Environmental Research Letters

LETTER

Cattle production in Southern Amazonia: implications for land and water management

Michael J Lathuillière1,2, Kylen Solvik3,4, Marcia N Macedo4,5, Jordan Graesser6,7, Eduardo J Miranda7, Eduardo G Couto8 and Mark S Johnson2,8

1 Stockholm Environment Institute, Stockholm 10451, Sweden
2 Institute for Resources, Environment and Sustainability, University of British Columbia, Vancouver, B.C. V6T 1Z4, Canada
3 Department of Geography, University of Colorado, Boulder, CO 80309-0260, United States of America
4 Woods Hole Research Center, Falmouth, MA 02540-1644, United States of America
5 Instituto de Pesquisa Ambiental da Amazônia, Brasília, DF, 71503-505, Brazil
6 Department of Earth and Environment, Boston University, Boston, MA 02215, United States of America
7 Departamento de Solos e Engenharia Rural, Faculdade de Agronomia e Zootecnia, Universidade Federal de Mato Grosso, 78060-900, Cuiabá, MT, Brazil
8 Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, B.C. V6T 1Z4, Canada

E-mail: michael.lathuilliere@sei.org

Keywords: cattle, land footprint, water footprint, pasture, impoundments, Mato Grosso

Supplementary material for this article is available online

Abstract

The expansion of cattle in central western Brazil has been under scrutiny because of the region’s historic reliance on Amazon and Cerrado deforestation for cropland and pastureland expansion. In this study, we determined the volumetric water footprint (VWF) and the land footprint (LF) of cattle in Mato Grosso state for the years 2000, 2005, 2010 and 2014 using official statistics and remote sensing imagery. We found the average VWF of cattle for the time period to be $265 \pm 270$ kg m$^{-1}$ LW$^{-1}$ (LW as live weight of cattle) and a LF which decreased from 71 to 47 m$^2$ kg$^{-1}$ LW$^{-1}$. The largest contribution to VWF came from farm impoundments whose total area increased from roughly 46 000 to 51 000 ha between 2000 and 2014, leading to a total evaporation as high as $7.31 \times 10^{11}$ ly r$^{-1}$ in 2014. Analysis at the municipality level showed a tendency towards greater density of cattle with respect to both pasture area and impoundments. While cattle intensification on current pastureland is commonly viewed as a means to prevent further deforestation and greenhouse gas emissions, we stress the need to also consider the increasing demand for water associated with a growing cattle herd and the potential appropriation of additional resources for feed for feedlot finishing. Land and water resource management need to be considered together for future planning of cattle intensification at the Brazilian agricultural frontier as illustrated by the footprints reported here.

1. Introduction

South America has been the largest agricultural frontier on the planet for almost two decades. Since 2001, 96.9 Mha of pasture expansion took place on the continent, including large areas in Brazil and Paraguay (Graesser et al 2015). In 2012, Brazil was the largest producer of cattle globally with a population of 211 million, 13% of which were raised in the central western state of Mato Grosso (IBGE 2017). Recently, Mato Grosso’s cattle production has been under scrutiny, particularly with respect to pastureland expansion into both the Cerrado (or savanna) and Amazon biomes (figure 1). Between 2000 and 2009, total pasture area in Mato Grosso only varied marginally between 22 and 24 Mha (Lathuillière et al 2012), similar to the national trend (Dias et al 2016). This apparent stagnation masks indirect land use change dynamics that took place during the 2000s, particularly related to soybean expansion. From 2000 to 2010, about half of the 5.5 Mha of forest clearings in Mato Grosso were utilized for pasture, while soybean expanded primarily into previously established pastures (Macedo et al 2012). The wave of soybean
expansion may have displaced pasturelands farther into the Amazon agricultural frontier (Barona et al 2010, Arima et al 2011), indirectly causing more deforestation.

The agricultural sector’s role in deforestation in both the Amazon and Cerrado biomes has been the subject of much research (Barona et al 2010, Macedo et al 2012, Gollnow and Lakes 2014, Nepstad et al 2014, Zalles et al 2019). One proposed solution to avoid additional land use change is to enable cattle intensification through, for example, a set of complementary policies (Cohn et al 2014). Brazilian pastureland was found to sustain 32%–34% of the potential pasture carrying capacity, which indicates opportunities to increase productivity nationwide to meet the demand for cattle in 2040. While meeting demand through an increase in cattle density may help achieve deforestation targets, Mato Grosso would still need to consider questions regarding future water availability and usage.

Little information is available at present on water use for cattle in Mato Grosso. Research on the water consumption of production systems and supply chains has increased considerably with the development of the volumetric water footprint (VWF) (Hoekstra et al 2011). Many global and regional studies on animal products have attempted to quantify resource appropriation (Mekonnen and Hoekstra 2012, Gerbens-Leenes et al 2013, Vanham et al 2013) or environmental impacts of water consumption through life cycle assessments (e.g. Ridoutt et al 2012, 2014). The VWF exclusively quantifies the appropriation of water resources by combining direct (operations) and indirect (supply chain) water consumption, thus providing a comprehensive picture of the water use of a product or service over its entire life cycle (Hoekstra et al 2011). Unlike water withdrawals, water consumption refers to water that is removed from the watershed because of product integration, evaporation, inter-basin transfers, or direct release into the sea (Bayart et al 2010).

In Mato Grosso, cattle typically drink from small impoundments that are either rain-fed or created by damming first- or second-order streams. These water sources have to be carefully managed to guarantee year-long availability to cattle. Reduced precipitation and high evaporation rates can severely diminish water availability in impoundments during the dry season (May–November), implying vulnerability of the production system to extended droughts. This study’s objectives are to (1) evaluate land and water resource appropriation for cattle production in Mato Grosso by quantifying its land footprint (LF) and VWF, (2) understand the combined evolution of pasture and impoundment area for cattle in Mato Grosso between 2000 and 2014, and (3) provide guidance on future strategies for land and water management. This information is paramount to understanding possible limits to future intensification of cattle in the region.

