises (see Section 3.2), while land-use policy itself affects the land's water recycling ability and thus influences the availability of water and energy [35,37,97].

3.5. Water-energy-food – indirect land-use change and deforestation

The deforestation of the Amazon was initially attributed, besides infrastructure extension and selective logging [98], to expanding cattle and soy industries [47]. Deforestation was shown to be statistically related to changes in the international soy price [47]. However, it was later established that the expansion of soybean crops takes place at the expense of pastures, which are less profitable, and that it is the increasing search for new pastureland that predominantly accounts for forest clearing [34,44,45]. In other words, soybeans producers are not directly responsible for setting fire to the forest for clearing purposes. Yet, soybean producers are not merely displacing cattle ranchers; they are also acquiring newly deforested land from them. Indeed, cattle ranchers often speculate on the future sale price of the land they want to deforest and the land is used for grazing until it is sold to soybean farmers [48]. How illegally deforested land is initially acquired is not fully clear, although it seems to be a combination of deficient land registration, poor law enforcement, legal loopholes, bribes and risk-taking.

A close relationship exists between the Brazilian soybean industry and the Chinese meat industry [99]. China imports over half of Brazil's production of soybeans to supply fast growing pork and poultry industries (Figs. 5 and 6a-b), for direct human consumption of derivatives (oil, flour, etc), and to produce biodiesel. China's demand for meat follows its fast domestic income growth, allowing consumers to eat meat more frequently. Due to their high protein content, soybeans are predominantly used to feed animals.

China's consumption of soybeans has far outpaced its domestic production (Fig. 6c-d), partly as a result of its water shortages. Increasing desertification in areas previously used to grow this crop has

indirectly transferred production to Brazil [99]. Under climate change scenarios, larger amounts of land-use may be transferred from China to Brazil in this way.

The USA is the largest producer of soybeans in the world. However, its soybean cropland area is not expanding, and thus production growth allocates itself to Brazil, which has historically been able to accommodate it. Meanwhile, the sugarcane-based ethanol industry is also growing in Brazil, expanding far outside of its traditional growing region in the State of São Paulo [93]. It could potentially occupy land currently used for soybean crops or cattle, depending on prices, and trigger ever more complex cascades of ILUC and deforestation [46].

As stated in Sections 2.2 and 3.3, deforestation of the Amazon and of the Cerrado could in fact also explain changes in the water cycle that has led to water scarcity in cities and in the hydroelectric system. It is well established that cutting trees down reduces evapotranspiration. Roots pump belowground water vertically upward, it then transpires through the leaves and the resulting humidity rises to the atmosphere to form clouds. Over the Amazon this biotic pump is so powerful that the resulting pressure difference attracts additional humidity from the Atlantic, which in return falls down as rain in the Eastern/ North-eastern Amazon. Deforestation has recently been shown to alter the feedback between land and atmosphere in the water cycle [37]. While this is not fully established, water scarcity events thus could potentially ultimately be associated to ILUC and to the expansion of food commodity production for exports.

From 2004–2014, deforestation in the Amazon Forest slowed down in Brazil due to a complex combination of factors. Amongst the public policies adopted by Brazilian authorities, the 2004 Action Plan for Prevention and Control of Deforestation in the Legal Amazon (PPCDAm – SI.21 and 22) has achieved effective results in monitoring, controlling and taking enforcement actions in areas affected by deforestation. The PPCDAm includes the regularization of occupied federal public lands, the expansion of protected areas, the granting of legal status to indigenous land, and some restrictions in access to credit from public financial institutions imposed on those who have infringed environmental legislation.

Whereas such policies partly explain the slowing down in deforestation in the Amazon, other important factors include a temporary slowdown in the demand for soy and beef, intensification of beef production, and measures targeting the supply-chain governance of these commodities. Amongst the latter, of note are the moratoria on soy (SI.23) and beef produced on recently deforested land and steps to meet technical standards in foreign markets [46,100,101], including a certificate system for sustainable soy, managed by the Roundtable for Responsible Soy (SI.17). These developments are encouraging but, realistically, their effectiveness will be truly tested when international demand for soy and beef is again on the rise.

With a lower level of protection than the Amazon, the Cerrado has lost half of its native vegetation, mainly due to forest fires, agriculture and cattle rearing [102]. In 2014, a variant of the PPCDAm was developed for the Cerrado, the Action Plan for Prevention and Control of Deforestation and Fires in the Cerrado (PPCerrado – SI.24). However, although the Brazilian government has expressed the intention to extend the moratoria on soy and beef to the Cerrado (MMA, 2016 – SI.25), so far it remains restricted to the Amazon.

The Forest Code enacted in 2012 (SI.26) establishes rules for the protection of native vegetation in private rural lands, including in the Amazon and in the Cerrado. The Forest Code is a result of an intense debate, confronting the interests of environmentalists and the agribusiness' economic lobby. Environmentalists were staunchly opposed to the Forest Code's amnesty for illegal deforestation that occurred before 2008 [103] and to the disparities in the conservation requirements for Legal Reserve (LR), which are more rigorous for the Amazon than for the Cerrado. While 80% of native vegetation of the Amazon on large land holdings cannot be lawfully cleared, in the Cerrado the protection targets range from 20% (for the majority of the biome) to 35% (for the

