System Complexity and Policy Integration Challenges: the Brazilian Energy-Water-Food Nexus

J.-F. **Mercure**, M. A. **Paim**, P. **Bocquillon**, S. **Lindner**, P. **Salas**, P. **Martinelli**, I.I. **Berchin**, J.B.S.O.A. **Guerra**, C. **Derani**, C. L. **de Albuquerque Junior,** J.M.P. **Ribeiro**, F. **Knobloch**, H. **Pollitt,** N. R. **Edwards**, P. B. **Holden**, A. **Foley**, S. **Schaphoff**, R.A. **Faraco**, J. E. **Viñuales**

C-EENRG Working Papers, 2017-6

November 2017

UNIVERSITY OF CAMBRIDGE

CEENRG
Cambridge Centre for Enviroment, Energy and Natural Resource Governance

Please cite this paper as:

> J.-F. Mercure, M. A. Paim, P. Bocquillon, S. Lindner, P. Salas, P. Martinelli, I.I. Berchin, J.B.S.O.A. Guerra, C. Derani, C. L. de Albuquerque Junior, J.M.P. Ribeiro, F. Knobloch, H. Pollitt, N. R. Edwards, P. B. Holden, A. Foley, S. Schaphoff, R.A. Faraco, J. E. Viñuales. "System complexity and policy integration challenges: the Brazilian Energy-Water-Food Nexus". C-EENRG Working Papers, 2017-6. pp. 1-47. Cambridge Centre for Environment, Energy and Natural Resource Governance, University of Cambridge.

The **Cambridge Centre for Environment, Energy and Natural Resource Governance (C-EENRG)** was established in 2014 within the Department of Land Economy in order to conduct integrative research on the governance of environmental transitions, such as the climate-driven transition from a carbon-intensive inefficient energy matrix to a decarbonised and efficient one, or the water/population-driven transformation of food production systems. The role of law and governance in such transitions is of particular importance. C-EENRG approaches law as a technology to bring, guide and/or manage environment-driven societal transformations. Whereas other research groups within the University of Cambridge cover questions relating to the environment, energy and natural resources from a natural science, engineering, conservation and policy perspective, until 2014 there was no centre concentrating on the law and governance aspects of environmental transitions. C-EENRG was established to fill this gap in the policy research cycle, in line with University's strategic research initiatives on energy, conservation, global food security and public policy.

The **C-EENRG Working Papers** provide a platform to convey research aiming to support the effective governance of such environmental transitions. The series hosts research across disciplines, including law, economics, policy, and modelling, and welcomes research on a wide range of environmental topics across the food-energy-water-land nexus.

Send your enquiries regarding the C-EENRG Working Papers to the editors: Dr Pablo **Salas**, pas80@cam.ac.uk , Chung-Han **Yang**, chy26@cam.ac.uk and Paul Lohmann, pml44@cam.ac.uk

GUIDELINES FOR AUTHORS

Submit your manuscript in *.odt, *.doc, *.docx, or *.rtf format, together with a *.pdf version. It should contain title, abstract, keywords, and contact details for the lead author. Email your file to the editor. The manuscript will be processed and sent to two reviewers. The editor will process the reviewers' feedback and request the scientific committee to adopt a final decision about the publication of the manuscript.

DISCLAIMER

The opinions expressed in this working paper do not necessarily reflect the position of C-EENRG, the Department of Land Economy, or the University of Cambridge as a whole.

C-EENRG, 2017, http://www.ceenrg.landecon.cam.ac.uk/

Contents

Jean-Francois Mercure
Department of Environmental Science, Radboud University, The Netherlands

Maria Augusta Paim
Department of Land Economy, University of Cambridge, UK

Pierre Bocquillon
School of Politics, Philosophy, Language and Communication, University of East Anglia, UK

Sören Lindner
Department of Environmental Science, Radboud University, The Netherlands

Pablo Salas
Department of Land Economy, University of Cambridge, UK

Paula Martinelli
Department of Environmental Science, Radboud University, The Netherlands

Issa Ibrahim Berchin
Centre for Sustainable Development, Universidade do Sul de Santa Catarina, Brazil

José Baltazar Salgueirinho Osório de Andrade Guerra
Centre for Sustainable Development, Universidade do Sul de Santa Catarina, Brazil

Cristiane Derani
Center of Legal Sciences, Federal University of Santa Catarina, Brazil

Celso Lopes de Albuquerque Junior
Centre for Sustainable Development, Universidade do Sul de Santa Catarina, Brazil

João Marcelo Pereira Ribeiro
Centre for Sustainable Development, Universidade do Sul de Santa Catarina, Brazil

Florian Knobloch
Department of Environmental Science, Radboud University, The Netherlands

Hector Pollitt
Cambridge Econometrics Ltd, UK

Neil Robert Edwards
School of Environment, Earth and Ecosystem Sciences, The Open University, UK

Phil Bernard Holden
School of Environment, Earth and Ecosystem Sciences, The Open University, UK

Aideen Foley
Department of Geography, University of London, UK

Sibyll Schaphoff
Potsdam Institute for Climate Impact Research, Germany

Rafael Ávila Faraco
Centre for Sustainable Development, Universidade do Sul de Santa Catarina, Brazil

Jorge E. Viñuales
Department of Land Economy, University of Cambridge, UK

Contact:
Dr Jean-Francois Mercure
Department of Environmental Science
Radboud University
Nijmegen, The Netherlands
J.Mercure@science.ru.nl
Tel: +31 24 36 53256

System Complexity and Policy Integration Challenges: the Brazilian Energy-Water-Food Nexus

J.-F. Mercure, M. A. Paim, P. Bocquillon, S. Lindner, P. Salas, P. Martinelli, I.I. Berchin, J.B.S.O.A. Guerra, C. Derani, C. L. de Albuquerque Junior, J.M.P. Ribeiro, F. Knobloch, H. Pollitt, N. R. Edwards, P. B. Holden, A. Foley, S. Schaphoff, R.A. Faraco, J. E. Viñuales

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 survey current scientific and economic knowledge, and existing policy, 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 on the need to adjust the scientific approach to these challenges as an enabling condition for stronger science-policy bridges for sustainability policy-making.

Keywords*: Science-based policy; water scarcity; climate change; ILUC; biofuels; food security*

JEL codes: *Q15; Q18; Q25; Q27; Q54*

System Complexity and Policy Integration Challenges: the Brazilian Energy-Water-Food Nexus

J.-F. Mercure, M. A. Paim, P. Bocquillon, S. Lindner, P. Salas, P. Martinelli, I.I. Berchin, J.B.S.O.A. Guerra, C. Derani, C. L. de Albuquerque Junior, J.M.P.Ribeiro, F. Knobloch, H. Pollitt, N. R. Edwards, P. B. Holden, A. Foley, S. Schaphoff, R.A. Faraco, J. E. Viñuales

1. INTRODUCTION

Income growth, industrialisation, economic change and globalisation are bringing the 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, 5). 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 6, 7-9). 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 attributes typically characteristic of so-called 'wicked' problems (10): 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 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' (10), 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 (11). On the other, it is an economy highly driven by and tied to global economic change, through exports of agricultural and energy commodities. Both of these drive environmental degradation and social challenges, at all scales of analysis, which is 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 reaching tipping points in Brazil could have far-reaching consequences across the world: for the global climate system (12, 13), food supplies (14) and land-use change emissions (15).

Nexus governance can be supported by robust science, but robust science does not automatically lead to effective policy implementation (7). Engineering-oriented views (5, 6, 16) focus on searching for optimal policy solutions in order to internalise system-wide externalities, maximise system efficiency and minimise waste. This approach suggests that it would be possible to have sufficiently good models to optimise the Nexus (8). But complexity science warns of the dangers in such assumptions. Indeed, complex interactions may lead to new and unpredictable phenomena (17). 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 optimize such a complex system. Moreover, overreliance on optimization has the effect of downplaying path-dependent phenomena, such as behavioural feedbacks on technology uptake, despite their practical importance (17). Furthermore, such paths (representing developmental, technological and socio-political histories) are 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 a front-runner 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 (8)), 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.

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 illustrating 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, further described 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.

2. REVIEW OF THE GENERAL CONTEXT

2.1 Global and local environmental change

Current trajectories of greenhouse gas (GHG) emissions are leading the planet towards somewhere between 3 and 6 degrees warming, unless stringent mitigation policies are adopted worldwide (18). These emission trajectories imply changes in average temperatures and rainfall that are un-evenly 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 over its territory.

Figure 1 shows maps of changes in mean temperatures and rainfall in Brazil for high and low emissions scenarios (RCPs 2.6 and 8.5). In a scenario of continued high global emissions, temperature changes of up to 3°C (winter) and 6°C (summer) 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 (19, 20).