2. Methodology

2.1. Cattle production in Mato Grosso

We analyzed land use and water consumption for cattle production in Mato Grosso using a suite of indicators. First, we estimated an average LF and VWF related to the total live cattle population of cattle in the region. This study’s objectives are to (1) evaluate land and water resource appropriation for cattle production in Mato Grosso by quantifying its land footprint (LF) and VWF, (2) understand the combined evolution of pasture and impoundment area for cattle in Mato Grosso between 2000 and 2014, and (3) provide guidance on future strategies for land and water management. This information is paramount to understanding possible limits to future intensification of cattle in the region.

In Mato Grosso, cattle typically drink from small impoundments that are either rain-fed or created by damming first- or second-order streams. These water sources have to be carefully managed to guarantee year-long availability to cattle. Reduced precipitation and high evaporation rates can severely diminish water availability in impoundments during the dry season (May–November), implying vulnerability of the production system to extended droughts. This study’s objectives are to (1) evaluate land and water resource appropriation for cattle production in Mato Grosso by quantifying its land footprint (LF) and VWF, (2) understand the combined evolution of pasture and impoundment area for cattle in Mato Grosso between 2000 and 2014, and (3) provide guidance on future strategies for land and water management. This information is paramount to understanding possible limits to future intensification of cattle in the region.

2. Methodology

2.1. Cattle production in Mato Grosso

We analyzed land use and water consumption for cattle production in Mato Grosso using a suite of indicators. First, we estimated an average LF and VWF related to the total live cattle population (see supplemental material, equation (S1) is available online at stacks.iop.org/ERL/14/114025/mmedia). We considered cattle production involving the Nelore breed from the species Bos taurus indicus which represents 90% of the cattle breeds in Mato Grosso (FABOV 2007). We assumed a state-wide average cradle-to-farm gate cattle production system that follows a 46–51 month cycle according to practices described for Mato Grosso (FABOV 2007, Cardoso et al 2016, Cerri et al 2016), during which females (heifers, cows) and males (steers, bulls) reach 430 kg and 520 kg, respectively. This system does not include any potential breeding stock with a longer life cycle.

Calves were assumed to weigh 30 kg at birth and to be weaned at 165 kg (Cardoso et al 2016) (table S1). In

![Figure 1. The Brazilian state of Mato Grosso divided into the 104 municipal units (MUs) used in this study (IBGE 2017).](image-url)
this system, cattle spend most of their lives on open pasturelands except in the finishing stage when they can either remain in pasture or be transferred to confinement (figure 2). Pasture finishing is a continuation of the adult development phase with pasture dry matter intakes (DMIs) continuing until slaughter. Confinement may occur in the last 6–8 months of the animal’s life when cattle is generally fed a diet of 70% feed and 30% silage.

Secondly, we analyzed the evolution of pasture and water reservoir areas for 2000, 2005, 2010 and 2014 for all the municipalities of Mato Grosso derived using a combination of official statistics and remote sensing information. Given the change in size, shape, and number of municipalities in Mato Grosso during the study period, we combined the municipalities that had changed into greater municipal units (MUs) that remained constant over the study period, following methods outlined by Lathuillière et al. (2012). This combination of political units resulted in 104 MUs for the entire state (figure 1).

2.2. Volumetric water footprint of cattle production

The water footprint has been used by distinct communities following separate guidelines and standards: (1) the water resources management community, which typically follows the Water Footprint Assessment Manual (Hoekstra et al. 2011), and (2) the life cycle assessment community, which follows the ISO 14046 standard (ISO 2015). While these approaches are complementary (Boulay et al. 2013, Lathuillière et al. 2018), they differ in their objectives as they may emphasize either water resources appropriation or impact assessment, respectively. Here, we focus specifically on water resources appropriation, or the volume of freshwater consumed for cattle production, which we have designated as the VWF of cattle. The VWF highlights how water is consumed in the production system and, therefore, can identify water management strategies to reduce the water consumed per kg live weight (LW), as well as the overall water consumed by the sector between 2000 and 2014. This VWF can also undergo a characterization step in which the volume of freshwater consumed is translated into impacts according to local water scarcity conditions (Pfister et al. 2009, Ridoutt and Pfister 2010, Boulay et al. 2013, 2018, Berger et al. 2014), with extension to impacts to human health and ecosystem quality (Boulay et al. 2015, Núñez et al. 2016) within a life cycle assessment. Our VWF is synonymous with water productivity (as its inverse) (Giordano et al. 2017) or a water footprint inventory following ISO 14046 (ISO 2015). We do not carry out a life cycle assessment.

2.2.1. Animal water consumptive use

Water for cattle is sourced from drinking water and moisture content in feed as well as additional water created by the animal’s digestion system (metabolic water) (FAO 2019). We applied the animal water balance of Ridoutt et al. (2012) to derive the volume of freshwater consumed by the animal based on its development cycle and finishing stage (open pasture or feedlot). The method also calls for the characterization of this volume considering local water stress conditions (Ridoutt et al. 2012), which, as described above, we did not apply in this research. Here, the total water consumed by the animal (l d⁻¹ month⁻¹) is expressed as

\[ W_{\text{feed}} + W_{\text{drink}} + W_{\text{met}} = W_{\text{evap}} + W_{\text{WG}} + W_{\text{feces}} + W_{\text{urine}}. \]  

(1)

On the water input side of equation (1), \( W_{\text{feed}} \) is the water contained in the feed that depends on DMI (kg d⁻¹), the moisture content of the feed (MC, %), the amount of milk consumed by the calf until eight months of age (\( W_{\text{milk}}, \text{l d}^{-1} \)), and the amount of water needed to mix feed (\( W_{\text{mix}}, \text{l d}^{-1} \)) assumed to be 0.5 l kg DMI⁻¹ according to Mekonnen and Hoekstra (2011) (equation (2)). \( W_{\text{drink}} \) is the amount of water drunk by the animal, and \( W_{\text{met}} \) is the water resulting from metabolic production as a function of feed digestibility (D, %) and described in equation (3) (Ridoutt et al. 2012). The sum \( W_{\text{feed}} + W_{\text{drink}} \) represents the

