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EDITORIAL

Carbon-optimised land management strategies for southern Amazonia

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Challenges

The Brazilian Amazon region is perceived a most precious biome due to its various globally relevant functions and resources. The Amazon forest is considered a key control for the global and regional climate system (Trumbore et al. 2015; Coe et al. 2017) and is a principal driver for the global and regional water cycle (Castello and Macedo 2016; Getirana 2016; Gimeno et al. 2012). It is home to a unique share of Earth's genetic resources (Laurance et al. 2012; Pimm et al. 2014; Myers et al. 2000) as well as a rich human cultural heritage which includes indigenous populations yet unexplored (Walker et al. 2016; Pringle 2014). The Brazilian savannah ecosystems, known as Cerrado, add another set of unique wildlife habitats (Simon et al. 2009). Both ecosystems represent important resources for the Brazilian and global economy, yet there are still serious issues regarding sustainable natural resources management. Up until today, the ongoing destruction of both ecosystems has stirred attention worldwide.

More than 750,000 km^2 of pristine forest has been lumbered in the Amazon between 1970 and 2013 (Nogueira et al. 2015; INPE 2017). During this period, deforestation rates have steadily increased until 2003/2004 (INPE 2014; Nepstad et al. 2014), and then slowed down as a result of political will and enforcement until 2013 (Boucher et al. 2013; Hansen et al. 2013; Nepstad et al. 2014). Since then, its rate is again increasing (Schönenberg et al. 2015; INPE 2016). Similarly, the Cerrado has also become subject to significant land use change (Jepson 2005; Beuchle et al. 2015; de Oliveira et al. 2017). The conversion of both ecosystems into cattle pastures and agricultural land already considerably affected biodiversity (Lees and Peres 2006), but also carbon (C) stocks and emissions, and the consequences for environment

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and society, are currently under debate, also in the context of climate change (Fearnside 2005; Cox et al. 2000; Malhi et al. 2008; Schaldach et al. 2018). The Brazilian Amazon is one of the world's largest biomass carbon pools, containing approximately 149 Mg C ha^{-1} (Nogueira et al. 2015). The risk of releasing all this carbon into the atmosphere explains a large part of the attention being currently paid to the fate of the Amazon rainforest. A change in land use (LUC), from forest to anything else, implies massive releases of C, which are expected to boost atmospheric carbon dioxide concentration [CO_2] with potentially catastrophic consequences for Earth's climate system. Apparently, Brazil is the place where human society seems to have the most immediate control of LUC-associated C emissions into the atmosphere (Fearnside and Laurance 2004; Fearnside et al. 2009). A loss of 2.7 million km^2 of rainforest by 2050 and of another 0.5 million km^2 of Cerrado have been predicted from an early millennium perspective (Soares-Filho et al. 2006; Resck et al. 2000). Even today, at the basis of much slower deforestation rates, trend scenarios see losses of 144,000 km^2 rainforest and 47,000 km^2 savannahs only in the states of Mato Grosso and Pará (Göpel et al. 2018) or around 800,000 km^2 rainforest in the total Amazon biome until 2030 (Aguiar et al. 2016). If such trend continues unaltered, a tipping point of the planet's climate system is feared to be triggered, with irreversible consequences for the whole planet (Lenton et al. 2008; Nepstad et al. 2008; Boers et al. 2017).