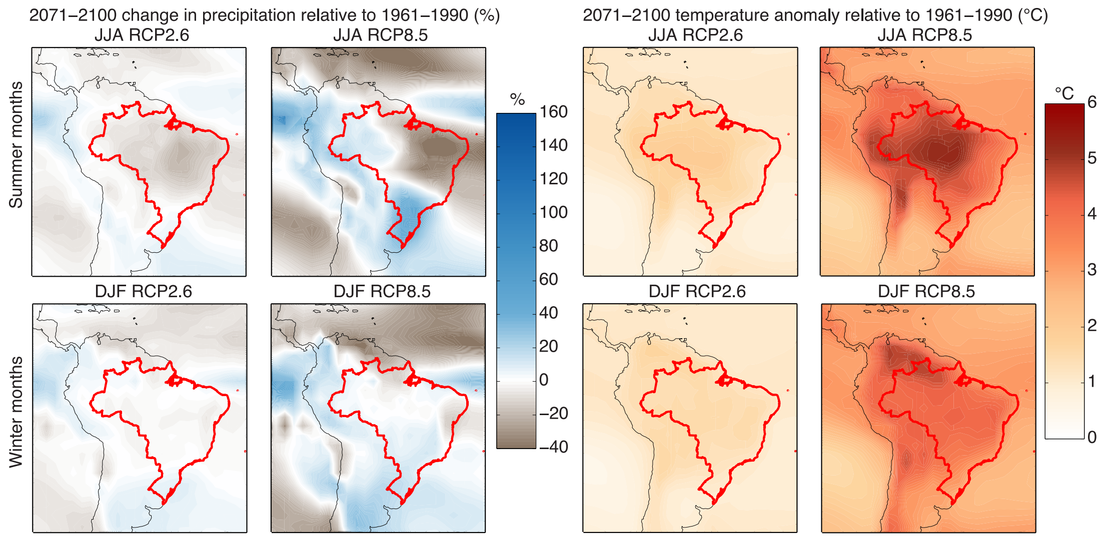

Figure 1: Changes in annual average rainfall (as a % change to annual averages) and mean temperature, in the summer (top panels) and the winter (bottom panels), for low cumulative global GHG emissions (left panels) and high cumulative emissions (right panels). In scenarios of high emissions, temperature 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.

These patterns of weather change and warming are uncertain but well studied (21, 22). Brazil has recently faced several droughts, and there is evidence suggesting that changing patterns of rainfall lead to reduced river flows in several Brazilian catchment areas (23-26). The Brazilian rainforest is particularly sensitive to drought events (22). A self-reinforcing interaction exists between temperature change, drying, forest fires, deforestation and a collapse of the Amazonian rainforest (27, 28). In particular, drought-fire interactions generate one of the possible tipping points (12). However, tipping points come about through a combination of direct (e.g. LUC) and indirect (e.g. climate change) anthropogenic factors (28).

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 (29). 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 (30, 31). During the drought period, the regional atmospheric circulation was blocked by a high-pressure system in the mid-troposphere (32, 33). 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 (34) and/or evolve (35). In Brazil, this phenomenon affects agricultural activities, as land productivity changes with the climate (36), 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, this alters Brazilian society itself. 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.

2.2 Global economic change driving environmental degradation

The Brazilian economy benefits from lucrative exports of agricultural and food products. These account for over one third of total Brazilian exports making Brazil one of the countries with highest export shares in that sector (Figure 2a). These goods have traditionally accounted for a major component of Brazilian exports (Figure 2b) and their production employs a significant portion of the entire Brazilian labour force (Figure 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 highly driven by economic growth in other large emerging economies (37). 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 28), a phenomenon often involving indirect land-use change (ILUC).

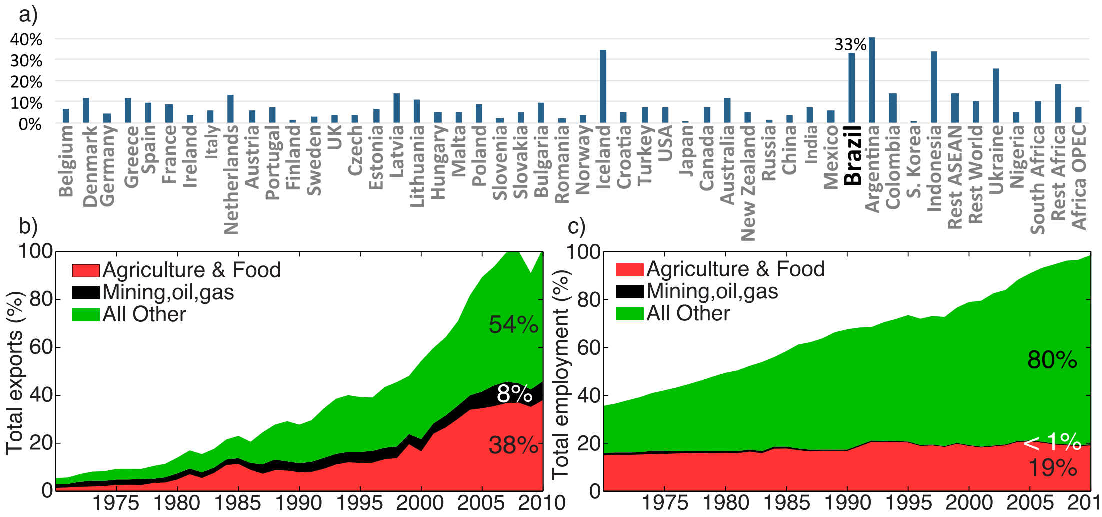

Figure 2: (a) Current share of total exports made of agricultural products and food by country (33% for Brazil). (b) Total exports made of agricultural products and food, normalised to 2010. (c) Employment devoted to agriculture and food production, normalised to 2010. Data from Eurostat, OECD, national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

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 (38, 39). In Brazil, this typically involves a hierarchy of production associated to land productivity, where the most productive land is converted to produce new lucrative crops for exports (e.g. soybeans, sugar cane), displacing cattle farming, which itself moves to occupy other areas which are deforested to be put to use (39-41). 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 (42). Intensification and commoditisation of agriculture also contributed to reduced rates of deforestation (42). However, the deforestation in the Amazon has increased again from August 2015 to July 2016. Over the last 30 years the Cerrado has lost 46% of its native vegetation cover. Deforestation is likely to continue mostly because it is linked to the growth of global markets for agricultural commodities, mediated by prices, and made possible by globalisation, giving rise to high incentives for the agribusiness to acquire new land in Brazil (37).

Agricultural products, grown either as feedstock for biofuel production or to feed animals, contribute to this phenomenon (28, 40, 43, 44). Under climate change mitigation policy following the Paris Agreement, global markets for biofuels are virtually unbounded (45). Meanwhile, under growing affluence and increasingly meat-intense diets in middle-income countries, global markets for soy as animal feed can become very large (discussed below, Fig. 4). Concerns over the sustainability of biofuel mandates have raised sufficient concern in Europe to revise this policy trajectory (see e.g. 46), but this may not necessarily deter policy-makers in other large economies. Indeed, despite sustainability concerns (40, 44, 47), biofuels remain a key component of the national strategy of many countries to mitigate climate change (46, 48). Thus a large global market for liquid biofuels for transport could be expected to emerge by 2050 (49).

Estimates of the world's carrying capacity for biofuels production (50-53), 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 (37). Brazil will very likely face this intricate problem.

2.3 Overview of the domestic policy landscape addressing the nexus in Brazil

It is clear that climate change impacts combined to an increasing global demand 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 organized 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, to encourage farmers to adopt renewable energy sources and to promote the sustainable and efficient use of water resources; (ii) in the energy sector, to assess the interactions between adaptive measures for water, energy and land use; and (iii) in the water sector, to integrate the 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).

Other examples exist of Nexus legislation in Brazil. The 2013 National Policy on Integration of Farming, Livestock and Forestry (Law N. 12.805 – SI.5) is designed to mitigate deforestation, support best practices to develop these sectors in a sustainable manner, and contribute to the recovery of degraded areas, including through the certification of products. The 2013 National Irrigation Policy (Law N. 12.787 – SI.6) 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. The 2015 Law on Renegotiation of the Hydrological Risk for the electric power generation (Law N. 13.203 – SI.7) is an instrument with which, in case of droughts, hydropower companies can obtain protection by buying and stocking renewable energy through reserve energy auctions. These examples notwithstanding, Nexus challenges are only partially taken into account in the relevant governing frameworks, when they are at all.

2.4 International law and policy influencing the nexus in Brazil

Measures also exist in Brazil at the supply-chain governance level in relation to the rest of the world, to improve sustainability in agricultural commodity production. These measures include the regulation of access to global markets by certain products or incentives. This includes certification requirements for producers to respect certain 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 members (54).

Furthermore, the global finance mechanism REDD+[1], 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 (55).

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 salient[2] 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) the Energy-Water-Food simultaneous 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. Using a literature review, primary data for descriptive purposes, biophysical model data, legal and policy mapping based mainly on secondary literature and legislative and policy documents, we define and apply a Nexus lens to observe the dynamics of these problems and derive common patterns. We use these common patterns to formulate more specifically the core components of a Nexus approach to science-informed

[1] "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"

[2] We note that several more Nexus linkages exist and could be covered, but we cannot do so within space constraints.

policy-making. The goal of this paper is to lay down the foundations of a Nexus research agenda,[3] 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 (18, 26). A water crisis has emerged in recent years, which has resulted in record low levels in hydroelectric dam reservoirs (25, 27). Persistent drought has also affected agriculture in the North-East region (23). In the São Paulo region, where 10% of the Brazilian population live and one third of GDP is produced, water scarcity from 2014 to 2015 generated both electricity blackouts and a drinking water crisis leading to the rationing of both (27). 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 (56).