---

**Figure 2.** Process flow for cattle production in Mato Grosso, Brazil, representing a typical cycle for both males and females and does not include a breeding stock.
total daily water intake of the animal. On the water output side of equation (1), \( W_{\text{evap}} \) is the amount of water lost by the animal to evaporation, \( W_{\text{WG}} \) is the amount of water incorporated by the animal and represented by a weight gain, \( W_{\text{feces}} \) is the water content in animal feces, while \( W_{\text{urine}} \) is the water content in urine (Ridoutt et al. 2012). Following the above definitions, \( W_{\text{feed}}, W_{\text{drinks}}, W_{\text{milk}}, W_{\text{feces}} \) and \( W_{\text{urine}} \) represent water flows into and out of the animal, while \( W_{\text{WG}} \) and \( W_{\text{evap}} \) represent water consumptive uses

\[
W_{\text{feed}} = \frac{\text{DMI} \times \text{MC}}{100 - \text{MC}} + W_{\text{milk}} + W_{\text{mix}} \quad (2)
\]

\[
W_{\text{water}} = 0.6 \text{DMI} \frac{D}{100} \quad (3)
\]

We assumed that water contained in urine and feces are entirely evaporated, thereby simplifying \( W_{\text{feces}} \) and \( W_{\text{urine}} \) as water consumptive uses. This is a slight deviation from Ridoutt et al. (2012) who considered \( W_{\text{feces}} \) lost to evaporation, but \( W_{\text{urine}} \) as a flow added to local discharge with potential water quality impacts (not considered in our study). We believe our assumption to be reasonable for Mato Grosso considering the region’s high potential evapotranspiration (potential ET). On pastureland, moisture in cattle urine and feces can evaporate rapidly, as opposed to industrially confined cattle whose waste is typically collected in pits for subsequent spraying into fields.

The above assumption allows us to equate total animal water input to total water consumption in equation (1). Consequently, our calculation of the VWF of cattle relies exclusively on \( W_{\text{feed}}, W_{\text{drinks}}, W_{\text{milk}}, \) and \( W_{\text{water}} \). All parameters used for these calculations are listed in table S2. We did not include water consumed for transport between stages of development as the production system in this study was assumed to be confined to one single property, nor do we include water consumed for the production of minerals, vitamins, and veterinarian services administered to the herd.

2.2.2. Feed water consumptive use

Water consumption from pasture and crops used for feed were considered as additional consumption indirectly attributed to cattle production. Diets depend on the animal, the production system considered, and whether confinement is involved at the finishing stage (figure 2). The VWF of pasture was estimated for each MU using spatial precipitation data from CHIRPS v.2.0 (Funk et al. 2015) input into the model from Zhang et al. (2001) to derive pasture ET (see equation (S2) in the supplemental material). Pasture ET was then related to two pasture productivity scenarios to derive the volume of water consumed per kg of dry matter (DM) corresponding to 3 tons of DM ha\(^{-1}\) (low productivity) and 5.3 tons of DM ha\(^{-1}\) (high productivity at 1.5 animal units ha\(^{-1}\) following Thiago and Silva (2006)) (table S3). Together, these scenarios provided a range of VWF of pasture that we used to represent potential VWF of feed in Mato Grosso. All feed for feedlot finishing (61% maize, 10% sorghum, 8% soy meal, 8% cottonseed, 8% soybean grain following Millen et al. (2009)) was assumed to be sourced in Mato Grosso, with VWF for these crops from previous research (table S4) (Mekonnen and Hoekstra 2011, Lathuillière et al. 2012), which resulted in a total feed VWF of 20.9 kg\(^{-1}\) LW\(^{-1}\) d\(^{-1}\), assuming the average feed composition. Given that there was minimal cropland or pastureland irrigation in Mato Grosso during the study period, all feed water use was assumed to be sourced exclusively from green water (i.e. soil moisture regenerated by precipitation (Lathuillière et al. 2012)).

2.2.3. Water consumption from evaporation of small farm impoundments

Evaporation from small reservoirs used for cattle drinking water needs to be accounted as a blue water (surface water) consumptive use (Ridoutt et al. 2012). Little information is available on such reservoirs in the region other than a recent estimate of size and depth by Rodrigues et al. (2012) in central western Brazil, where reservoirs were typically less than 50 ha in size and up to 10 m deep (Rodrigues et al. 2012). Impoundment area within each MU was determined using remote sensing (see supplemental material).

Total impoundment area was then multiplied by the average reference ET (ET\(_{0}\), mm yr\(^{-1}\)) obtained from Xavier et al. (2015) to be allocated to the total herd LW in each MU. We then obtained an average Mato Grosso small reservoir evaporation (in kg\(^{-1}\) LW\(^{-1}\) d\(^{-1}\)) from which we subtracted evaporation from fish tanks considering both the range of possible yields described above, and average ET\(_{0}\) from all MUs in Mato Grosso. Since the Xavier et al. (2015) time series ended in 2013, we assumed that ET\(_{0}\) in 2014 was equal to that in 2013. Total animal LW was calculated for each MU assuming a 50:50 ratio of males and females in each MU (IBGE 2018, from 2006 census information) and their average LW in each of the calf (94.86 kg), mid-life (267.96 kg) and finishing stages (427.93 kg). Lastly, we combined our estimates of impoundment area with data on the number of live animals (see supplemental material) to calculate the reservoir cattle density (RCD, cattle heads per ha of water) for each MU and for each study year.