The Brazilian Government and international organisations have developed a number of different action programs which aim at the development of sustainable land management practices in the context of climate change mitigation and nature conservation (e.g. related to the Kyoto Process, Brazilian ABC Program, National Climate Change Policy of Brazil, Amazon Fund; Assunção et al. 2015; Fearnside 2005; Nepstad et al. 2014; Soares-Filho et al. 2010; Strassburg et al. 2014). Officially, Brazil plans to reduce deforestation in the Amazon by 80% by 2020 (Soares-Filho et al. 2010) and initially made successful efforts to reach the objective by reducing clear cutting of mature forest from 27,772 km^2 a^{-1} in 2004 to 4571 km^2 a^{-1} in 2012 (INPE 2017) as a result of public policy and frontier governance (PPCDAm, Plan for the Protection and Control of Deforestation in the Amazon; Soy Moratorium; Cattle Moratorium, Arco Verde+, Critical Counties program, Amazon Region Protected Areas Program; Nepstad et al. 2014; Tollefson 2015). Since August 2014, however, deforestation has begun to soar again. This drastically illustrates that "the battle for the Amazon is far from won" (Fearnside 2015) and that monitoring (Detection of Deforestation in Real Time–DETER) and effective inspection via Brazilian governmental institutions (e.g. IBAMA) must be accompanied by an increased understanding of the socio-economic driving forces and political aspects in the global, national and regional agro-economic development (Nepstad et al. 2014; Schönenberg et al. 2015). In fact, property rights in the Amazon region are still not well regulated and the lack of law enforcement gives rise to wariness of smallholder farmers and a very volatile colonisation pattern (Benatti and Fischer 2018). Profits from timber logging and agricultural production drive a cascade of land use change, starting with pioneer cattle ranching on freshly cleared forest, with industry-style soybean production following a few years after. With this, more financial power enters the region, facilitating the construction of paved roads and railways to improve accessibility to markets and ports and to further increase the profits (Barona et al. 2010; Boucher et al. 2013; Fearnside 2005; Macedo et al. 2012; Meyfroidt et al. 2013; Richards 2012). Initially, such land use change processes in the southern Amazon region were first triggered by global market incentives (demand for beef and soybean-based feedstock), but as a result of increasing policy interventions since 2004 (PPCDAm, Soy and Cattle Moratoria), these drivers are now temporally decoupled from land use displacement (soybean expansion in Mato Grosso and deforestation with cattle expansion at the pioneer front in Pará; Gollnow and Lakes 2014).

To date, deforestation has been concentrated in the "arc of deforestation" along the eastern and southern edges of the Amazon (see Fig. 2 in Barni et al. 2014). Before 2004, more than half of the forest clearing in the Amazon region occurred in the state of Mato Grosso, Brazil's largest producer of cotton (59%), maize (37%) and soybean (30%; CONAB 2017), and many studies have investigated the impact of deforestation on various ecosystem services (Davidson et al. 2012; Laurance et al. 2012). However, similar studies for the Brazilian Cerrado biome are rare. The Cerrado covers around 204 million hectares of Central and part of Northern Brazil (IBGE 2013). Due to rainfall seasonality, soil fertility, drainage properties and the occurrence of fire, the Cerrado structure ranges from the treeless "campo" to a relatively dense forest of trees of approximately 15 m in height (Neri et al. 2012). Indeed, its biodiversity is very high, including the existence of endemic species. However, its current state is also at risk of being irreversibly destroyed; a reduction of around 50% of its natural vegetation cover has been observed in the last decades (Beuchle et al. 2015; Rocha et al. 2011) and climate change is expected to add to this (Lima et al. 2017). Although deforestation is still the dominant transition form, portions of the Cerrado are experiencing a recovery of secondary woody vegetation (Redo et al. 2013).

A large body of literature on the Amazon region addresses the impact of LUC on ecosystem services (ESS), including C sequestration and climate regulation, in a separated manner and with partly contradictory results (Fearnside 2005). However, holistic examinations on multiple ESSs and their relation to local drivers and actors are scarce among these studies. Next-generation assessments of land use and climate change impacts on local and global climate, biodiversity and society along the southern Amazon land use frontier will need to follow an inter- or even transdisciplinary approach to capture the full range of interactions in the coupled socio-ecological system. This special issue reports the highlights of such an attempt, summarising results of a bilateral Brazilian-German research program which has been active in the period between 2011 and 2016.

Regional focus

The research activity puts its focus at the section of the BR-163 highway between Cuiabá in Mato Grosso and Novo Progresso in Southern Pará, at the southern marge of the Brazilian rainforest (Fig. 1). Along its route, the highway follows a historical land use gradient which passes through three distinct zones of agricultural expansion and development. Around the city of Cuiabá, notable agricultural land use started around 1975 and has expanded northwards ever since. The pioneer front then passed through the area of Sinop during the 1990s and reached southern Pará approximately 10 years later. Today, Central Mato Grosso is a highly industrialised area, with large-scale soybean, cotton and maize production. Northern Mato Grosso is still dominated by intensive cattle ranching, which in Southern Pará only recently started to replace timber logging as the main income source for the local pioneer communities. The BR-163 is an excellent illustration of all the problems associated with pioneer front development in the Amazon (Brando et al. 2013). It is continuously being paved northwards to improve the connection between the soy and cotton production region in Northern Mato Grosso with the export harbour of Santarem (Coy and Klingler 2011) (Fig. 1).