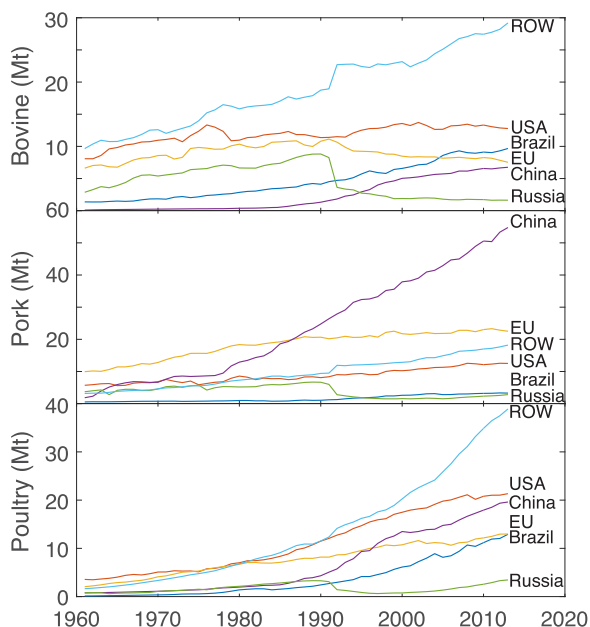


Fig. 5. Meat production around the world, for bovine, pork and poultry. Data from FAOSTAT 2017.

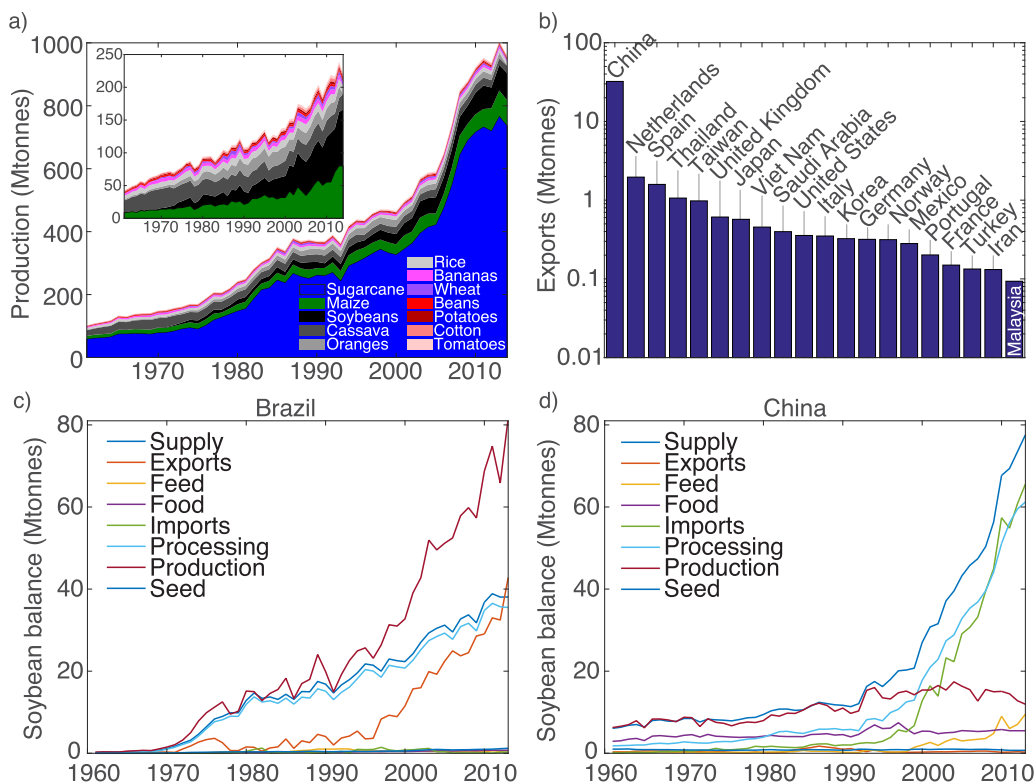


Fig. 6. a) Main crops produced in Brazil. The inset shows the same data for clarity. b) Main export destinations for soybeans. c-d) Balance of soybeans in Brazil and China. The ‘domestic supply’ equals ‘production’ plus ‘imports’ minus ‘exports’, while ‘food’ denotes domestic consumption as food. ‘Feed’ denotes direct (unprocessed) use to feed animals, although soybeans mostly go through ‘processing’ before they are used as feed. Over 50% of soybeans produced in Brazil are destined for the Chinese market, processed there for feeding pigs. Data from FAOSTAT 2017.

portion of the Cerrado within the Legal Amazon).

The Forest Code forbids the clearing of Permanent Protected Areas (PPA), and establishes new mechanisms to improve the conservation of forests, such as the Environmental Rural Register (CAR). The CAR is a national public electronic registry, mandatory for all rural properties. It requires property owners and landholders to show proof of ownership or land-use and to declare the geo-referenced property boundaries and remnant vegetation areas on their land, including protected areas such as the LR and PPA. The CAR is expected to enhance monitoring, environmental and economic planning, and enforcement of the environmental legislation against deforestation [104].

Yet, it is not clear whether these measures for reduction in deforestation are sufficient, given that demand for agricultural commodities continues to grow at a rapid pace, creating ever stronger economic incentives to create more agricultural land, through legal or illegal pathways [105]. A long-standing problem of property rights exists in remote areas [48]. Under Brazilian Law, acquisition and maintenance of the property rights require evidence of the productive use of land, putting landowners and squatters in competition for control over land [106]. Landowners clear forest for pasture or agriculture, as evidence of productivity to avoid risk of confiscation and redistribution amongst squatters [107]. Clearing forest is also a strategy used by landowners to protect the land from illegal occupation by squatters [107], leading to both a tragedy of the commons effect and challenges to law enforcement [48].