The Brazilian electricity system is largely based on hydroelectricity (>75% 57), making it low-carbon, but also vulnerable to changes in climate and rainfall (58, 59). The Brazilian electricity system features 220 hydroelectric dams (MME, June/2017 – SI.10), one of the largest systems in the world (60). The vast majority of the large-scale generators (97%) 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 (58). These projections place constraints on what the composition of a future Brazilian electricity sector can be, and technological diversification appears inevitable. This is challenging if the objective is to simultaneously maintain low CO2 emissions,

[3] For 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://bridgeproject.net and http://gtr.rcuk.ac.uk/projects?ref=ES/N013174/1

although non-hydro renewables could contribute to alleviate pressure on water resources (61).

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 62). 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 (63). This suggests a large potential for efficiency improvements in the Nexus that can be realized by targeted policies.[4] But also, the "energy efficiency gap" unveiled an underlying "water efficiency gap" (64).

Despite these known issues, hydropower projects continue to obtain the go-ahead from authorities. Most new dam projects are in the Amazon basin, where most of Brazil's remaining hydroelectric potential lies (Plano Decenal de Energia – PDE, Ten Year Plan 2024 – SI.11), demanding comparatively large investments to connect these to the transmission grid, with environmental impacts associated to flooding areas of rich biodiversity and often under indigenous occupation. The implementation of the Belo Monte hydropower power plant offers a good illustration of the emerging complexity (65).

In 2002, the 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, divided in two stages. The first stage established the target to generate of 3,300MW from renewable

[4] Energy efficiency is integral part of Brazilian policy, for instance: Procel (1985); National Programme for the Energy Efficiency, requiring the distributors to invest a percentage of their revenues to reduce power grid losses; Law 10.295/2001 - Law for the Energy Efficiency and its Decree 10.295/2001; and the National Plan for the Energy Efficiency (2011). According to the government, these policies have resulted in investments on 1704 projects from 2008-2016 (R$5 Billions) that could (potentially) save 4.6 GWh (http://www.brasil.gov.br/economia-e-emprego/2016/10/projetos-de-eficiencia-energetica-economizam-4-6-gwh). However, reports demonstrate that over the last 3 years Brazil has lost 143,647 GWh (1.4 times the volume of all the energy produced by Itaipu 2016, equivalent to R$ 61.71 billion), including technical losses in electricity transmission and distribution, energy theft and measurement errors (http://www.abesco.com.br/pt/novidade/desperdicio-de-energia-atinge-r-617-bi-em-tres-anos/). In 2016, Brazil was evaluated as the second worst in the ACEEE's international energy efficiency ranking of major economies: http://aceee.org/sites/default/files/pdf/country/2016/brazil.pdf.

energy through a system of subsidies and incentives. The second stage set the target to increase the renewable sources energy to 10% of annual consumption within 20 years. This phase was due to come into force after the target capacity of the first stage was concluded but it was subsequently replaced by the regulator ANEEL's energy auctions.

Current long-term power planning in Brazil nevertheless reserves a disproportionate role for large hydropower systems, which maintains existing risks for water and energy availability. It remains comparatively less ambitious with non-hydro renewables, overlooking Brazil's vast potential for low-cost solar and wind resources. On the other hand, 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". However, the NAP does not indicate how this goal is to become operative in the context of long-term power plans oriented towards the expansion of hydroelectricity. Meanwhile, water policy establishment of 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. S1). 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 (Fig. 4). 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 and lead to food price volatility as well as restrict access to food (e.g. 28, 42, 44, 47). These studies primarily emphasise the effects of ILUC (38, 39) 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. 45, 66, 67).

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 (67)[5], 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)(68). 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) (69). Land requirements for biofuel feedstocks are of between 20.2 and 2.3 ha/1000GJ (soybeans and sugarcane) (70). Thus, between <37 EJ and <2 EJ of bioenergy can be produced in Brazil. 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 (71-74). 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 (44, 47).

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

---

[5] Own calculations with the model E3ME-FTT-GENIE1. 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.

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).[6] 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, Pantanal and Alto Paraguai Basin biomes; and others (e.g. indigenous land, conservation areas). It prioritizes expansion in under-used areas, areas occupied by livestock and degraded pastures (75). 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 – damaging to the environment – and to replace it with mechanical harvesting (76).[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 reducing significantly emissions of particles with harmful impacts on health, GHG emissions, as well as water consumption.

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 (76, 77). 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.15), and the Round Table on

[6] A similar ecological zoning was also adopted for palm oil by decree in 2010 (Decree 7172/2010).

[7] The targets are 2014 for declivity $< 12\%$; and 2017 for declivity $> 12\%$.

Responsible Soy (RTRS – SI.16). However, uptake has been uneven (78) 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 address adequately 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).

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 (23, 79), while lands in the South are likely to suffer from more frequent flooding and erosion (80). A tipping point involving the collapse of the Amazon through droughts and fires may also exist (21, 26, 81). Inhabitants of the North-East of Brazil (the Caatinga) traditionally cope with frequent droughts (23), but this area could undergo desertification as a result of climate change. Under scenarios of collapse of land productivity, people migrate (82), 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 (83). Climate change will lead to substantial regional economic losses for the North-East and other areas (84).

The effects of climate change will likely push maize, soybeans and sugarcane grown over much of the territory to migrate, as land productivity evolves (Figure 3). Land productivity simulations 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 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, and currently expanding to drier areas in the North where irrigation is required (86, 87); would become difficult in most of its current area of cultivation. Finally, pastures could also be displaced from their traditional southern heartland.

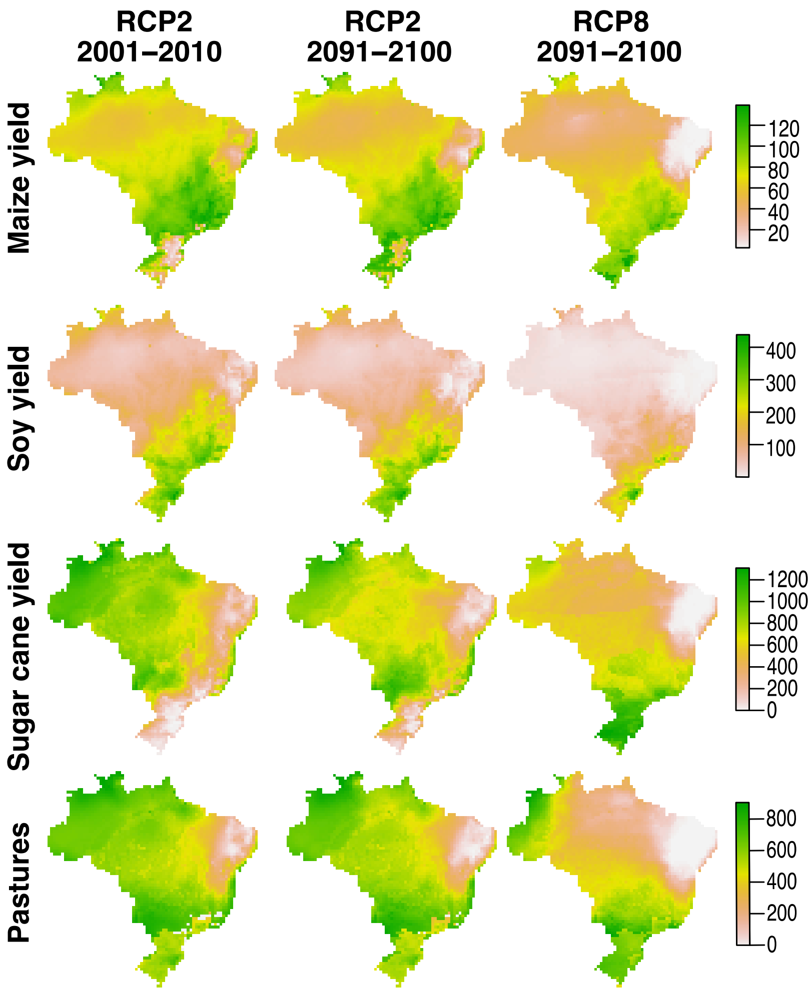

Figure 3: Simulated future productivity across Brazil under climate change for various land-uses in comparison to the 2001-2010 decade. Colour bar units are in units of gC/m2, where high productivity is represented by dark green colours and low productivity grey-white. The data were generated by the LPJml4 model (85).

Brazil has experience in designing policies to deal with the effects of climate variability on the farming sector. Three of them deserve particular note. First, in 1996, the Agricultural Climate-Risk Zoning (ZARC – Zoneamento Agrícola de Risco Climático – SI.17) 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 (88). 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.