The land use gradient parallels a climatological gradient, from the Cerrado biome in the semi-humid tropics at central Mato Grosso to the evergreen rainforest of the humid tropics in Pará (Fig. 1). Along this gradient, the mean annual precipitation increases from 1700 mm at Cuiabá to 2100 mm in the southern Amazon, while seasonality is changing from a distinct wet and dry season to an all-year hot and wet tropical pattern (Moreno and Souza Higa 2005).

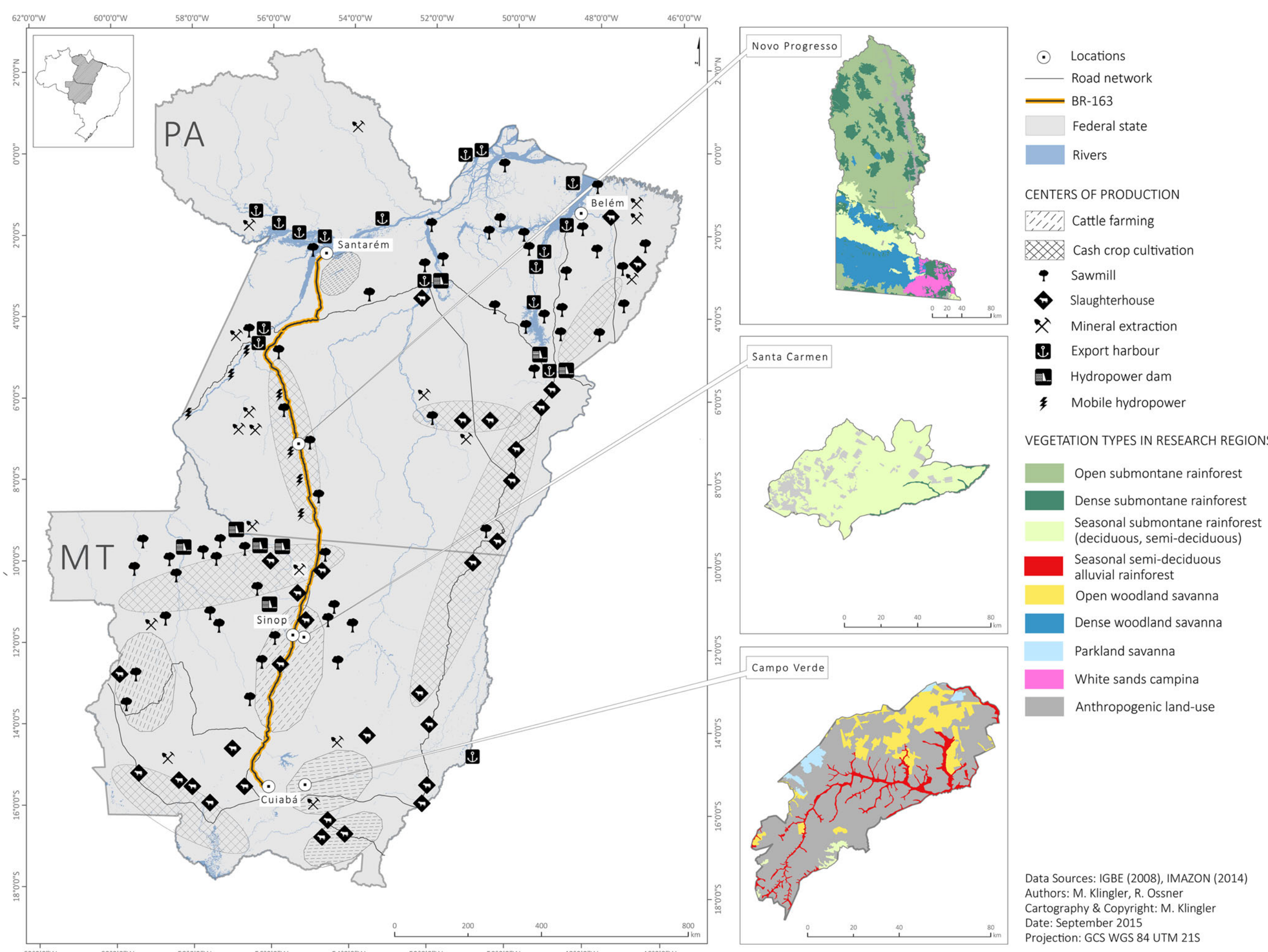

Fig. 1 Carbiocial research regions with their rural production centres and vegetation types

Three representative investigation sites have been selected along the BR-163: (1) Campo Verde (15° 33′ S; 55° 10′ W) as a typical example of the intensively used agricultural area of the Cerrados; (2) Sinop (11° 51′ S; 55° 30′ W) in northern Mato Grosso as an intermediate stage with industrialised soy, corn and cattle production; and (3) Novo Progresso (7° 02′ S; 55° 25′ W) in southern Pará, representing the agricultural pioneer front with extensive cattle pastures and emerging patches of crop production in the rainforest (Fig. 1). At each of these sites, four farms of different sizes and similar land use histories were selected (Table 1). Much of the experimental work that forms the basis for a large part of the research presented in the following articles has been performed on these farms.