The combination of climate change, climate policy and growing food consumption internationally could unleash a new complex deforestation storm in Brazil, depending on how it is governed. Recent evidence suggests that deforestation rates in the Amazon are increasing again, and in the Cerrado it has never been under control.⁹ Climate

⁹ See “Projeto PRODES: Monitoramento da floresta Amazônia Brasileira por satélite.” [The PRODES Project Monitoring the Brazilian Amazon forest by satellite], http://www.obt.inpe.br/prodes/prodes_1988_2016n.htm, and also <http://www.obt.inpe.br/prodes/index.php>.

change will reduce land productivity, forcing rent-seeking farmers to source additional cropland, which would likely be supplied through ILUC. Climate policy, inside and outside Brazil, could develop a substantial global demand for biofuels, which could induce larger expansion of sugarcane plantations leading to additional ILUC. Globally growing demand for meat and biofuels can give rise to unprecedented pressures on remaining natural resources and forests in Brazil.

Brazil is taking measures to fight deforestation. Policy-makers expect that once the Forest Code mechanism CAR is fully implemented, deforestation will decrease due to clearer land tenure rights, a more accurate land registry and better law enforcement [104]. However, while crucial, this approach does not tackle international demand for commodities as an underlying driver, further affected by climate change pressures. The combination of inter-sectoral agriculture, forest policies and trade measures, at the global level, could be part of a broader and more effective solution. The moratoria on soy is an example of the supply-chain governance of commodities that has helped reduce deforestation for soy in the Amazon, although it does not in fact prevent ILUC [108]. The supply-chain governance can include other policies, such as certification and labelling requirements, although the certificate system for sustainable soy in Brazil has not been as effective as the moratorium on soy, mainly due to higher risks for producers not selling their produce [109].

In conclusion, what emerges from studying ILUC and Amazon/Cerrado deforestation in Brazil is that many processes contribute to this effect, all of which are Nexus-related and involve all scales from local to global: (1) global demand for agricultural commodities (notably soybeans going to China for meat production) requires increasing amounts of land; (2) existing policies prevent direct land-use change but not ILUC, incentivising the use of loop-holes in which complex ILUC cascades emerge; (3) climate change, deforestation and associated changes in the water cycle lead to changes in the productivity of the land, and crop yields, which may exacerbate land scarcity and accelerate the process of ILUC and deforestation; and finally, (4) insufficiently resilient governance structures are made weaker by strong economic incentives for land grabbing to produce ever larger amounts of food

commodities for export. However, deforestation could lead to the ultimate downfall of the whole Brazilian agribusiness as the Amazon and Cerrado biomes are irreversibly altered. Thus, the issue of ILUC and deforestation affects all nodes and aspects of the Nexus in Brazil: water security (deforestation destabilises the water cycle), food security (competition for land between the agri-business and other uses) and energy security (water instability affecting rainfall and hydropower, land availability for biofuel feedstocks).

4. Policy implications

It is challenging to devise clear policy implications when faced with a ‘wicked’ problem such as the Nexus, precisely for the reasons that define a ‘wicked’ problem: knowledge is incomplete, and optimal solutions can by definition not be identified. Possible optimal solutions identified with current knowledge are only ever illusory, as new information and scientific advances change the constraints of optimisation problems, leading to different solutions, while ad-hoc assumptions that could be used to cover for missing knowledge can lead to misleading conclusions. A profound recognition of the complexity of the Nexus and of our limited understanding is paramount to making any progress addressing the Nexus with public policies.

Table 1 summarises the Nexus challenges surveyed in this article. Fig. 7a illustrates the Brazilian Nexus with its external influences related to global economic and environmental change, and relevant institutions at various scales. Fig. 7b illustrates a proposed science-policy-law bridge. These elements must be recalled as context for the policy implications of our approach.

Nexus-resilient policy-making requires integration and consistency of action across sectors according to current scientific knowledge. It is important to note, however, that we do not recommend the creation of integrated ministries, or of a Nexus government department. By contrast, we recommend an enhancement of the science-policy interface for all governance institutions in order to make it Nexus-savvy. This can be achieved in two main forms. First, following the EU approach to impact assessment of policy frameworks [110], we recommend using a scientific board of Nexus experts to check for Nexus feedbacks in proposed policies, using a standardised procedure that makes use of Nexus modelling tools, that promotes finding empirical evidence and makes use of qualitative studies on the coherence of new and existing

regulations and law. Secondly, a similar interface, and possibly the same board, could be used to design policies based on knowledge of Nexus feedbacks. A possible example, in the Brazilian case, would be the adoption of an export duty on soybeans. Indeed, as Nexus feedbacks at the global level suggest that increasing demand for soybeans from China (due to the trade war with the US) will renew pressures on land use and deforestation, one potential avenue to counteract this phenomenon would be to introduce in Brazil an export duty on soybeans, the rate of which would be progressive (growing more than proportionally with the increase in the export volume) so as to counteract exports that are ‘excessive’ in terms of the pressure on land use they are likely to cause. Such a policy does not require administrative re-organisation or any substantial institutional integration. It is a simply targeted policy, which would be based on knowledge of the Nexus feedbacks (the above-studied ILUC).

The Nexus-savvy input provided by the proposed boards or other similar networks of Nexus experts could be organised in different ways according to the structure of the science and policy interface in a given country. One key consideration in making such interfaces functional and useful to policy-makers and other stakeholders is the interface’s iterative nature or ‘bidirectional’ character (Fig. 7c). It should involve policy-makers and stakeholders expressing their needs and normative views to policy-analysts, department experts and legal experts, who would interpret this information to either develop or test detailed policy proposals within existing windows of opportunity and build an evidence-base that will ultimately support these proposals under a parliament vote. By obtaining results, Nexus experts can convey their findings to policy-makers and stakeholders, who can then adjust their requirements and strategies or, alternatively, ask for further analysis under additional political parameters. Through an iterative process, the policy frameworks eventually identified would be supported by a substantial evidence-base, which can be politically tested in parliament. The science-policy bridge should be used continuously as policy is implemented, its effectiveness evaluated over time, more data and better models become available, and as the nature of policy problems evolve.