2.3. Land footprint of the cattle production

We used official statistics combined to the inverse of product yields (ha ton\(^{-1}\)) to obtain direct and indirect land use estimates for cattle. First, total pasture area was obtained for each MU using agricultural census information (1995, 2006, 2017) (IBGE 2018) following previous assessments in Mato Grosso (Barona et al. 2010, Lathuillière et al. 2012) (see supplemental material). We then combined the total pasture area with the live animal population in each MU to derive the pasture cattle density (PCD, cattle heads per ha of pasture, henceforth as cattle production area).
per ha) assuming that the pasture area was used exclusively by cattle rather than other animals. MU specific pasture areas were validated against the remote sensing images of Graesser and Ramankutty (2017) used to derive reservoirs to ensure compatibility in the total area allocated to cattle within the political units (see figure S1). The direct LF was then determined as the inverse of the PCD by allocating all pasture to living cattle. In addition, we estimated the amount of land required to grow inputs for the feed composition by considering the Mato Grosso average inverse yields in 2000, 2005, 2010 and 2014 for maize ($2.77 \times 10^{-4}$ ha kg$^{-1}$), soybean ($3.33 \times 10^{-4}$ ha kg$^{-1}$), cotton ($2.72 \times 10^{-4}$ ha kg$^{-1}$), and sorghum ($5.54 \times 10^{-4}$ ha kg$^{-1}$) (IBGE 2017). When considering the average feed composition, we estimated the indirect LF of feed to be $7.35 \times 10^{-6}$ ha d$^{-1}$ kg$^{-1}$ LW$^{-1}$.

# 3. Results

## 3.1. Cattle volumetric water and land and footprints

Mato Grosso’s average VWF for cattle at farm gate for the 2000–2014 period was $265–270$ l kg$^{-1}$ LW$^{-1}$, considering sex, and finishing stage (figure 3). In the case of pasture finishing, the VWF of cattle was comprised of $20%–24%$ green water (from $W_{\text{feed}}$) and $76%–80%$ blue water (from $W_{\text{mix}}$, $W_{\text{drink}}$, $W_{\text{res}}$ and $W_{\text{met}}$), based on sex. Reservoir evaporation as allocated to cattle production (as reservoirs detected within pastureland) was the largest contributor to the VWF of cattle representing $47%$ of total water consumed ($W_{\text{res}}$), followed by drinking (30%–31% for $W_{\text{drink}}$) and water contained in feed (18%–21% for $W_{\text{feed}}$ based on finishing stage), the remainder being water from $W_{\text{met}}$, $W_{\text{mix}}$ and $W_{\text{res}}$ (figure 3). During the same period, the average LF of cattle was $71$ m$^{2}$ kg$^{-1}$ LW$^{-1}$ in 2000 and $47$ m$^{2}$ kg$^{-1}$ LW$^{-1}$ in 2014 following ranges of PCD across Mato Grosso (PCD, described below) (table 1). The use of feed in the finishing stage provided an additional $12.9$ m$^{2}$ kg$^{-1}$ LW$^{-1}$ when considering agricultural products going in to the feed (13.5 m$^{2}$ kg$^{-1}$ LW$^{-1}$ for males and 12.3 m$^{2}$ kg$^{-1}$ LW$^{-1}$ for females) (table 1).

Confinement in the finishing stage slightly decreased the cattle VWF attributed to the animal (excluding $W_{\text{res}}$) from $132$ to $126$ l kg$^{-1}$ LW$^{-1}$ in males and $156$ to $153$ l kg$^{-1}$ LW$^{-1}$ in females due to

![Figure 3. Average volumetric water footprint (VWFanimal, l kg$^{-1}$ LW$^{-1}$) for cattle (male and female) in the state of Mato Grosso, Brazil, modeled considering pasture and feedlot finishing stages, and average 2000–2014 reservoir evaporation allocated to cattle. Values of VWFanimal are separated into water content of feed (Wfood), milk consumption (Wmilk, < 1 l kg$^{-1}$ LW$^{-1}$ not shown in the graph), animal drinking water (Wdrink), water used to mix feed (Wmix), water evaporated by farm reservoirs detected within pastureland (Wres), and metabolic water (Wmet). Values of Wres represents total small farm reservoir evaporation minus evaporation allocated to fish tanks with fish tank area determined by mean fish production (3.5–7 ton ha$^{-1}$ of water). Numbers on the graph represent individual contributions to the VWFanimal for a total of 270 l kg$^{-1}$ LW$^{-1}$ and 265 l kg$^{-1}$ LW$^{-1}$ for pasture and feedlot finishing, respectively.](image-url)

### Table 1. Mean pasture and reservoir cattle density, volumetric water and land footprints for cattle production (male and female animals, and pasture and feedlot finishing) in Mato Grosso for the 2000–2014 period.

| Description                              | Component | Ranges                        |
|------------------------------------------|-----------|-------------------------------|
| Cattle density (2000–14) (cattle ha$^{-1}$) | Pasture   | 0.68 (0.27)–0.97 (0.31)       |
|                                          | Reservoir total area | 835 (1258)–683 (639)         |
| Volumetric water footprint (l kg$^{-1}$ LW$^{-1}$) | Animal$^a$ | 142 (3)                      |
|                                          | Reservoir$^b$ | 126                         |
|                                          | Feed      | (2.44–4.75) × 10$^4$        |
| Land footprint (m$^2$ kg$^{-1}$ LW$^{-1}$) | Animal    | 71 (34)–47 (19)              |
|                                          | Feed      | 12.3–13.5                    |

$^a$ Average considering both pasture and feedlot finishing, and male and female development cycles.

$^b$ Excluding fish tanks, standard deviation of all years.
differences in moisture content between pasture and feed, with only marginal increases in blue water from mixing water (3–7 l kg\(^{-1}\) LW\(^{-1}\)). The average VWF of feed ranged between \(2.44 \times 10^4\) and \(4.75 \times 10^4\) l kg\(^{-1}\) LW\(^{-1}\), based on the typical diet in the finishing stage and pasture productivity as identified within MUs. The mean green VWF of pasture between 2000 and 2014 ranged from 1.41 to 2.72 m\(^3\) kg\(^{-1}\) DM\(^{-1}\) for the high and low productivity scenarios, respectively (table S3). These values showed small variability across Mato Grosso between 2000 and 2014 with the lowest VWF estimated at 1.41 m\(^3\) kg\(^{-1}\) DM\(^{-1}\) (sd = 0.11) in 2010 and the highest at 2.72 m\(^3\) kg\(^{-1}\) DM\(^{-1}\) (sd = 0.15) in 2014 (table S3) (see section 11 in the supplemental material for further discussion on estimates).