Inter- and transdisciplinary research approach

Two research projects were established to foster Brazilian-German collaboration and inter- and transdisciplinary research in the southern Amazon region. In the scope of the German BMBF-FONA program (Federal Ministry for Education and Research–Research for Sustainable Development), the *Carbiocial* consortium (www.carbiocial.de) investigated C stock changes, greenhouse gas (GHG) emissions, erosion, catchment hydrology, agricultural production, land cover, socio-economic drivers, policy impact and actor networks using experiments, monitoring, surveys, remote sensing and dynamic simulation modelling. In Brazil, the corresponding research project *Carbioma* focused more specifically on the political programs which were established to mitigate environmental problems arising from inappropriate land use, such as Brazil's Sector Plan for the Mitigation and Adaptation to Climate Change for the Consolidation of Low Carbon Emission Agricuture (ABC Plan; Plano Setorial de Mitigação e de Adaptação às Mudanças Climáticas para a Consolidação de uma Economia de Baixa Emissão de Carbono na Agricultura; MAPA–MDA 2012), the Nationally Appropriate Mitigation Actions (NAMAS) and the intended Nationally Determined Contributions (iNDC; Brazil 2015). For this, *Carbioma* performed field experiments at the different experimental field stations of the Empresa Brasileira de Pesquisa Agropecuária (Embrapa).

The main objective of both project consortia was to investigate viable, carbon-optimised land management strategies for this hotspot of global change research. Together with its Brazilian partners, collaborators and local stakeholders, *Carbiocial* concentrated on obtaining parameters for simulation models, which are then used to test and improve carbon-optimised land use management strategies. The project collaborators studied soil, water, climate, agro-economics, social context and policy relevance to identify possible entry points for mitigating the pressure on pristine rainforest and to derive recommendations and scenario simulations to integrate improved carbon storage, social well-being and ecological requirements by providing a sound trade-off analysis of different ecosystem services. *Carbioma* focused on developing sustainable management options for agriculture in the Cerrado and the Cerrado-Amazon transition zone. It contributed to the evaluation of integrated agricultural production systems in the context of carbon sequestration and sustainable land use (Oliveira et al. 2018).

The multidisciplinary project consortia were built around four thematic priorities: (1) closing knowledge and data gaps related to LUC impact on water supply and quality, greenhouse gas reduction, soil C stocks and soil erosion; (2) testing management strategy using experimental farming with C enrichment; (3) scenario building and simulation of future land use change using dynamic models; (4) simulation of agro-economic developments and socio-economic assessments and consequences. Both projects followed an inter- and transdisciplinary research strategy (Schönenberg et al. 2017). The authors demonstrate how the different disciplines were interwoven within the projects and which conflicts, but also new insights arose from the collaboration, especially between natural science and social disciplines. Schönenberg et al. (2017) illustrate furthermore how stakeholder involvement from the very first beginning of the research activities determined content and direction of the research and how results were continuously played back to the stakeholders, who reflected upon the consequences for practical application. The art of finding the crucial deciders and actors for such an approach is a research on its own. Schönenberg et al. (2015) investigated in depth the network of decision-makers, looking back to more than 30 years' experience of on-site research (Coy and Klingler 2011) in the study region and evaluating recent changes in the local society and the reasons given for the observed fluctuations of people and their objects of work. Much of the insecurity which drives the local people to change continuously is the lack of land regularisation and juridical certainty. Benatti and Fischer (2018) take up this issue and shed light on the problems that especially the poorest land users face when arriving at new lands in Mato Grosso and Pará, and on the entry points for illegal actions that drive some of the societal and proprietary changes. Policies of environmental command-and-control, environmental regulation (CAR) and land tenure regularisation (Terra Legal) were discussed in relation to the efficiency of recent environmental governance strategies and its potential for alternative land use pathways on the local scale. Klingler et al. (2018) show the low effectivity of TAC cattle agreements to control extensive pasture use on newly deforested land because of contradictions between land tenure security and environmental laws (see also Benatti and Fischer 2018). Together with biographic research (Schumann et al. 2015) and institutional research (e.g. actor constellation) along the BR-163, qualitative data