5. Conclusion

Although Brazil has to some extent responded to Nexus challenges, such measures do not fully address the complex interconnections within

Table 1
Summary of Nexus challenges in Brazil.

Case Study	Challenges		
	Environmental	Socio-economic	Policy
W-E: Hydro-electricity	<ul style="list-style-type: none"> • Water scarcity • Competition among users • Reserve thermoelectric plants increase GHG emissions • Dam projects in the Amazon affect biodiversity and indigenous land. 	<ul style="list-style-type: none"> • Energy security • Overreliance on hydroelectricity • Diversification of the energy matrix, increasing non-hydro renewable • Investment in new capacity, due to increasing energy demand 	<ul style="list-style-type: none"> • Improving policy-coherence • Incorporating climate change impacts in long-term energy planning • Reducing reliance on water resources in long-term energy planning
E-F: Biofuels	<ul style="list-style-type: none"> • Crop expansion beyond traditional areas • ILUC • Water use • Unsustainable agricultural practices including sugarcane burning for manual harvesting 	<ul style="list-style-type: none"> • Biofuel crops displace food crops • ILUC leading to deforestation • Competition for land can threaten food security (non-cash crops) 	<ul style="list-style-type: none"> • Elaborating plan for high potential renewables • Defining protected areas and areas suitable for expansion for energy crop production. • Reducing burning practices and developing mechanisation • Linking national policy with the international framework of global commodities governance, including certification schemes.
W-F: Food production	<ul style="list-style-type: none"> • Rise in frequency of extreme weather events, floods, droughts • Changes in temperature and rain patterns affect crop yield 	<ul style="list-style-type: none"> • Changes in land productivity produce crop and people migration and changes in agricultural output 	<ul style="list-style-type: none"> • Adapting existing policies (e.g., ZARC), and creating new policies, that incorporate climate change uncertainty and risk management
W-E-F: Deforestation	<ul style="list-style-type: none"> • Deforestation • Land degradation • Potential Amazon collapse 	<ul style="list-style-type: none"> • Expansion of soy plantations • Displacement of pastures • ILUC leading to deforestation • Unclear or absent property rights • Land grabbing 	<ul style="list-style-type: none"> • Strengthening national policies against deforestation, including law enforcement, monitoring, regulation of property ownership and land tenure rights • Linking national policy with the international framework of global commodities governance