Second, 2011 saw the development of the Low-Carbon (ABC) Plan (SI.18) (as part of Brazil's NPCC) to reduce agricultural GHG emissions, which 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 in order (i) to increase the efficiency and resilience of agro-ecosystems, (ii) to maintain productivity under biotic and abiotic climate change pressures, (iii) to foster the sustainable and integrated uses of water and soil, and (iv) to consider the climate modelling of different agricultural systems. Of note is the establishment of the Programme of Climate Intelligence in Agriculture, which is tasked with the identification of vulnerabilities and the mapping of areas vulnerable to climate risks, and the development of an integrated Climate Alert System. 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 (89).

The third measure is the integration into the NAP of official insurance programmes previously in force to minimize risks associated with agricultural production, such as the Agricultural Activity Guarantee Programme (PROAGRO) and the Family Agricultural Activity Guarantee Programme (PROAGRO-Mais) (SI.19), which insured farmers against the commodity-price variations and harvest failures caused by climate events.

Projected climate variations call for further agricultural risk-management policies. Some steps have been taken to integrate climate 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 (29, 31, 90).

[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.

3.5 Energy-Water-Food – indirect land-use change and deforestation

The deforestation of the Amazon was initially attributed, besides infrastructure extension and selective logging (91), to the expansion of the cattle and the soy industries (41). Deforestation was shown to be statistically related to changes in the international price of soy (41). 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 (28, 38, 39). 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 (42). 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 (Fig. 5, see 92). China imports over half of Brazil's production of soybeans to supply fast growing pork and poultry industries (Fig. S2), for direct human consumption of derivatives (oil, flour, etc), and as feedstocks 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, partly as a result of its water shortages. Increasing desertification in areas previously used to grow this crop has indirectly transferred production to Brazil (92). 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 (86). 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 (40).

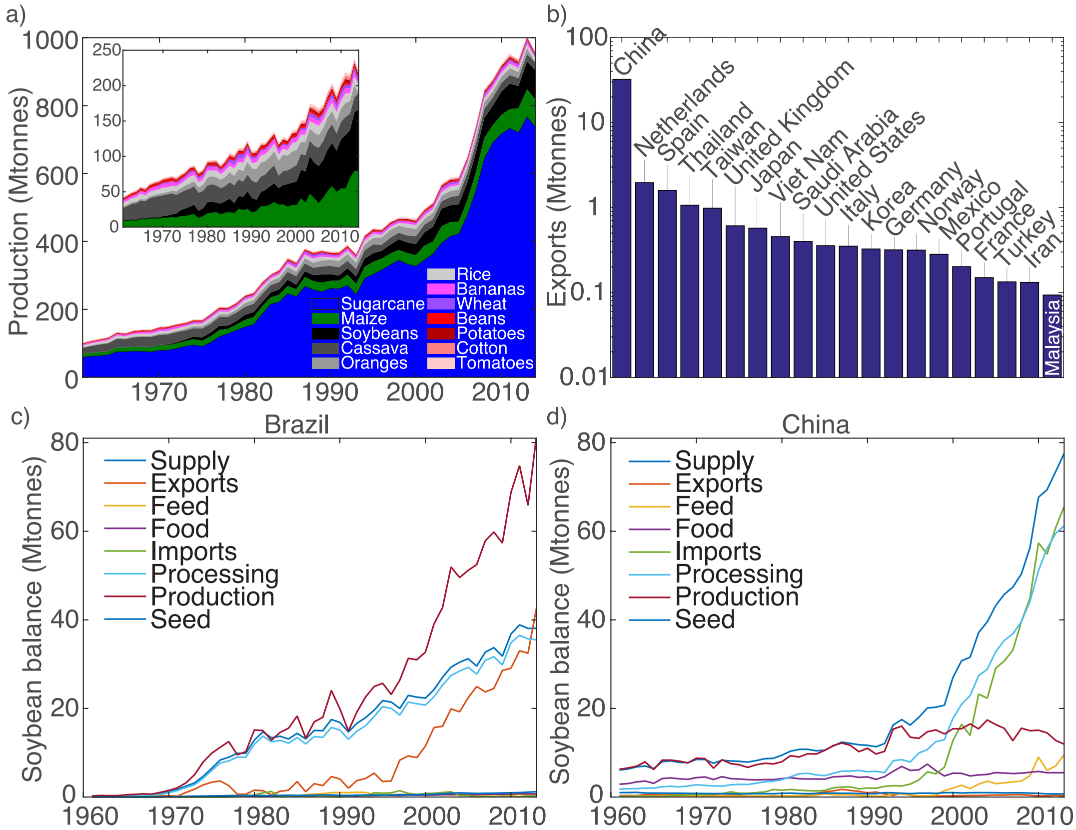

Figure 4: a) Main crops produced in Brazil. The inset shows the same data for clarity. b) Main export destinations for soybeans. c-d) Balance of soybeans in Brazil and China. The 'domestic supply' equals 'production' plus 'imports' minus 'exports', while 'food' denotes domestic consumption as food. 'Feed' 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 (see **Figure SI1** in Supplementary Information). Data from FAOSTAT 2017.

From 2004 to 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.20 and 21) 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.22) and beef produced on recently deforested land and steps to meet technical standards in foreign markets (42, 93, 94), including a certificate system for sustainable soy, managed by the Roundtable for Responsible Soy (SI.16), which issued the first soy certificate in 2011. 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 almost half of its native vegetation, mainly due to forest fires (natural and human-made), agriculture and cattle rearing (95). 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.23). However, although the Brazilian government has expressed the intention to extend the moratoria on soy and beef to the Cerrado (MMA, 2016 – SI.24), so far it remains restricted to the Amazon.

The Forest Code enacted in 2012 (SI.25) 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 (96) 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 the 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 portion of the Cerrado within the Legal Amazon). The Forest Code also forbids the clearing of sensitive areas such as primary vegetation on steep slopes and along the margins of rivers and streams, classified as Permanent Protected Areas (PPA).

The Forest Code establishes new mechanisms to improve the conservation of forests, amongst which the Environmental Rural Register (CAR) is expected to enhance monitoring, environmental and economic planning, and enforcement of the environmental legislation against deforestation (97). The CAR is a national public electronic registry, mandatory for all rural properties, with the aim to gather environmental information. 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.

Yet, it is not clear whether these measures for reduction in deforestation are sufficient, given that the 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 (98). A long-standing problem of property rights exists in remote areas (42). 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 (99). Landowners clear forest for pasture or agriculture, as evidence of productivity to avoid risk of confiscation and redistribution amongst squatters (100). Clearing forest is also a strategy used by landowners to protect the land from illegal occupation by squatters (100), leading to both a tragedy of the commons effect and challenges to law enforcement (42).

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 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 (97). 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 and 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 (101). The supply-chain

[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.

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 (102).

4. DISCUSSION AND CONCLUDING REMARKS

Although Brazil has to some extent responded to Nexus challenges, such measures do not fully address the complex interconnections within 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. Table 1 summarises the Nexus challenges surveyed in this article. Albeit not exhaustive, it 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 (17). 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 ways sometimes unpredictable. 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.

Case Study	**Challenges**		
	Environmental	**Socio-economic**	**Policy**
W-E: Hydro-electricity	• Water scarcity • Competition among users • Reserve thermoelectric plants increase GHG emissions • Dam projects in the Amazon affect biodiversity and indigenous land.	• Energy security • Overreliance on hydroelectricity • Diversification of the energy matrix, increasing non-hydro renewable • Investment in new capacity, due to increasing energy demand	• Improving policy-coherence • Incorporating climate change impacts in long-term energy planning • Reducing reliance on water resources in long-term energy planning • Elaborating plan for high potential renewables
E-F: Biofuels	• Crop expansion beyond traditional areas • ILUC • Water use • Unsustainable agricultural practices including sugarcane burning for manual harvesting	• Biofuel crops displace food crops • ILUC leading to deforestation • Competition for land can threaten food security (non-cash crops)	• 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	• Rise in frequency of extreme weather events, floods, droughts • Changes in temperature and rain patterns affect crop yield	• Changes in land productivity produce crop and people migration and changes in agricultural output	• Adapting existing policies (e.g., ZARC), and creating new policies, that incorporate climate change uncertainty and risk management
E-W-F: Deforestation	• Deforestation • Land degradation • Potential Amazon collapse	• Expansion of soy plantations • Displacement of pastures • ILUC leading to deforestation • Unclear or absent property rights • Land grabbing	• 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

Table 1: Summary of Nexus challenges in Brazil

5. ACKNOWLEDGEMENTS

This paper inaugurates the BRIDGE project by framing the boundaries of the Brazilian Nexus. BRIDGE (http://bridgeproject.net) 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 Horizon2020 (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. JFM coordinated the work, supported by JEV, JFM and PB designed the paper, all authors contributed to the text and/or data.