Table 1 Farm positions, size, characteristics and land use types used within *Carbiocial*

Region	Farm	Coordinates	Characteristics	Land use types
Novo Progresso, Pará	Missassi	7.04501° S 55.3752° W	2247 ha, since 1979 2000 cattle	Old, new and meliorated pastures, vereda, rainforest, hilly sites
	Rubens	6.8585° S 55.5037° W	4500 ha, since 1990 pasture melioration in 2007	Old, new and mulched pastures, vereda, gallery forests, rainforest
	Florentino	7.1378° S 55.4066° W	3600 ha, since 1985 since 1980 pasture Since 2002 rice	Rice, maize soybean fields, pastures, vereda, gallery forests, rainforest
	Machado	7.1740° S 55.3964° W	260 ha, since 1985 400 cattle 2–3 years of rice	Old and new pastures, vereda, gallery forests, rainforest
Sinop, Northern Mato Grosso	Dona Isabina	12.0550° S 55.3516° W	1200 ha, since 1990 pasture since 2005 “plantio direto”	Soybean, maize, mechanised pastures, vereda, gallery forests, rainforest
	Santa Carmem	12.0550° S 55.3516° W	39,000 ha, since 1985	Crops, pastures
	São Vicente	11.9313° S 54.9497° W	2000 ha, since 1995 Pasture since 2005 “plantio direto” No melioration	Soybean, maize, old and new pastures, vereda, gallery forests, rainforest
	Dona Dozolina	11.9932° S 55.1876° W	10,000 ha, since 2002 “Plantio direto”	Soybean, maize, former pastures, vereda, gallery forests, rainforest
	Sao Valentim (farm experiment)	11.5858° S 55.3026° W	120 ha, soy + corn, “plantio direto”	Soy, corn
Campo Verde, Central Mato Grosso	Rio Engano (farm experiment)	15.2424° S 54.5091° W	1500 ha, since 1984 Soy, since 1996 “safrinha”	Soybean, maize, old pasture, vereda, gallery forests, Cerrado
	Gianetta	15.8050° S 55.3373° W	Since 2001	Old pasture
	Rancho do Sol	15.7953° S 55.3378° W	1150 ha, since 2001	Cerrado
	Santa Luzia	15.7381° S 55.3618° W	10,000 ha, since 1980; since 1997 soy, since 2005 “plantio direto” Since 1960 pasture	Soybean, old pastures, Cerrado, gallery forests
	Ilha Grande	15.4939° S 54.1252° W	1150 ha, since 1980s, 1112 ha “plantio direto”	Soybean, pasture, gallery forest

was gathered which was used for scenario development, along with regional and local expert knowledge for the southern Amazon region (Schönenberg et al. 2017). These narratives were later translated into quantitative parameters to be used for LUC and impact modelling (Göpel et al. 2018; Schaldach et al. 2018) with the development of four regional adapted LUC scenarios. LUC simulations (until 2030) were carried out using LandSHIFT (Schaldach and Koch 2009) on data obtained from The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), IBGE statistics and agricultural yield predictions obtained from the MONICA agro-ecosystem model (Nendel et al. 2011). MONICA simulates the growth and yield of the main agricultural crops (soybean, maize and cotton) and their response to weather variables and rising atmospheric CO_2 concentrations (Carauta et al. 2018). In the concept of *Carbiocial*, this is the entry point for climate change (CC) considerations being produced from two different downscaling approaches for a resolution of 30 km^2, driven by the ECHAM5/MPI-OM global circulation model. The statistical regional climate modelling (STAR) showed a clear decreasing trend of precipitation for the whole study area (15–25%; 1981–2010 to 2011–2040), while dynamic WRF downscaling gave a much more heterogeneous spatial distribution with slightly increasing and decreasing areas. Agro-economic simulation using MPMAS (Carauta et al. 2018) on detailed data on farm asset endowments and production requirements, crop management practices, historical prices for agricultural products and inputs, available sources of credit, relevant taxes and use of ABC program, as well as storage and transportation costs, produced the probably most complete dataset available for farm-level simulation in Mato Grosso, Brazil, including a detailed analysis of integrated crop-livestock systems (iCL) as part of the Brazilian ABC Program on their potential to improve land management and soil carbon storage (Oliveira et al. 2018; Carauta et al. 2018; Gil et al. 2015).