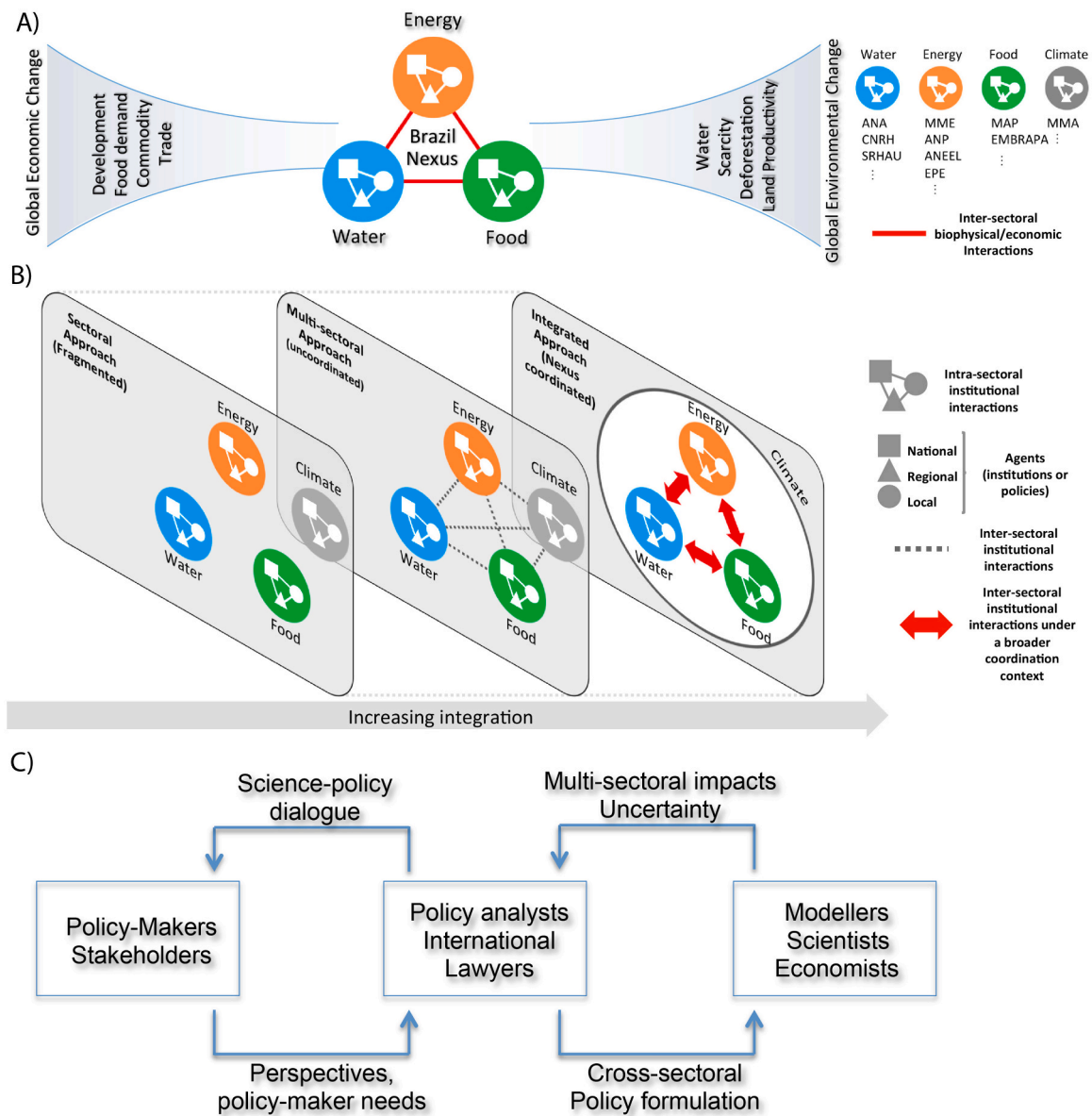


Fig. 7. Schematic representation of the Nexus and relevant Brazilian institutions, and of the science-policy interface. A) The Nexus involves global to local interactions, and strong interactions between the actions of each institution in each of its nodes. Each institution is attached to one of the sectors. B) Different regimes of policy integration are illustrated using layers. In the fully fragmented policy situation, interactions exist between institutions and frameworks for each node of the Nexus and climate change, without interactions across nodes. In a situation of higher degrees of communication, interactions exist between institutions and between nodes and climate change-related institutions. However, in a desired Nexus integrated framework, coordinated interaction takes place between nodes of the Nexus in a framework defined by climate policy. C) The science-policy-law interface involves an iterative dialogue between policy-makers and scientists, mediated/translated by policy analysts and legal experts.

the Nexus. This is partly due to limited understanding of the underlying drivers. For example, the full causation chain in ILUC still needs to be elucidated, and some of the policy responses may have to be taken beyond Brazil. Albeit not exhaustive, Table 1 covers the most pressing challenges currently faced by Brazil. Solutions to the policy challenges are not straightforward and, therefore, there is a clear need for more knowledge on the dynamics involved in each of the processes discussed.

A Nexus approach to science-informed policy-making must involve, primarily, an effort to integrate and condense existing knowledge in all of the domains concerned, to be delivered to decision-makers, in digestible form, across the various scales of governance in Brazil. This requires a change in the scientific approach to Nexus problems [21]. As illustrated by the four case studies reviewed, energy, water and food are highly interrelated in Brazil, such that policy for managing one likely affects the other two in sometimes unpredictable ways. A nexus

approach is one that not only captures these interlinkages, but that does so in a way that is understandable and actionable by decision-makers that are currently organised sectorially and at different scales.

In order to make it understandable and actionable, we submit that the scientific analysis of the Nexus interlinkages in Brazil has to rely on three key considerations: (a) a different type of modelling, in which unrealistic social planner assumptions are abandoned, giving voice instead to complex interdisciplinary phenomena and path-dependency, while allowing for incomplete knowledge and uncertainty; (b) a more interactive and integrative approach to understanding the problems and conveying the solutions, whereby (i) the sectorial and federal/state/municipal stakeholders are both providers of data and receivers of integrated (modelled) analysis, (ii) the state of the system is understood not only from a natural science perspective but also from that of the political economy, politics and legal constraints both in Brazil and

elsewhere, and (iii) the sectorial and federal/state/municipal stakeholders participate in the scientific analysis; and finally (c) the interactions between the global and the local are fully taken into account, both in the design of the model (i.e. in (a)) and in the type of participation (i.e. in (b)), with potentially transnational interdisciplinary panels and discussions. This approach would not only translate into more participation but also into policy approaches that account for constraints arising from previous actions (in Brazil, but also e.g. in China, the EU, the US and in the governance of international trade), as suggested by the ILUC phenomenon. The case of Brazil is therefore informative well beyond Brazilian policy.

Acknowledgements

This paper inaugurates the BRIDGE project by framing the boundaries of the Brazilian Nexus. BRIDGE (<https://www.ceenrg.landecon.cam.ac.uk/research/the-bridge-project>) is funded by the Newton Fund, a collaboration between the Brazilian FAPESC and the UK ESRC Research Councils, grant no ES/N013174/1. This work started under the LINKS2015, project also funded by the Newton Fund (EPSRC and FAPESC), grant no EP/N002504/1. Other funders include EPSRC and European Union (European Commission) (JFM; EP/K007254/1, 689150 SIM4NEXUS), NERC (NRE, PBH; NE/P015093/1), CONICYT (PS), Philomathia Foundation (JEV, PB). The authors are indebted to the BRIDGE stakeholder network and advisory board, in particular Amaro Pereira for insightful comments. JFM coordinated the work, supported by JEV, JFM and PB designed the paper, MAP contributed the policy and legal analysis, and all authors contributed to the text and/or data. The authors acknowledge the support and environment offered by the Cambridge Centre for Environment, Energy and Natural Resource Governance (C-EENRG) for the research leading to this paper.

Competing interests

The authors have no competing interests to declare.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.rser.2019.01.045](https://doi.org/10.1016/j.rser.2019.01.045).