6. REFERENCES

1. Beddington J (2012) Food, energy, water and the climate: a perfect storm of global events? Journal http://webarchive.nationalarchives.gov.uk/20121206120858/http://www.bis.gov.uk/assets/goscience/docs/p/perfect-storm-paper.pdf.
2. Rockström J, *et al.* (2009) A safe operating space for humanity. *nature* 461(7263):472-475.
3. Steffen W, *et al.* (2015) Planetary boundaries: Guiding human development on a changing planet. *Science* 347(6223):1259855.
4. Hertel TW (2015) The challenges of sustainably feeding a growing planet. *Food Security* 7(2):185-198.
5. Hoff H (2011) Understanding the Nexus. Background Paper for the Bonn2011 Conference: The Water Energy and Food Security Nexus. . Journal http://wef-conference.gwsp.org/fileadmin/documents_news/understanding_the_nexus.pdf.
6. Bazilian M, *et al.* (2011) Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy* 39(12):7896-7906.
7. Kurian M (2017) The water-energy-food nexus: Trade-offs, thresholds and transdisciplinary approaches to sustainable development. *Environmental Science & Policy* 68:97-106.

8. Leck H, Conway D, Bradshaw M, & Rees J (2015) Tracing the water–energy–food nexus: description, theory and practice. *Geography Compass* 9(8):445-460.
9. Weitz N, Strambo C, Kemp-Benedict E, & Nilsson M (2017) Closing the governance gaps in the water-energy-food nexus: Insights from integrative governance. *Global Environmental Change* 45:165-173.
10. Rittel HW & Webber MM (1973) Dilemmas in a general theory of planning. *Policy sciences* 4(2):155-169.
11. Stocker T*, et al.* (2013) *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).
12. Brando PM*, et al.* (2014) Abrupt increases in Amazonian tree mortality due to drought-fire interactions. *P Natl Acad Sci USA* 111(17):6347-6352.
13. Lenton TM*, et al.* (2008) Tipping elements in the Earth's climate system. *Proceedings of the national Academy of Sciences* 105(6):1786-1793.
14. Piesse J & Thirtle C (2009) Three bubbles and a panic: An explanatory review of recent food commodity price events. *Food Policy* 34(2):119-129.
15. Baccini A*, et al.* (2012) Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nat Clim Change* 2(3):182-185.
16. Bajželj B*, et al.* (2014) Importance of food-demand management for climate mitigation. *Nat Clim Change* 4(10):924-929.
17. Mercure J-F, Pollitt H, Bassi AM, Viñuales JE, & Edwards NR (2016) Modelling complex systems of heterogeneous agents to better design sustainability transitions policy. *Global Environmental Change* 37:102-115.
18. IPCC (2014) *Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change* (Cambridge University Press).
19. Christensen JH, B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr, P. Whetton (2007) Regional Climate Projections. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate*

Change, ed Solomon S, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (Cambridge University Press, Cambridge).

20. Christensen JH, K. Krishna Kumar, E. Aldrian, S.-I. An, I.F.A. Cavalcanti, M. de Castro, W. Dong, P. Goswami, A. Hall, J.K. Kanyanga, A. Kitoh, J. Kossin, N.-C. Lau, J. Renwick, D.B. Stephenson, S.-P. Xie, T. Zhou (2013) Climate Phenomena and their Relevance for Future Regional Climate Change. *Climate Change 2013: The Physical Sci- ence Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed Stocker TF, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P.M. Midgley (Cambridge University Press, Cambridge).
21. Malhi Y*, et al.* (2008) Climate change, deforestation, and the fate of the Amazon. *science* 319(5860):169-172.
22. Phillips OL*, et al.* (2009) Drought Sensitivity of the Amazon Rainforest. *Science* 323(5919):1344-1347.
23. Marengo JA & Bernasconi M (2015) Regional differences in aridity/drought conditions over Northeast Brazil: present state and future projections. *Climatic Change* 129(1-2):103-115.
24. Lewis SL, Brando PM, Phillips OL, van der Heijden GMF, & Nepstad D (2011) The 2010 Amazon Drought. *Science* 331(6017):554-554.
25. Escobar H (2015) Water security. Drought triggers alarms in Brazil's biggest metropolis. *Science* 347(6224):812.
26. Davidson EA*, et al.* (2012) The Amazon basin in transition. *Nature* 481(7381):321-328.
27. Nobre CA*, et al.* (2016) Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. *P Natl Acad Sci USA* 113(39):10759-10768.
28. Nepstad DC, Stickler CM, Soares B, & Merry F (2008) Interactions among Amazon land use, forests and climate: prospects for a near-term forest tipping point. *Philos T R Soc B* 363(1498):1737-1746.
29. Marengo JA, Tomasella J, Alves LM, Soares WR, & Rodriguez DA (2011) The drought of 2010 in the context of historical droughts in the Amazon region. *Geophys Res Lett* 38(12).
30. Fearnside PM (2005) Deforestation in Brazilian Amazonia: history, rates, and consequences. *Conserv Biol* 19(3):680-688.
31. Zemp DC*, et al.* (2017) Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks. *Nature Communications* 8:14681.
32. Marengo JA, Williams ER, Alves LM, Soares WR, & Rodriguez DA (2016) Extreme seasonal climate variations in the Amazon basin:

droughts and floods. *Interactions Between Biosphere, Atmosphere and Human Land Use in the Amazon Basin*, (Springer), pp 55-76.

33. Nobre CA, Marengo JA, Seluchi ME, Cuartas LA, & Alves LM (2016) Some characteristics and impacts of the drought and water crisis in Southeastern Brazil during 2014 and 2015. *Journal of Water Resource and Protection* 8(02):252.
34. Burrows MT*, et al.* (2011) The Pace of Shifting Climate in Marine and Terrestrial Ecosystems. *Science* 334(6056):652-655.
35. Jump AS & Penuelas J (2005) Running to stand still: adaptation and the response of plants to rapid climate change. *Ecol Lett* 8(9):1010-1020.
36. Wheeler T & von Braun J (2013) Climate Change Impacts on Global Food Security. *Science* 341(6145):508-513.
37. Lambin EF & Meyfroidt P (2011) Global land use change, economic globalization, and the looming land scarcity. *P Natl Acad Sci USA* 108(9):3465-3472.
38. Barona E, Ramankutty N, Hyman G, & Coomes OT (2010) The role of pasture and soybean in deforestation of the Brazilian Amazon. *Environ Res Lett* 5(2).
39. Arima EY, Richards P, Walker R, & Caldas MM (2011) Statistical confirmation of indirect land use change in the Brazilian Amazon. *Environ Res Lett* 6(2).
40. Lapola DM*, et al.* (2010) Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *P Natl Acad Sci USA* 107(8):3388-3393.
41. Morton DC*, et al.* (2006) Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. *P Natl Acad Sci USA* 103(39):14637-14641.
42. Lapola DM*, et al.* (2014) Pervasive transition of the Brazilian land-use system. *Nat Clim Change* 4(1):27-35.
43. Nepstad DC, Stickler CM, & Almeida OT (2006) Globalization of the Amazon soy and beef industries: Opportunities for conservation. *Conserv Biol* 20(6):1595-1603.
44. Searchinger T*, et al.* (2008) Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 319(5867):1238-1240.
45. IPCC (2014) Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press, Cambridge, UK and New York, NY.*

46. Bowyer C & Kretschmer B (2010) 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 (March 2011)*:8-9.
47. Fargione J, Hill J, Tilman D, Polasky S, & Hawthorne P (2008) Land clearing and the biofuel carbon debt. *Science* 319(5867):1235-1238.
48. Harvey M & Pilgrim S (2011) The new competition for land: Food, energy, and climate change. *Food Policy* 36:S40-S51.
49. IEA (2015) *IEA World Energy Outlook* (OECD/IEA).
50. Hoogwijk M, Faaij A, de Vries B, & Turkenburg W (2009) 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 Bioenerg* 33(1):26-43.
51. Smeets EMW, Faaij APC, Lewandowski IM, & Turkenburg WC (2007) A bottom-up assessment and review of global bio-energy potentials to 2050. *Prog Energ Combust* 33(1):56-106.
52. Mercure JF & Salas P (2012) An assessement of global energy resource economic potentials. *Energy* 46(1):322-336.
53. GEA (2012) Global Energy Assessment—toward a sustainable future. *Cambridge, UK, and Laxenburg, Austria: Cambridge University Press and the International Institute for Applied Systems Analysis.*
54. Newton P, Agrawal A, & Wollenberg L (2013) Enhancing the sustainability of commodity supply chains in tropical forest and agricultural landscapes. *Global Environmental Change* 23(6):1761-1772.
55. Lima MGB, Visseren-Hamakers IJ, Braña-Varela J, & Gupta A (2017) A reality check on the landscape approach to REDD+: Lessons from Latin America. *Forest Policy and Economics* 78:10-20.
56. Benjamin AH, Marques CL, & Tinker C (2004) The water giant awakes: an overview of water law in Brazil. *Tex L. Rev.* 83:2185.
57. IEA (2017) *IEA World Energy Balances dataset* (OECD/IEA).
58. De Lucena AFP*, et al.* (2009) The vulnerability of renewable energy to climate change in Brazil. *Energy Policy* 37(3):879-889.
59. Prado FA*, et al.* (2016) How much is enough? An integrated examination of energy security, economic growth and climate change related to hydropower expansion in Brazil. *Renewable and Sustainable Energy Reviews* 53:1132-1136.
60. da Silva Soito JL & Freitas MAV (2011) Amazon and the expansion of hydropower in Brazil: Vulnerability, impacts and possibilities for adaptation to global climate change. *Renewable and Sustainable Energy Reviews* 15(6):3165-3177.