From these farm-level insights and from further extrapolation of the current yield trends towards a certain levelling in the near future as observed today in highly industrialised counties, the LandSHIFT simulations were driven along the future LUC scenarios (Göpel et al. 2018) and produced a land use distribution which was subsequently used for further impact analysis, such as simulations or calculations for soil organic C (SOC) stock change, GHG emissions, soil erosion and water balance simulation (Schaldach et al. 2018). Outputs from LandSHIFT were additionally used at the regional scale to set up different panel regression models to test processes of deforestation and land use displacement (Gollnow et al. 2018).

Parameters for impact analysis were obtained from four farms which were selected for each study region along the false time series of land use change (Table 1), representing combinations of main land use types and natural vegetation. Field work was carried out in plot-based and micro-catchment studies for each land use type, including SOC stock and GHG emission measurements. On the basis of SOC stock investigations, Boy et al. (2018) found that the impact from land use change on SOC stocks was much smaller than initially expected. However, SOC stock change may be higher in subsoils than in topsoils, which emphases the need to properly account for subsoil C when evaluating the potential for C gains and losses under LUC. The soil type itself also strongly influences more the size and even the direction of the modification of SOC stocks compared to LUC, but the proportion of carbon lost from soils was negligible as compared to the emissions from biomass reduction by deforestation itself, a fact that questions the use of dynamic modelling for SOC changes under LUC. Fearnside (2018) also points out the high uncertainty of quantifying carbon stocks in the Amazon for impact studies on global warming. The same conclusion was also drawn for the emissions of N_2O which—maybe except for a short period directly after a clear cut—seem to persist at a very low level and do also not respond very lively to rewetting events after a dry period, something that earlier has been identified as a hot moment of N_2O emissions in other environments. These results find their entry into a modelling of future greenhouse gas emissions by land use change in the southern Amazon region (Göpel et al. 2018).

In addition to the plot-based investigations, five micro-catchments were instrumented for catchment-scale hydrology investigations (Nobrega et al. 2015), where continuous measurements are being carried out since October 2012. Results suggest a relevant increase of runoff for pure pasture catchments compared to natural vegetation (Nobrega et al. 2015; Guzha et al. 2014), but no increase of discharge in the cropland catchment due to adapted land management (no-till soybean–maize double cropping). Macro-catchment modelling using SWAT (Lamparter et al. 2018) with CC and dynamic LUC showed only small changes in discharge components due to the large groundwater buffer in the Cerrado region. Discharge significantly increases with increasing pasture area as a consequence of forest cut down in the Cerrado and rainforest biome, but less after conversion to cropland (Lamparter et al. 2018). No-tillage crop systems with flat contour banks being established after Cerrado conversion showed the lowest soil erosion risk and sediment and carbon loss to the rivers. Large area remote-sensing classification of pasture, cropland and natural vegetation distribution (Müller et al. 2015) allowed upscaling from local field measurements to the watershed scale for erosion modelling, using EROSION-3D (Schob et al. 2006). Also here, the increase of pastures in combination with CC (rainfall pattern) and pasture degradation (Müller et al. 2016) results in a high risk of soil erosion, being highest in the first year after clearance (eightfold after Cerrado conversion, 20-fold after rainforest conversion). The importance of gallery forests in the agricultural landscape was supported by EROSION-3D modelling. With decreasing buffer width, sediment inputs are increasing exponentially with at least doubled input after buffer clearance. This demonstrates the importance of gallery forest conservation as discharge buffer and as sediment and nutrient filter for water quality as well as for biodiversity and adds to the present discussion of the New Forest Code which sees a further decrease of gallery forest width. Siqueira et al. (2018) illustrate the ongoing process of fragmentation of native vegetation and importance of conserving and linking the patches of "Legal Reserves" inside private rural properties to avoid further environmental deterioration of ESS. Also, Hissa et al. (2018) point out with a detailed assessment of carbon loss from deforestation along the BR-163 highway an increase of GHG emissions (1984–2012) with fragmentation, not considered in the official Brazilian deforestation assessments (PRODES).

Linking the interdisciplinary results of the C*arbiocial* and *Carbioma* projects, the importance of a greater distribution of integrated agro-silvo-pastoril systems within a better implementation of the ABC program (see Carauta et al. 2018) combined with an intensified crop production along a sustainability pathway (Göpel et al. 2018) is necessary for better land management to reach the GHG reduction goals of the Brazilian Climate Plan.

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