References

- Beddington, J., Food, energy, water and the climate: a perfect storm of global events? *Journal*, 2012. <http://webarchive.nationalarchives.gov.uk/20121206120858/http://www.bis.gov.uk/assets/goscience/docs/p/perfect-storm-paper.pdf>.
- Rockström J, et al. A safe operating space for humanity. *Nature* 2009;461(7263):472–5.
- Steffen W, et al. Planetary boundaries: guiding human development on a changing planet. *Science* 2015;347(6223):1259855.
- Hertel TW. The challenges of sustainably feeding a growing planet. *Food Secur* 2015;7(2):185–98.
- Hoff, H., Understanding the Nexus. Background Paper for the Bonn 2011 Conference: The Water Energy and Food Security Nexus. *Journal*; 2011. http://wef-conference.gwsp.org/fileadmin/documents_news/understanding_the_nexus.pdf.
- Liu J, et al. Systems integration for global sustainability. *Science* 2015;347(6225):1258832.
- Bazilian M, et al. Considering the energy, water and food nexus: towards an integrated modelling approach. *Energy Policy* 2011;39(12):7896–906.
- Keairns D, Darton R, Irabien A. The energy-water-food nexus. *Annu Rev Chem Biomol Eng* 2016;7:239–62.
- Kurian M. The water-energy-food nexus: trade-offs, thresholds and transdisciplinary approaches to sustainable development. *Environ Sci Policy* 2017;68:97–106.
- Leck H, et al. Tracing the water–energy–food nexus: description, theory and practice. *Geogr Compass* 2015;9(8):445–60.
- Weitz N, et al. Closing the governance gaps in the water-energy-food nexus: insights from integrative governance. *Glob Environ Change* 2017;45:165–73.
- Rittel HW, Webber MM. Dilemmas in a general theory of planning. *Policy Sci* 1973;4(2):155–69.
- Head BW, Alford J. Wicked problems: implications for public policy and management. *Adm Soc* 2015;47(6):711–39.
- Stocker T, et al. IPCC, 2013: climate change 2013: the physical science basis [Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change]. Cambridge University Press; 2013.
- Brando PM, et al. Abrupt increases in Amazonian tree mortality due to drought-fire interactions. *Proc Natl Acad Sci USA* 2014;111(17):6347–52.
- Lenton TM, et al. Tipping elements in the Earth's climate system. *Proc Natl Acad Sci USA* 2008;105(6):1786–93.
- Piesse J, Thirtle C. Three bubbles and a panic: an explanatory review of recent food commodity price events. *Food Policy* 2009;34(2):119–29.
- Baccini A, et al. Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nat Clim Change* 2012;2(3):182–5.
- Bajželj B, et al. Importance of food-demand management for climate mitigation. *Nat Clim Change* 2014;4(10):924–9.
- Garcia DJ, You F. The water-energy-food nexus and process systems engineering: a new focus. *Comput Chem Eng* 2016;91:49–67.
- Mercure J-F, et al. Modelling complex systems of heterogeneous agents to better design sustainability transitions policy. *Glob Environ Change* 2016;37:102–15.
- Brouwer F, et al. Energy modelling and the Nexus concept. *Energy Strategy Rev* 2018;19:1–6.
- Howells M, et al. Integrated analysis of climate change, land-use, energy and water strategies. *Nat Clim Change* 2013;3(7):621.
- Stocker T, et al. IPCC, 2013: summary for policymakers in climate change 2013: the physical science basis, contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge, New York, USA: Cambridge University Press; 2013.
- Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon W-T, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen J, Rinke A, Sarr A, Whetton P. Regional climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, editors. *Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge: Cambridge University Press; 2007.
- Christensen JH, Krishna Kumar K, Aldrian E, An S-I, Cavalcanti IFA, de Castro M, Dong W, Goswami P, Hall A, Kanyanga JK, Kitoh A, Kossin J, Lau N-C, Renwick J, Stephenson DB, Xie S-P, Zhou T. Climate phenomena and their relevance for future regional climate change. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM, editors. *Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge: Cambridge University Press; 2013.
- Malhi Y, et al. Climate change, deforestation, and the fate of the Amazon. *Science* 2008;319(5860):169–72.
- Phillips OL, et al. Drought sensitivity of the Amazon rainforest. *Science* 2009;323(5919):1344–7.
- Marengo JA, Bernasconi M. Regional differences in aridity/drought conditions over Northeast Brazil: present state and future projections. *Clim Change* 2015;129(1–2):103–15.
- Lewis SL, et al. The 2010 Amazon drought. *Science* 2011;331(6017):554. [554].
- Escobar H. Water security. Drought triggers alarms in Brazil's biggest metropolis. *Science* 2015;347(6224):812.
- Davidson EA, et al. The Amazon basin in transition. *Nature* 2012;481(7381):321–8.
- Nobre CA, et al. Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. *Proc Natl Acad Sci USA* 2016;113(39):10759–68.
- Nepstad DC, et al. Interactions among Amazon land use, forests and climate: prospects for a near-term forest tipping point. *Philos Trans R Soc B-Biol Sci* 2008;363(1498):1737–46.
- Marengo JA, et al. The drought of 2010 in the context of historical droughts in the Amazon region. *Geophys Res Lett* 2011;38(12).
- Fearnside PM. Deforestation in Brazilian Amazonia: history, rates, and consequences. *Conserv Biol* 2005;19(3):680–8.
- Zemp DC, et al. Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks. *Nat Commun* 2017;8:14681.
- Marengo JA, et al. Extreme seasonal climate variations in the Amazon basin: droughts and floods. Interactions between biosphere, atmosphere and human land use in the Amazon basin. Springer; 2016. p. 55–76.
- Nobre CA, et al. Some characteristics and impacts of the drought and water crisis in Southeastern Brazil during 2014 and 2015. *J Water Resour Prot* 2016;8(02):252.
- Burrows MT, et al. The pace of shifting climate in marine and terrestrial ecosystems. *Science* 2011;334(6056):652–5.
- Jump AS, Penuelas J. Running to stand still: adaptation and the response of plants to rapid climate change. *Ecol Lett* 2005;8(9):1010–20.
- Wheeler T, von Braun J. Climate change impacts on Global food security. *Science* 2013;341(6145):508–13.
- Lambin EF, Meyfroidt P. Global land use change, economic globalization, and the looming land scarcity. *Proc Natl Acad Sci USA* 2011;108(9):3465–72.
- Barona E, et al. The role of pasture and soybean in deforestation of the Brazilian Amazon. *Environ Res Lett* 2010;5(2).
- Arima EY, et al. Statistical confirmation of indirect land use change in the Brazilian Amazon. *Environ Res Lett* 2011;6(2).
- Lapola DM, et al. Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proc Natl Acad Sci USA* 2010;107(8):3388–93.