61. da Silva RC, de Marchi Neto I, & Seifert SS (2016) Electricity supply security and the future role of renewable energy sources in Brazil. *Renewable and Sustainable Energy Reviews* 59:328-341.
62. Maurer L, Pereira M, & Rosenblatt J (2005) Implementing power rationing in a sensible way: lessons learned and international best practices.
63. Costa F (2013) Can Rationing Affect Long Run Behavior? Evidence from Brazil. *SSRN*.
64. Lynham J & Tarui N (2014) What can water demand programs learn from electricity demand programs? *Routledge Handbook of Water Economics and Institutions*:201.
65. Berchin II*, et al.* (2015) Energy production and sustainability: A study of Belo Monte hydroelectric power plant. *Natural Resources Forum*, (Wiley Online Library), pp 224-237.
66. Rose SK*, et al.* (2014) Bioenergy in energy transformation and climate management. *Climatic Change* 123(3-4):477-493.
67. Mercure J-F, Lam A, Billington S, & Pollitt H (2017) Integrated assessment modelling as a positive science: modelling policy impacts in road transport to meet a climate target well below 2C. *arXiv:1702.04133*.
68. Adami M*, et al.* (2012) Remote sensing time series to evaluate direct land use change of recent expanded sugarcane crop in Brazil. *Sustainability* 4(4):574-585.
69. Lossau S*, et al.* (2015) Brazil's current and future land balances: Is there residual land for bioenergy production? *Biomass and Bioenergy* 81:452-461.
70. Miller SA (2010) Minimizing land use and nitrogen intensity of bioenergy. *Environmental science & technology* 44(10):3932-3939.
71. Garcez CAG & de Souza Vianna JN (2009) Brazilian biodiesel policy: social and environmental considerations of sustainability. *Energy* 34(5):645-654.
72. La Rovere EL, Pereira AS, & Simões AF (2011) Biofuels and sustainable energy development in Brazil. *World Development* 39(6):1026-1036.
73. Wilkinson J & Herrera S (2010) Biofuels in Brazil: debates and impacts. *The Journal of Peasant Studies* 37(4):749-768.
74. Moreira JR & Goldemberg J (1999) The alcohol program. *Energy policy* 27(4):229-245.
75. EMBRAPA SOLOS (2009) Agro-ecological Zoning of Sugarcane. Zoneamento Agro-ecológico da Cana-de-açucar. *Documentos Embrapa Solos*.

76. Janssen R & Rutz DD (2011) Sustainability of biofuels in Latin America: risks and opportunities. *Energy Policy* 39(10):5717-5725.
77. Scarlat N & Dallemand J-F (2011) Recent developments of biofuels/bioenergy sustainability certification: A global overview. *Energy Policy* 39(3):1630-1646.
78. Schleifer P (2016) Private regulation and global economic change: The drivers of sustainable agriculture in Brazil. *Governance*.
79. Marengo JA*, et al.* (2013) Two contrasting severe seasonal extremes in tropical South America in 2012: flood in Amazonia and drought in northeast Brazil. *J Climate* 26(22):9137-9154.
80. Barros VR, Garavaglia CR, & Doyle ME (2013) Twenty-first century projections of extreme precipitations in the Plata Basin. *International Journal of River Basin Management* 11(4):373-387.
81. Cook B, Zeng N, & Yoon J-H (2012) Will Amazonia dry out? Magnitude and causes of change from IPCC climate model projections. *Earth Interactions* 16(3):1-27.
82. Barbieri AF*, et al.* (2010) Climate change and population migration in Brazil's Northeast: scenarios for 2025–2050. *Population and environment* 31(5):344-370.
83. Confalonieri UE, Lima ACL, Brito I, & Quintão AF (2014) Social, environmental and health vulnerability to climate change in the Brazilian Northeastern Region. *Climatic Change* 127(1):123-137.
84. de Souza Ferreira Filho JB & De Moraes GI (2015) Climate change, agriculture and economic effects on different regions of Brazil. *Environment and Development Economics* 20(1):37-56.
85. Bondeau A*, et al.* (2007) Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology* 13(3):679-706.
86. Fachinelli NP & Pereira AO (2015) Impacts of sugarcane ethanol production in the Paranaiba basin water resources. *Biomass and Bioenergy* 83:8-16.
87. Rudorff BFT*, et al.* (2010) Studies on the rapid expansion of sugarcane for ethanol production in São Paulo State (Brazil) using Landsat data. *Remote sensing* 2(4):1057-1076.
88. Bambini MD, Furtado AT, & Zullo Jr J (Agricultural Zoning of Climatic Hazards: an instrument of Agriculture Policy in Brazil from Innovation Sociology perspective.
89. Newton P*, et al.* (2016) Overcoming barriers to low carbon agriculture and forest restoration in Brazil: The Rural Sustentável project. *World Development Perspectives* 4:5-7.
90. Spera SA, Galford GL, Coe MT, Macedo MN, & Mustard JF (2016)

Land-use change affects water recycling in Brazil's last agricultural frontier. *Global change biology* 22(10):3405-3413.
91. Garcia B (2011) *The Amazon from an international law perspective* (Cambridge University Press).
92. Brown-Lima C, Cooney M, & Cleary D (2010) An overview of the Brazil-China soybean trade and its strategic implications for conservation. *The Nature Conservancy Latin America Region.(Citing figures from the Secretariat of Foreign Trade (SECEX)) The Nature Conservancy, Brazil*:40.
93. Nepstad D*, et al.* (2014) Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. *science* 344(6188):1118-1123.
94. Tollefson J (2015) Battle for the Amazon. *Nature* 520(7545):20.
95. Lahsen M, Bustamante MM, & Dalla-Nora EL (2016) Undervaluing and overexploiting the Brazilian Cerrado at our peril. *Environment: Science and Policy for Sustainable Development* 58(6):4-15.
96. Soares-Filho B*, et al.* (2014) Cracking Brazil's forest code. *Science* 344(6182):363-364.
97. Jung S, Rasmussen LV, Watkins C, Newton P, & Agrawal A (2017) Brazil's National Environmental Registry of Rural Properties: Implications for Livelihoods. *Ecological Economics* 136:53-61.
98. Azevedo AA*, et al.* (2017) Limits of Brazil's Forest Code as a means to end illegal deforestation. *Proceedings of the National Academy of Sciences* 114(29):7653-7658.
99. Brown DS, Brown JC, & Brown C (2016) Land occupations and deforestation in the Brazilian Amazon. *Land Use Policy* 54:331-338.
100. Araujo C, Bonjean CA, Combes J-L, Motel PC, & Reis EJ (2009) Property rights and deforestation in the Brazilian Amazon. *Ecological economics* 68(8):2461-2468.
101. Gibbs HK*, et al.* (2015) Brazil's soy moratorium. *Science* 347(6220):377-378.
102. Meijer KS (2015) A comparative analysis of the effectiveness of four supply chain initiatives to reduce deforestation. *Tropical Conservation Science* 8(2):583-597.

SUPLEMENTARY INFORMATION

Data and models

The preparation of this review paper included an extensive review of policy documents for Brazil: policy and governance frameworks were reviewed and referenced throughout the text. In the supplementary information (SI) we elaborate on the assessment and use of these documents.

We also list here the methods and datasets used to create the figures. As indicated in their captions, Figures 1, 2 and 4 were generated by the authors using various accessible datasets.

Figure 1 illustrates modelled changes in mean temperatures and rainfall in Brazil for high and low emissions scenarios (representative concentration pathways (RCPs) 2.6 and 8.5). The climate model output used was generated for the Coupled Model Inter-comparison Project Phase 5 (CMIP5). Data was obtained through the KNMI Climate Explorer. Where multiple experiments have been completed with the same model configuration, only one has been included in the calculation of the CMIP5 ensemble mean, to avoid bias. Seasonal means are calculated for the end-of-century (2071-2100) and baseline (1961-1990) periods to obtain the modelled difference. (https://climexp.knmi.nl/).

Figure 2 uses economic data from Eurostat, the OECD, National Statistics of various countries and the Asian Development Bank, formatted as part of the database used to parameterise the economic model E3ME (http://www.e3me.com). Figure SI1 uses data from the IEA's world energy balances. Figures 4 and SI2 use data from FAOSTAT (http://www.fao.org/faostat/).

Scenarios on land productivity changes and yield of crop types in Brazil captured in Figure 4 have been derived with the latest version of the Lund-Potsdam-Jena model with managed land (LPJmL4), a global dynamic vegetation model (1). LPJmL4 simulates the transient changes in carbon and water cycles due to land use, specific phenology and seasonal CO2 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. LPJmL has 13 different crop functional types rain-fed and/or irrigated and has been built on a 0.5-degree grid. It allows for simulating the management of crops (irrigation, intercropping, treatment of residues), which leads to different maximum levels for leave areas (1, 2). We ran two different scenarios (RCP 2 and 8) for atmospheric CO2 between 2000 and 2100 using data from the Hadley centre climate model (HAD-GCM) as inputs to LPJmL4.