3.2. Reservoir and pasture contributions

Total small reservoir area allocated to cattle production across Mato Grosso and excluding fish tanks ranged from 46 000 ha in 2000 to 51 000 ha in 2014 (figure 4), which represented a total evaporation of 6.50 \(\times\) 10\(^{11}\) l yr\(^{-1}\) and 7.31 \(\times\) 10\(^{11}\) l yr\(^{-1}\), respectively (tables S5, S6). The mean RCD (considering total reservoir area in a MU allocated to cattle) decreased from 835 cattle ha\(^{-1}\) (sd = 1258) in 2000 to 683 cattle ha\(^{-1}\) (sd = 639) in 2014 (table S6). One MU showed significant changes in RCD observed between 2000 and 2014 (figure S5), with the highest densities occurring in southeastern and northern Mato Grosso in 2014 (figure S4). Removal of the MUs located in the Pantanal wetland only slightly changed the mean \(W_{res}\) RCD and total evaporation (table S5). Allocation of evaporation to fish tanks decreased the value of \(W_{res}\) by as much as 41% in 2010 and 2014 (table S6).

3.3. Evolution of land and water use for cattle in Mato Grosso

We observed few significant changes in pasture area within the study time period, with different rates of change observed when dividing the results into two periods (2000–2014 and 2005–2014). A total of 46 MUs showed increases in pasture area (mean \(R^2 = 0.47\), with a significant increase in 1 MU) from 2000 to 2014, but only 26 MUs showed increases from 2005 to 2014. A total of 94 MUs showed increases in total reservoir area (mean \(R^2 = 0.54\), and significantly in 6 MUs) from 2000 to 2014, and 88 MUs showed increases from 2005 to 2014 (table 2). We noted a correlation between reservoir area and pasture area in the 104 MUs expressed as \(\log A_{res} = 0.86\log A_p - 2.13\) (\(R^2 = 0.46\) in 2000, and \(\log A_{res} 0.72A_p - 1.23\) in 2014 (\(R^2 = 0.44\)) (figure S7). Changes in pasture and reservoir areas were accompanied by an increase in live cattle population from 15.7 million in 2000 to 22.1 million in 2005, before stabilizing to 23.7 million in 2014 (see supplementary data). At the political boundary level, 90 MUs exhibited increases in live cattle population (mean \(R^2 = 0.62\), significantly in 16 MUs) between 2000 and 2014, with more than half of MUs showing increases in cattle population between 2005 and 2014 (table 2).

General trends for cattle production in Mato Grosso showed an increase in PCD and a decrease in RCD. In 2014, greater values of PCD were observed in northern and southwestern Mato Grosso and some MUs in the south east (figure S6), with greater values of RCD in the northwest and south east (figure S4). We combine individual MUs into groups to separate the evolution of both PCD and RCD and highlight land and water management for cattle in the different MUs of Mato Grosso. We follow the evolution of four groups according to values between 2000 and 2014 compared to median 2000 values of PCD of 0.81 cattle ha\(^{-1}\) and of RCD of 560 cattle ha\(^{-1}\), respectively: the ‘Pasture Dense’ group contains MUs with PCD > 0.81 cattle ha\(^{-1}\) and RCD < 560 cattle ha\(^{-1}\) where we highlight a larger density of cattle in pasture containing a greater reservoir area; the ‘High Density’ group has MUs with PCD > 0.81 cattle ha\(^{-1}\) and RCD > 560 cattle ha\(^{-1}\) shows MUs of greater than...
median density of cattle in pasture with smaller reservoir area; the ‘Low Density’ group has MUs with PCD < 0.81 cattle ha\(^{-1}\) and RCD < 560 cattle ha\(^{-1}\), or MUs with greater pasture and reservoir area per cattle; and the ‘Water Dense’ group has MUs with PCD < 0.81 cattle ha\(^{-1}\) and RCD > 560 cattle ha\(^{-1}\) showing larger pasture extent but smaller reservoir area (figure 5). Between 2000 and 2014, the number of MUs with PCD > 0.81 cattle ha\(^{-1}\) (Pasture Dense and High Density groups) increased from 32 to 71, while the number of MUs with RCD > 560 cattle ha\(^{-1}\) (Water Dense and High Density groups) changed from 69 to 62. The most important change in PCD and RCD occurred in the High Density group which saw an increase in 22 MUs from groups that were either Low Density or Water Dense.

4. Discussion

4.1. On-farm land and water appropriation for cattle

By combining the above information with previously published results on the carbon footprint (CF) of cattle (table S7) we obtained ranges of VWF, LF and CF for cattle in Mato Grosso for the time steps considered, including both direct (animal) and indirect (feed) land and water appropriation. Reported values for the CF include emissions from the animal and inputs into the production system totaling 4.8–8.2 kg CO\(_2\)-eq
kg\(^{-1}\) LW\(^{-1}\) (Cerri et al. 2016). Land use change emissions attributed to cattle in 2010 was 33 kg CO\(_2\)-eq kg\(^{-1}\) LW\(^{-1}\) (Persson et al. 2014) considering both Amazon and Cerrado biomes (table S7).

The VWF, LF and CF are typically studied separately, but together can provide additional insight into on- and off-farm resource management strategies. Our results reproduced the general trend of pasture expansion for Mato Grosso for the 2000–2010 period as described in previous research (Barona et al. 2010, Macedo et al. 2012) with a progression towards intensification of land use for cattle, which is expressed by the LF. Previous studies indicate that although the pasture areas in Mato Grosso remained relatively constant between 2000 and 2010, the landscape changed dramatically within this time period. Large expanses of forest were converted to pasture at a rate of 400 000–600 000 ha yr\(^{-1}\) between 2000 and 2005, but 800 000 ha of pastures were subsequently converted into cropland between 2006 and 2010 (Macedo et al. 2012). The conversion of pasture into cropland was found to be a nationwide phenomenon between 2000 and 2014, representing 79% of all conversions (compared to 20% of conversions of natural vegetation into cropland) (Zalles et al. 2019). The pasture-to-cropland transitions in Mato Grosso were shown to push pastureland farther north into the Amazon (Barona et al. 2010, Arima et al. 2011), and likely also into the Cerrado biome. Between 2003 and 2013, cropland area doubled in the Cerrado region from 1.2 to 2.5 Mha with 74% of land use change occurring in natural vegetation (Spera et al. 2016), while in the same period conversions to pasture affected 3.18 Mha of natural vegetation (Noojipady et al. 2017).