- [47] Morton DC, et al. Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. *Proc Natl Acad Sci USA* 2006;103(39):14637–41.
- [48] Lapola DM, et al. Pervasive transition of the Brazilian land-use system. *Nat Clim Change* 2014;4(1):27–35.
- [49] Nepstad DC, Stickler CM, Almeida OT. Globalization of the Amazon soy and beef industries: opportunities for conservation. *Conserv Biol* 2006;20(6):1595–603.
- [50] Searchinger T, et al. Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 2008;319(5867):1238–40.
- [51] IPCC. Mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change. Cambridge, UK and New York, NY: Cambridge University Press; 2014.
- [52] Bowyer C, Kretschmer B. Anticipated indirect land use change associated with expanded use of biofuels and bioliquids in the EU—an analysis of the national renewable energy action plans. *IIEP* 2010;8–9. (March 2011).
- [53] Fargione J, et al. Land clearing and the biofuel carbon debt. *Science* 2008;319(5867):1235–8.
- [54] Harvey M, Pilgrim S. The new competition for land: food, energy, and climate change. *Food Policy* 2011;36:S40–51.
- [55] IEA. IEA world energy outlook. OECD/IEA; 2015.
- [56] Hoogwijk M, et al. Exploration of regional and global cost-supply curves of biomass energy from short-rotation crops at abandoned cropland and rest land under four IPCC SRES land-use scenarios. *Biomass - Bioenergy* 2009;33(1):26–43.
- [57] Smeets EMW, et al. A bottom-up assessment and review of global bio-energy potentials to 2050. *Prog Energy Combust Sci* 2007;33(1):56–106.
- [58] Mercure J-F, Salas P. An assessment of global energy resource economic potentials. *Energy* 2012;46(1):322–36.
- [59] GEA. Global energy assessment—toward a sustainable future. Cambridge, UK, and Laxenburg, Austria: Cambridge University Press and the International Institute for Applied Systems Analysis; 2012.
- [60] Newton P, Agrawal A, Wollenberg L. Enhancing the sustainability of commodity supply chains in tropical forest and agricultural landscapes. *Glob Environ Change* 2013;23(6):1761–72.
- [61] Lima MGB, et al. A reality check on the landscape approach to REDD+: lessons from Latin America. *For Policy Econ* 2017;78:10–20.
- [62] Benjamin AH, Marques CL, Tinker C. The water giant awakes: an overview of water law in Brazil. *Tex L Rev* 2004;83:2185.
- [63] IEA. IEA world energy balances dataset. OECD/IEA; 2017.
- [64] De Lucena AFP, et al. The vulnerability of renewable energy to climate change in Brazil. *Energy Policy* 2009;37(3):879–89.
- [65] Prado FA, et al. How much is enough? An integrated examination of energy security, economic growth and climate change related to hydropower expansion in Brazil. *Renew Sustain Energy Rev* 2016;53:1132–6.
- [66] da Silva Soito JL, Freitas MAV. Amazon and the expansion of hydropower in Brazil: vulnerability, impacts and possibilities for adaptation to global climate change. *Renew Sustain Energy Rev* 2011;15(6):3165–77.
- [67] da Silva RC, de Marchi I, Neto, Seifert SS. Electricity supply security and the future role of renewable energy sources in Brazil. *Renew Sustain Energy Rev* 2016;59:328–41.
- [68] Maurer L, Pereira M, Rosenblatt J. Implementing power rationing in a sensible way: lessons learned and international best practices; 2005.
- [69] Costa F. Can rationing affect long run behavior? Evidence from Brazil. SSRN; 2013.
- [70] Lynham J, Tarui N. What can water demand programs learn from electricity demand programs? *Routledge Handbook of Water Economics and Institutions*; 2014. p. 201.
- [71] Berchin II, et al. Energy production and sustainability: a study of Belo Monte hydroelectric power plant [in Natural Resources Forum]. Wiley Online Library; 2015.
- [72] Rose SK, et al. Bioenergy in energy transformation and climate management. *Clim Change* 2014;123(3–4):477–93.
- [73] Mercure J-F, et al. Integrated assessment modelling as a positive science: private passenger road transport policies to meet a climate target well below 2 degrees C. *Clim Change* 2018.
- [74] Adami M, et al. Remote sensing time series to evaluate direct land use change of recent expanded sugarcane crop in Brazil. *Sustainability* 2012;4(4):574–85.
- [75] Lossau S, et al. Brazil's current and future land balances: is there residual land for bioenergy production? *Biomass - Bioenergy* 2015;81:452–61.
- [76] Miller SA. Minimizing land use and nitrogen intensity of bioenergy. *Environ Sci Technol* 2010;44(10):3932–9.
- [77] Garcez CAG, de Souza Vianna JN. Brazilian biodiesel policy: social and environmental considerations of sustainability. *Energy* 2009;34(5):645–54.
- [78] La Rovere EL, Pereira AS, Simões AF. Biofuels and sustainable energy development in Brazil. *World Dev* 2011;39(6):1026–36.