Supplementary figures

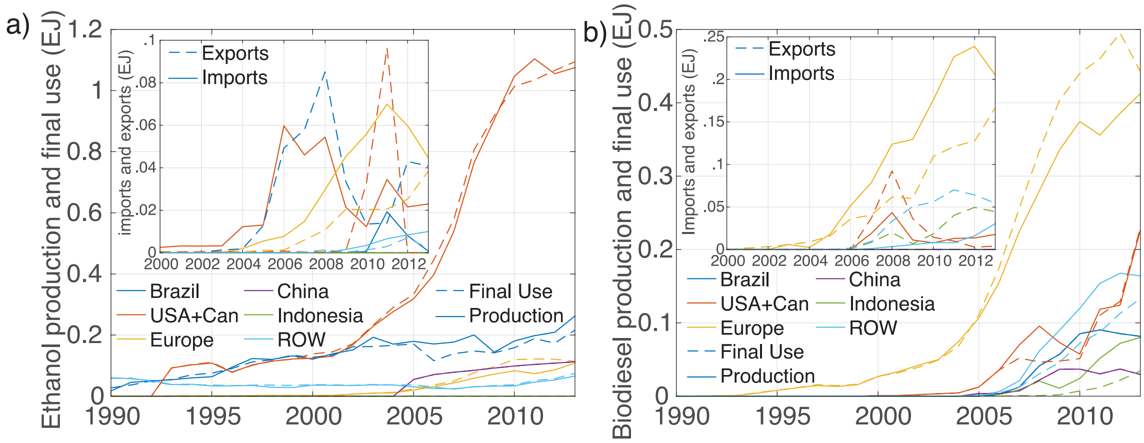

Figure SI1: Biofuel production, final use, imports and exports worldwide. a) Ethanol. b) Biodiesel. The main charts show production and final use, while the insets show imports and exports. Data from IEA World Energy Balances (2017).

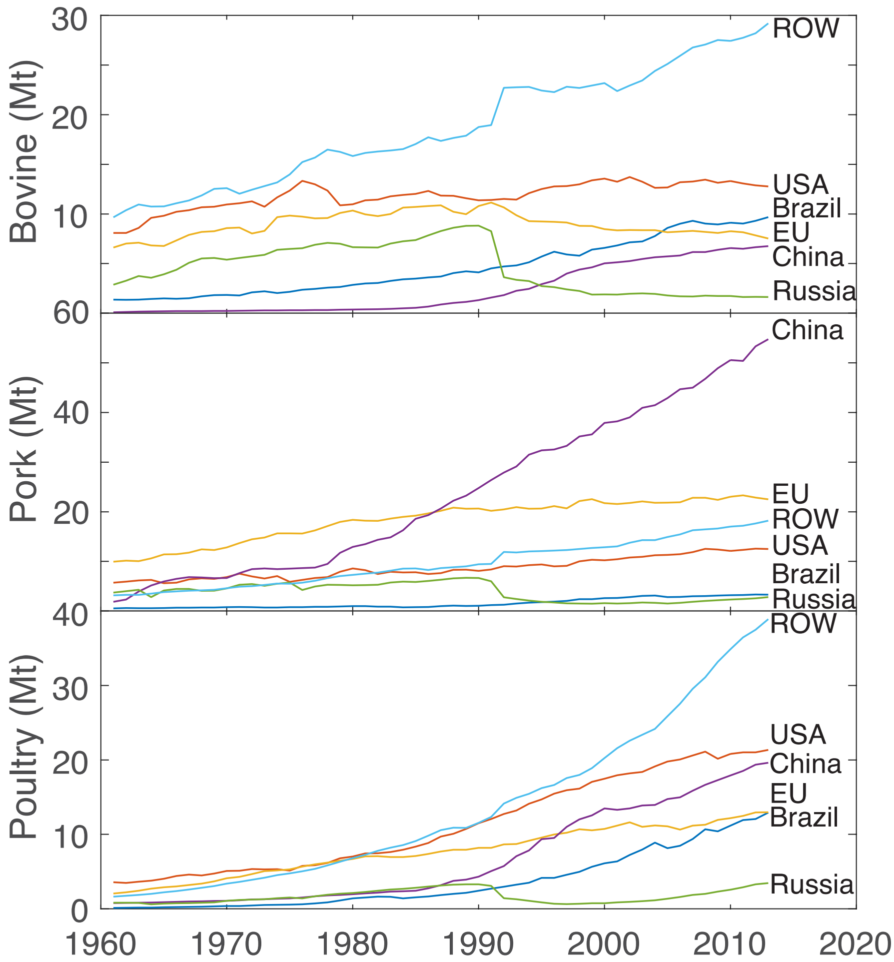

Figure SI2: Meat production around the world, for bovine, pork and poultry.

List of policy documents referred to in the main text

SI.1) 2008 National Plan on Climate Change

The National Plan on Climate Change was launched in December 2008, according to the Law-Decree No. 6.263, of 21 November 2007. It aims at identifying, planning and coordinating actions and measures for greenhouse gas mitigation and to implement actions for adaptation to climate change. The full text of the 2008 National Plan on Climate Change, is available (in Portuguese) at:

http://www.mma.gov.br/estruturas/smcq_climaticas/_arquivos/plano_nacional_mudanca_clima.pdf

and the Executive Summary of the 2008 National Plan on Climate Change is available (in English):

http://www.mma.gov.br/estruturas/smcq_climaticas/_arquivos/executive_summary_pnmc.pdf

SI.2) 2009 National Policy on Climate Change (Law N. 12.187 and Decree N. 7.390/2010)

Brazil has established its National Policy for Climate Change (NPCC) by Law N. 12.107/2009, available in Portuguese at

http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2009/lei/l12187.htm,

providing the principles, goals, guidelines and instruments of NPCC. The Law is regulated by the Decree N. 7.390/2010, which, amongst others provisions, contains the greenhouse gas emissions reduction targets, available in Portuguese at

http://www.planalto.gov.br/ccivil_03/_Ato2007-2010/2010/Decreto/D7390.htm.

SI.3) 2016 National Adaptation Plan to Climate Change

The National Adaptation Plan (NAP) was launched on May 2016, encompassing 11 themes (agriculture; biodiversity and ecosystems; cities; natural disasters; industry and mining; infrastructure (energy, transport and urban mobility); vulnerable peoples and communities; water resources; health; food and nutritional security; and coastal zones) and their cross-sector adaptation strategies to address the wide range of climate change uncertainties.

The NAP is available (in English) at the following links: the General Strategy – Volume I:

http://www.mma.gov.br/images/arquivo/80182/PNA_Volume%20I_EN.pdf

Sectoral and Thematic Strategies – Volume II:

http://www.mma.gov.br/images/arquivo/80182/BOOK_PNA_Volume%20II%20v4.pdf

The Executive Summary

http://www.mma.gov.br/images/arquivo/80182/BOOK_PNA_Executive%20Summary%20v4.pdf

SI.4) 1st National Adaptation Plan Monitoring Report, 2016-2017

One year of the launching of the NAP, in May 2017, Brazil published the 1st Monitoring Report, evaluating its first year of implementation. The Report is available (in Portuguese) at:

www.mma.gov.br/images/arquivo/80182/10%20reuniao/1%20Relatorio%20de%20Monitoramento%20PNA_%202016-2017_rms.pdf

SI.5) 2013 National Policy on Integration of Farming, Livestock and Forestry (Law N. 12.805)

The National Policy on Integration of Farming, Livestock and Forestry, established in 2013 by the Law N. 12.805, available in Portuguese at

http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2013/lei/l12805.htm,

provides the objectives and principles for a sustainable integration of the activities of farming and livestock in the forests.

SI.6) 2013 National Irrigation Policy (Law N. 12.787)

The National Irrigation Policy, created in 2013 by the Law N. 12.787, available in Portuguese at

http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2013/lei/l12787.htm,

governs the sustainable use of water for irrigation and policy integration for water resources.

SI.7) 2015 Law on Renegotiation of the Hydrological Risk for the electric power generation (Law N. 13.203)

The Law on Renegotiation of the Hydrological Risk for the electric power generation, enacted in 2015 under the N. 13.203, available in Portuguese at

http://www.planalto.gov.br/ccivil_03/_Ato2015-2018/2015/Lei/l13203.htm,

creates a mechanism to compensate hydropower companies from the losses in cases of droughts, by buying and stocking renewable energy through reserve energy auctions.

SI.8) National Strategy on the REDD+

On December 2015, Brazil has launched a National REDD+ Strategy (ENREDD+, in the Portuguese acronym), available in Portuguese at:

http://redd.mma.gov.br/images/publicacoes/enredd_documento_web.pdf.

The strategy's general objective is to contribute to mitigating climate change by eliminating illegal deforestation, conserving and recovering forest ecosystems, and developing a sustainable low carbon forest economy, thus generating economic, social and environmental benefits.