Emissions from land use change are typically the largest in the production process and can include legacy emissions (e.g. decomposition) with allocation schemes that extend decades following deforestation (Zaks et al. 2009, Karstensen et al. 2013). Intensification of cattle production on existing rangelands is a widely proposed strategy for curbing deforestation and reducing the CF of cattle (Cohn et al. 2014, 2016, Gibbs et al. 2016, Silva et al. 2016). This approach has been met with some skepticism given difficulties with enforcement of the Brazilian Forest code, which does not preclude large swaths of Cerrado from being legally deforested for pasture or crop production (Phalan et al. 2016, Azevedo et al. 2017, Soares-Filho et al. 2014). Intensification on already cleared land (or through confinement) would avert further greenhouse gas emissions from land use change; however, an increase in cattle herd (or total LW) would still increase total emissions of production at rates as high as 8.2 kg CO\(_2\)-eq kg\(^{-1}\) LW\(^{-1}\) (from Cerri et al. 2016) in 2011.

Identifying on-farm strategies and incentives to promote intensification has been challenging. Recent work indicates that individual producers were less likely to implement new practices to boost productivity unless the property was part of the Rural Environment Registry (CAR, Portuguese acronym) (Latawiec et al. 2017), Latawiec et al. (2017) report that, despite being considered a source of water on their property, 70% of farmers interviewed in northern Mato Grosso did not see any financial benefit to forests, which, along with constraints from access to qualified labour and capacity building, constitute important barriers to intensifying cattle production. At the state and federal levels, enforcement of the Forest Code and the 2009 ‘Cattle Agreement’ have helped decrease deforestation for cattle (Nepstad et al. 2014, Gibbs et al. 2016), whereas taxation or subsidies could help further increase cattle density and spare natural vegetation (Cohn et al. 2014).

The calculation of the VWF was largely reliant on the estimate of farm reservoirs, with different effects on RCD based on allocation of evaporation to fish tanks (see supplemental material). Small farm impoundments are a key source of drinking water for cattle in Mato Grosso and should be considered carefully when calculating on-farm water balances. Remote sensing can play an important role in identifying the extent of reservoir networks as a means to estimate reservoir capacity and evaporation. For example, in central Brazil, Rodrigues et al. (2012) used remote sensing to map 147 small reservoirs at a volumetric capacity of 1.8 × 10\(^{-3}\) hm\(^3\) km\(^{-2}\) in the Preto River basin. Small farm dams and reservoirs are also common in northeastern Brazil, where the area of small reservoirs has increased by 1.95% yr\(^{-1}\) between 1970 and 2002 (Malveira et al. 2012). Reservoir evaporation is known to be a major loss of water in Australia (Ridoutt et al. 2012), estimated nationally at 1.3–2.9 × 10\(^{12}\) l (Baillie 2008) for an average volumetric density of 0.01 hm\(^3\) km\(^{-2}\) (maximum of 0.12 hm\(^3\) km\(^{-2}\)) (Malveira et al. 2012). In Mato Grosso, small impoundments are often constructed in headwater streams, thereby creating up-stream and down-stream trade-offs for human and ecosystem water use (Lathuillière et al. 2016). The increase in surface area created by these impoundments can increase stream temperatures (Macedo et al. 2013) and evaporation (Lathuillière et al. 2016), while reducing runoff and stream connectivity (Gallow and Smettem 2009), as well as sediment loads (Morais and Pinheiro 2011), all of which can alter stream habitats and negatively impact stream biota. In this study, annual evaporative rates were fully allocated to cattle, but were also expected to vary over the course of wet and dry seasons, thereby potentially decreasing the water supply for cattle. Open water evaporation of a small reservoir in northeastern Brazil was 3593 mm yr\(^{-1}\) with a maximum of 8.9 mm d\(^{-1}\) (December) and a minimum of 5.3 mm d\(^{-1}\) (July) with water levels dropping by 1 m between September and December (Antonino et al. 2005). As such, we expect farmers to either supply additional water (surface or groundwater) to cattle or further concentrate animals near larger reservoirs.
when necessary, particularly during drought periods or during the finishing stages when cattle is confined.

From a water management perspective, a strategy focused on reducing reservoir evaporation would reduce water consumption of cattle from the impoundments. For instance, Baillie (2008) lists evaporation mitigation technologies that include floating covers or chemical barriers, but whose application is not anticipated to be widespread. Additional strategies to reduce evaporation (e.g. deeper reservoirs, allowing for partial regeneration of riparian vegetation) could also be considered. Reservoirs and other on-farm water management infrastructure may persist on the landscape, even following the discontinuation of cattle ranching on the property. For instance, the region that is now known as Tanguro ranch (Hayhoe et al 2011) was dedicated to cattle ranching for about 15 years prior to converting all of its pasture area to cropland, yet many of its reservoirs remain intact. The fate of impoundments following the removal of cattle on farm properties is an important question for future water resources management and use, given that these water bodies could be available for other agricultural purposes such as cropland irrigation or aquaculture production, with the latter showing substantial increases in the state in recent years.

4.2. Land and water appropriation for feed

Several studies have quantified the water used to produce feed as an indirect contributor to the VWF associated with animal products (Mekonnen and Hoekstra 2012, Gerbens-Leenes et al 2013, Palhares et al 2017). Others have examined the competition between water use for crops and feed (Ran et al 2017), in addition to land resources and greenhouse gas emissions, as metrics of environmental performance for livestock and animal products (FAO 2016). Since the production of animal feed is generally the largest contributor to the indirect VWF of cattle, reducing the water required to produce feed is often presented as a strategy for improving the efficiency of cattle production overall. Both the LF and VWF can be reduced by increasing feed productivity while reducing its water requirements, a strategy known as increasing feed water productivity (Giordano et al 2017). Since cropland and pasture in Mato Grosso are almost entirely rain-fed, reductions in the VWF of feed could be achieved through a water vapor shift favouring transpiration over evaporation (Rockström 2003), with potential savings of nearly $2 \times 10^4 \text{L} \text{kg}^{-1} \text{LW}^{-1}$ as shown from our pasture productivity scenarios.