- [79] Wilkinson J, Herrera S. Biofuels in Brazil: debates and impacts. *J Peasant Stud* 2010;37(4):749–68.
- [80] Moreira JR, Goldemberg J. The alcohol program. *Energy Policy* 1999;27(4):229–45.
- [81] EMBRAPA SOLOS. Agro-ecological Zoning of Sugarcane. Zoneamento Agro-ecológico da Cana-de-açúcar. Documentos Embrapa Solos.
- [82] Janssen R, Rutz DD. Sustainability of biofuels in Latin America: risks and opportunities. *Energy Policy* 2011;39(10):5717–25.
- [83] Scarlat N, Dallemand J-F. Recent developments of biofuels/bioenergy sustainability certification: a global overview. *Energy Policy* 2011;39(3):1630–46.
- [84] Schleifer P. Private regulation and global economic change: the drivers of sustainable agriculture in Brazil. *Governance*; 2016.
- [85] Marengo JA, et al. Two contrasting severe seasonal extremes in tropical South America in 2012: flood in Amazonia and drought in northeast Brazil. *J Clim* 2013;26(22):9137–54.
- [86] Barros VR, Garavaglia CR, Doyle ME. Twenty-first century projections of extreme precipitations in the Plata Basin. *Int J River Basin Manag* 2013;11(4):373–87.
- [87] Cook B, Zeng N, Yoon J-H. Will Amazonia dry out? Magnitude and causes of change from IPCC climate model projections. *Earth Interact* 2012;16(3):1–27.
- [88] Barbieri AF, et al. Climate change and population migration in Brazil's Northeast scenarios for 2025–2050. *Popul Environ* 2010;31(5):344–70.
- [89] Confalonieri UE, et al. Social, environmental and health vulnerability to climate change in the Brazilian Northeastern Region. *Clim Change* 2014;127(1):123–37.
- [90] de Souza Ferreira Filho JB, De Moraes GI. Climate change, agriculture and economic effects on different regions of Brazil. *Environ. Dev. Econ.* 2015;20(1):37–56.
- [91] Bondeau A, et al. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Glob Change Biol* 2007;13(3):679–706.
- [92] Schaphoff S, von Bloh W, Rammig A, Thonicke K, Biemans H, Forkel M, Gerten D, Heinke J, Jaegermeyr J, Knauer J, Langewiesch F, Lucht W, Mueller C, Rolinski S, Waha K. LPJmL4-a dynamic global vegetation model with managed land-Part 1: Model description. *Geosci. Model Dev.* 2018;11:1343–75.
- [93] Fachinelli NP, Pereira AO. Impacts of sugarcane ethanol production in the Paranaíba basin water resources. *Biomass - Bioenergy* 2015;83:8–16.
- [94] Rudorff BFT, et al. Studies on the rapid expansion of sugarcane for ethanol production in São Paulo State (Brazil) using Landsat data. *Remote Sens* 2010;2(4):1057–76.
- [95] Bambini MD, Furtado AT, J Zullo Jr. Agricultural Zoning of Climatic Hazards: an instrument of Agriculture Policy in Brazil from Innovation Sociology perspective.
- [96] Newton P, et al. Overcoming barriers to low carbon agriculture and forest restoration in Brazil: the rural sustentável project. *World Dev Perspect* 2016;4:5–7.
- [97] Spera SA, et al. Land-use change affects water recycling in Brazil's last agricultural frontier. *Glob Change Biol* 2016;22(10):3405–13.
- [98] Garcia B. The Amazon from an international law perspective. Cambridge University Press; 2011.
- [99] Brown-Lima C, Cooney M, Cleary D. An overview of the Brazil-China soybean trade and its strategic implications for conservation. *Brazil: The Nature Conservancy Latin America Region. (Citing figures from the Secretariat of Foreign Trade (SECEX)) The Nature Conservancy*; 2010. p. 40.
- [100] Nepstad D, et al. Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. *Science* 2014;344(6188):1118–23.
- [101] Tollefson J. Battle for the Amazon. *Nature* 2015;520(7545):20.
- [102] Lahsen M, Bustamante MM, Dalla-Nora EL. Undervaluing and overexploiting the Brazilian Cerrado at our peril. *Environ: Sci Policy Sustain Dev* 2016;58(6):4–15.
- [103] Soares-Filho B, et al. Cracking Brazil's forest code. *Science* 2014;344(6182):363–4.
- [104] Jung S, et al. Brazil's national environmental registry of rural properties: implications for livelihoods. *Ecol Econ* 2017;136:53–61.
- [105] Azevedo AA, et al. Limits of Brazil's Forest Code as a means to end illegal deforestation. *Proc Natl Acad Sci* 2017;114(29):7653–8.
- [106] Brown DS, Brown JC, Brown C. Land occupations and deforestation in the Brazilian Amazon. *Land Use Policy* 2016;54:331–8.
- [107] Araujo C, et al. Property rights and deforestation in the Brazilian Amazon. *Ecol Econ* 2009;68(8):2461–8.
- [108] Gibbs HK, et al. Brazil's soy moratorium. *Science* 2015;347(6220):377–8.
- [109] Meijer KS. A comparative analysis of the effectiveness of four supply chain initiatives to reduce deforestation. *Tropical conservation. Science* 2015;8(2):583–97.
- [110] European Commission Better regulation Guidelines, 2015. <http://ec.europa.eu/smart-regulation/guidelines/docs/swd_br_guidelines_en.pdf>.