SI.9) 1997 National Water Policy (Law N. 9.433)

Enacted in 1997 by the Law N. 9.433, available in Portuguese at

http://www.planalto.gov.br/ccivil_03/leis/L9433.htm,

the National Water Policy prescribes the multiple purposes doctrine according to which the water management must promote the multiple uses of the waters, without addressing priorities, exceptions arising only in case of water scarcity if the use of water for human consumption and watering animals becomes at risk (article 1, items III and IV).

SI.10) Monitoring of the Brazilian Power Sector - Monthly Bulletin (June/2017)

The Brazilian Ministry of Mines and Energy issues monthly bulletins with all the relevant data of the monitoring of the power sector, including: hydro-meteorological conditions, electric power exchanges, consumer market, generation installed capacity, transmission lines installed, generation of energy, expansion of generation, expansion of transmission, marginal cost of operation and thermal dispatch, sectoral charges and performance of the Brazilian electricity system. Our work is based on data of the electric power sector as of May/2017, released at the June/2017 Bulletin, available (in Portuguese) at:

http://www.mme.gov.br/documents/10584/4475726/Boletim+de+Monitoramento+do+Sistema+El%C3%A9trico+-+Junho+-+2017.pdf/0dd6b734-e3c2-4418-a6df-33d1a5087c86.

SI.11) 2024 Ten Year Brazil Energy Plan

Every year the Ministry of Mines and Energy - MME publishes the Brazilian Energy Ten Year Plan (Plano Decenal de Energia – PDE), that presents, to the next ten years, the results of prospective studies of energy demand and supply, and related projects such as electricity generation power plants, transmission lines, oil refineries, oil exploitation blocks, oil and gas pipelines, and bioenergy production facilities. The last version is the 2024 Plan, available (in Portuguese) at

http://www.epe.gov.br/PDEE/Relat%C3%B3rio%20Final%20do%20PDE%202024.pdf,

and its amendment at

http://www.epe.gov.br/Estudos/Documents/ERRATA%20-%20PDE%202024%20-%20%20PDF.pdf.

SI.12) 2002 PROINFA – Incentive Programme for Alternative Sources of Electric Power (Law N. 10.438/2002, modified by Law N. 10.762/2003)

The Law N. 10.438/2002 (article 3), later revised by the Law N. 10.762/2003, available in Portuguese at

http://www.planalto.gov.br/ccivil_03/leis/2002/L10438.htm,

created the PROINFA to diversify the electricity mix in the country by increasing the use of new alternative energy sources.

SI.13) The Sugar-Cane Agro-Environmental Zoning – ZAE Cana (approved by the Decree N. 6961/2009)

In 2009, the Agro-Environmental Zoning for sugarcane was launched by the presidential Decree N. 6.961/2009, available in Portuguese at

http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2009/decreto/d6961.htm,

as a response to the society calls to consider environmental sustainability criteria in expanding ethanol production and to obtain the approval of the international market. The Ministry of the Environment has issued a description of the programme, available (in Portuguese) at:

http://www.mma.gov.br/estruturas/182/_arquivos/zaecana_doc_182.pdf

SI.14) Etanol Verde Programme – State of Sao Paulo

The São Paulo state government adopted the 'Etanol Verde' programme as part of its agro-environmental protocol, in partnership with the representatives of the sugar-cane producers to create mechanisms to stimulate and consolidate the sustainable development of the sugar cane production in the State of São Paulo. Its official webpage is available in Portuguese at

http://www.ambiente.sp.gov.br/etanolverde/.

SI.15) BONSUCRO certification scheme

BONSUCRO is a certification scheme that aims at promoting sustainable sugar cane. Originated from the 2005 " better sugar: better business" meeting, it has established its certification activities in 2010. The programme official webpage is available (in English) at

https://www.bonsucro.com/en/.

SI.16) Round Table on Responsible Soy - RTRS

The RTRS issues certificates that assure soy is originated from a process that is environmentally correct, socially adequate and economically viable. Originated from the 2004 Responsible Soy Forum, the first producers were certified by June 2011. The programme official website is available (in English) at

http://www.responsiblesoy.org/?lang=en.

SI.17) The Agricultural Climate-Risk Zoning - ZARC

The agricultural zoning ZARC was created in 1996 by the Embrapa (the National Institute for Agricultural Research) and the Brazilian Ministry of Agriculture Livestock and Food Supply as a technical-scientific instrument based on the knowledge of environmental capability and vulnerabilities of a particular region, especially regarding the behaviour and characteristics of climate, soil, vegetation, geomorphology, and focusing on the land capability for agricultural use. It also considers the social and economic characteristics of each region. Each year the government publishes Executive Orders announcing the sowing seasons calendar for crops of social and economic interest, and they are available (in Portuguese) at:

http://www.agricultura.gov.br/assuntos/riscos-seguro/risco-agropecuario/portarias.

SI.18) Low-Carbon (ABC) Plan

The Low-Carbon Agriculture (ABC) Plan was launched in 2010 to help Brazil reduce carbon emissions by 2020 in the agricultural sector. The Plan is available in Portuguese at:

http://www.agricultura.gov.br/assuntos/sustentabilidade/plano-abc/arquivo-publicacoes-plano-abc/download.pdf.

Embrapa's website exhibits a thematic page about the Plan, with some information published in English:

https://www.embrapa.br/en/tema-agricultura-de-baixo-carbono.

SI.19) The Agricultural Activity Guarantee Programme (PROAGRO) and the Family Agricultural Activity Guarantee Programme (PROAGRO-Mais).

PROAGRO and PROAGRO-Mais are rural insurance instruments of the Brazilian agricultural policy, established by Law 8.171/1991, available in Portuguese at

http://www.planalto.gov.br/ccivil_03/leis/L8171.htm,

and intended to reduce the rural activities inherent risks. PROAGRO was regulated by the Decree N. 175/1991, available in Portuguese at

http://www.planalto.gov.br/ccivil_03/decreto/1990-1994/D0175.htm

and the PROAGRO-Mais, which expands the PROAGRO benefits to family agricultures, was implemented by the Resolution N. 3.234/2004 of the National Monetary Council, available in Portuguese at

www.bcb.gov.br/pre/normativos/busca/downloadNormativo.asp?arquivo=/Lists/Normati vos/Attachments/46344/Res_3234_v1_O.pdf.

SI.20) 2004 Action Plan for Prevention and Control of Deforestation in the Legal Amazon (PPCDAm)

The PPCDAm, launched in 2004, aims to reduce deforestation rates continuously and to create enabling conditions for a transition towards a sustainable development model in the Amazon region. The Plan official documents are available in Portuguese at:

http://www.mma.gov.br/informma/item/616-preven%C3%A7%C3%A3o-e-controle-do-desmatamento-na-amaz%C3%B4nia.

SI.21) Amazon Programme on Deforestation Monitoring (PRODES) by the National Institute for Space Research (INPE)

The monitoring system adopted by PPCDAm is based on the satellite images captured by the National Institute for Space Research (INPE) in the Amazon Programme on Deforestation Monitoring (PRODES) that provides annual deforestation rates. The report of the deforestation rates from 2004 to 2016 is available (in Portuguese) at

http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes.

SI.22) Moratoria on soy

Created in 2006, the moratoria on soy is an initiative from retailers' and NGOs' to pressure the major soy commodity traders not to purchase soy originated from forestland cleared after 2006 (date later replaced by 2008) in the Amazon. In 2008 the Brazilian government has become part of this initiative, originally designed to be temporary but indefinitely renewed in 2016 until no longer needed. The ABIOVE (Brazilian Vegetable Oil Industry Association) issues Soy Moratorium Reports every year, to see its goals, survey method and results, available (in English) at:

http://www.abiove.org.br/site/?page=relatorios&area=Ni05OTgtMw

SI.23) Action Plan for Prevention and Control of Deforestation and Fires in the Cerrado (PPCerrado)

The PPCerrado, launched in 2010, provides a specific strategy for the prevention and control of deforestation in the Cerrado. The Plan official documents are available in Portuguese at

http://www.mma.gov.br/component/k2/item/618-ppcerrado

SI.24) Declaration of the Ministry of the Environment expressing the intention to extend the moratoria on soy to the Cerrado

During a meeting to celebrate the 10th anniversary of the moratoria on soy, the Minister of the Environment Sarney Filho has declared the need to extend it to the Cerrado. This information is available in Portuguese at the Ministry of the Environment news' website:

http://www.mma.gov.br/index.php/comunicacao/agencia-informma?view=blog&id=1927

SI.25) 2012 Forest Code (Law N. 12.651)

The Forest Code, enacted in 2012 by Law N. 12.651, available in Portuguese at

http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2012/lei/l12651.htm,

regulates the protection of native vegetation in private rural lands in Brazil.

SI References

1. Schaphoff S, *et al.* (2017) LPJmL4–a dynamic global vegetation model with managed land: Part I–Model description. *Geoscientific Model Development Discussions*.
2. Bondeau A, *et al.* (2007) Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology* 13(3):679-706.