Feed VWF can vary greatly based on the individual VWF of crops, pasture and roughage, and the mix used in diets and production systems (Gerbens-Leenes et al 2013, Palhares et al 2017). For instance, the VWF of Brazilian meat was found to more than double when moving from a confined to a grazing system (Gerbens-Leenes et al 2013). Similarly, Palhares et al (2017) show that the choice of feed composition can dramatically change the VWF based on the inputs used. In contrast, the LF of cattle in a grazing system is much larger than the feed used in the feedlot finishing stage, and could potentially carry additional greenhouse gas emissions if the feed were to be sourced from cropland that expanded into previously deforested areas (Macedo et al 2012, Spera et al 2016). For instance, the CF of soybean grown in Mato Grosso, which could be used as feed, was estimated at 12.2 ton CO$_2$-eq ha$^{-1}$ yr$^{-1}$ (Novaes et al 2017) equivalent to 4.0 ton CO$_2$-eq ton$^{-1}$ soybean.

The use of feed to reduce water consumption or land use for cattle can be deceiving as this strategy often focuses on improving the efficiency per cattle. Feed type and efficiency can accelerate the cattle development cycle and reduce the time to slaughter, leading also to reduced enteric methane emissions per cattle (Talamini et al 2017). However, in absolute terms, a greater cattle population in feedlot finishing can increase water consumption and the indirect land use of the herd through feed; therefore, it is essential to understand the effects of product efficiency in the context of production output.

5. Conclusion

This study combined new estimates of VWF and LF of cattle production to show water appropriation and land use in Mato Grosso’s cattle production system. The live animal population grew by 8 million additional cattle between 2000 and 2014 to reach a total population of 23.7 million heads requiring 51 000 ha of farm impoundments and 27.5 Mha of pasture in 2014. The largest water consumption activity for cattle came from small farm reservoirs, whose evaporative losses should be considered in on-farm water management. The evolution of cattle production suggests that the demand for water resources will increase if cattle ranching intensifies. This water will be sourced either through further development of farm reservoirs, or by pumping from surface water bodies or groundwater. A greater use of feed for animal feedlot finishing will call for greater land and water appropriation for feed with potential water savings based on more efficient water use for cropland and pasture. Future research should explore further the details of the water balance of small farm reservoirs such as the inter-annual water availability and its relationship to cattle production, particularly considering the warmer and drier climate conditions expected for the region.

Acknowledgments

This work is a contribution to the project entitled ‘Integrating land use planning and water governance in Amazonia: towards improving freshwater security at the agricultural frontier of Mato Grosso’, supported
Data availability

Any data that support the findings of this study are included within the article, in the accompanying supplemental material and supplemental data.

ORCID iDs

Michael J Lathuilière https://orcid.org/0000-0001-6315-454X
Jordan Graesser https://orcid.org/0000-0002-6137-7050

References

Antonino A C D, Hamecker C, Montenegro S M L G, Netto A M, Angulo–Jaramillo R and Lira C A B O 2005 Subirrigation of land bordering small reservoirs in the semi-arid region in the Northeast of Brazil: monitoring and water balance Agric. Water Manage. 73 131–47
Arima E Y, Richards P, Walker R and Caldas M M 2011 Statistical confirmation of indirect land use change in the Brazilian Amazon Environ. Res. Lett. 6 024010
Azevedo A A, Rajão R, Costa M A, Stabile M C C, Macedo M N, dos Reis T N P, Alencar A, Soares–Filho B S and Pacheco R 2017 Limits of Brazil’s forest code as a means to end illegal deforestation Proc. Natl Acad. Sci. 114 7653–8
Baille C 2008 Assessment of evaporation losses and evaporation mitigation technologies for on farm water storages across Australia Report S 1–52 (https://www.irrigationaustralia.com.au/documents/item/281)
Barona E, Ramankutty N, Hyman G and Coomes O T 2010 The role of pasture and soybean in deforestation of the Brazilian Amazon Environ. Res. Lett. 5 024002
Bayati J B, Bulle C, Deschenes L, Margni M, Pfister S, Vincze F and Koehler A 2010 A framework for assessing off–stream freshwater use in LCA Int. J. Life Cycle Assess. 15 439–53
Berger M, van der Ent R, Eisner S, Bach V and Finkbeiner M 2014 Water accounting and vulnerability evaluation (WAVE): considering atmospheric evaporation recycling and the risk of freshwater depletion in water footprinting Environ. Sci. Technol. 48 4521–8
Boulay A M, Hoekstra A Y and Vionnet S 2013 Complementarities of water–focused life cycle assessment and water footprint assessment Environ. Sci. Technol. 47 11926–7
Boulay A M, Motoshita M, Pfister S, Bulle C, Muñoz I, Franceschini H and Margni M 2015 Analysis of water use impact assessment methods (part A): evaluation of modeling choices based on a quantitative comparison of scarcity and human health indicators Int. J. Life Cycle Assess. 20 139–60
Boulay A et al 2018 The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE) Int. J. Life Cycle Assess. 23 368–78
Callow J N and Smettem K R J 2009 The effect of farm dams and constructed banks on hydrologic connectivity and runoff estimation in agricultural landscapes Environ. Modelling Softw. 24 939–68
Cardoso A S, Berndt A, Leytem A, Alves B J R, de Carvalho L, das N O, de Barros Soares I H, Urquidi S and Boddy R M 2016 Impact of the intensification of beef production in Brazil on greenhouse gas emissions and land use Agric. Syst. 143 86–96
Cerri C C, Moreira C S, Alves P A, Raucci G S, Castigioni B D A, Mello F F C, Cerri D G P and Cerri C E P 2016 Assessing the carbon footprint of beef cattle in Brazil: a case study with 22 farms in the State of Mato Grosso J. Clean. Prod. 112 2593–600
Cohn A S, Gil J, Berger T, Pellegrina H and Toledo C 2016 Patterns and processes of pasture to crop conversion in Brazil: evidence from Mato Grosso State Land Use Policy 55 108–20
Cohn A S, Mosnier A, Havlík P, Valin H, Herrero M, Schmid E, O’Hare M and Obersteiner M 2014 Cattle ranching intensification in Brazil can reduce global greenhouse gas emissions by sparing land from deforestation Proc. Natl Acad. Sci. USA 111 7236–41
Dias I C P, Pimenta F M, Santos A B, Costa M H and Ladle R J 2016 Patterns of land use, extensification, and intensification of Brazilian agriculture Glob. Change Biol. 22 2887–2903
FABOV 2007 Diagnóstico da cadeia produtiva agroindustrial da bovinocultura de corte do estado de Mato Grosso (Cuiabá, MT: Fundo de Apoio a Bovinocultura de Corte)
FAO 2016 Environmental Performance of Animal Feeds Supply Chains (Rome: Livestock Environmental Assessment and Performance Partnership) (http://www.fao.org/3/a i6433e.pdf)
FAO 2019 Guidelines for Water use Assessment of Livestock Production Systems and Supply Chains (Rome: Livestock Environmental Assessment and Performance (LEAP) Partnership) (http://www.fao.org/3/ca5685en/ca5685en.pdf)
Funk C et al 2015 The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes Sci. Data 2 150066
Gerbens–Leeens P W, Mekonnen M M and Hoekstra A Y 2013 The water footprint of poultry, pork and beef: a comparative study in different countries and production systems Water Resour. Ind. 1 23–36
Gibbs H K, Munger J, L’Roe J, Barreto P, Pereira R, Christie M, Amaral T and Walker N F 2016 Did Ranchers and slaughterhouses respond to zero-deforestation agreements in the Brazilian Amazon? Conserv. Lett. 9 32–42
Giordano M, Turral H, Scheierling S M, Tréguier D O and McCormick P G 2017 Beyond ‘More Crop per Drop’: Evolving Thinking on Agricultural Water Productivity (Colombo: International Water Management Institute) (http://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/pub169/rs169.pdf)
Gollnow F and Lakes T 2014 Policy change, land use, and agriculture: the case of soy production and cattle ranching in Brazil, 2001–2012 Appl. Geogr. 55 203–11
Graesser J, Aide T M, Grau H R and Ramankutty N 2015 Cropland/pastureland dynamics and the slowdown of deforestation in Latin America Environ. Res. Lett. 10 034017
Graesser J and Ramankutty N 2017 Detection of cropland field parcels from Landsat imagery Remote Sens. Environ. 201 165–80
Hayhoe S J, Neil C, Porder S, McHorney R, Lefebvre P, Coo M T, Eisenber H and Krusche A V 2011 Conversion to soy on the Amazonian agricultural frontier increases streamflow without affecting stormflow dynamics Glob. Change Biol. 17 1821–33
Hoekstra A Y, Chapagain A K, Aldaya M M and Mekonnen M M 2011 The Water Footprint Assessment Manual: Setting the Global Standard (London: Earthscan) (https://waterfootprint.org/media/downloads/TheWaterFootprintAssessmentManual_2.pdf)
Noojipady P, Morton C D, Macedo N M, Victoria C D, Huang C, Nepstad D, Morais J O and Pinheiro L S 2011 The effect of semi-aridity and Millen D D, Pacheco R D L, Arrigoni M D B, Galyean M L and Mekonnen M M and Hoekstra A Y 2012 A global assessment of the Karstensen J, Peters G P and Andrew R M 2013 Attribution of CO2 ISO 14046:2014 2015 Macedo M N, Coe M T, DeFries R, Uriarte M, Brando P M, Mekonnen M M and Hoekstra A Y 2011 The green, blue and grey Lathuillière M J, Johnson M S and Donner S D 2012 Water use by Lathuillière M J, Coe M T and Johnson M S 2016 A review of green- Lathuillière M J, Bulle C and Johnson M S 2018 A contribution to harmonize water footprint assessments Glob. Environ. Change 53 252–64 Lathuillière M J, Coe M T and Johnson M S 2016 A review of green-blue water-resources and their trade-offs for future agricultural production in the Amazon Basin: what could irrigated agriculture mean for Amazonia? Hydrol. Earth Syst. Sci. 20 2179–94 Lathuillière M J, Johnson M S and Donner S D 2012 Water use by terrestrial ecosystems: temporal variability in rainfall amount and agricultural contributions to evapotranspiration in Mato Grosso, Brazil Environ. Res. Lett. 7 032024 Macedo M N, Coe M T, DeFries R, Uriarte M, Brando P M, Neill C and Walker W S 2013 Land-use-driven stream warming in southeastern Amazonia Phil. Trans. R. Soc. B 368 20120153–20120153 Macedo M N, DeFries R S, Morton D C, Sticker C M, Galford G L and Shimabukuro Y E 2012 Decoupling of deforestation and soy production in the southern Amazon during the late 2000s Proc. Natl Acad. Sci. 109 1341–6 Malveira V T C, Araujo J C D and Günther A 2012 Hydrological impact of a high-density reservoir network in semi-arid Northeastern Brazil J. Hydrol. Eng. 17 109–17 Mekonnen M M and Hoekstra A Y 2011 The green, blue and grey water footprint of crops and derived crop products Hydrol. Earth Syst. Sci. 15 577–600 Mekonnen M M and Hoekstra A Y 2012 A global carbon assessment of the water footprint of farm animal products Ecosystems 15 401–15 Millen D D, Pacheco R D L, Arrigoni M D B, Galván M L and Vasconcelos J T 2009 A snapshot of management practices and nutritional recommendations used by feedlot nutritionists in Brazil J. Animal Sci. 87 3427–39 Morais J O and Pinheiro L S 2011 The effect of semi-aridity and damming on sedimentary dynamics in estuaries –northeastern region of Brazil J. Coast. Res. 64 1540–4 Nepstad D et al 2014 Slowing Amazon deforestation through public policy and interventions in beef and soy production Science 344 1118–23 Noojipady P, Morton C D, Macedo N M, Victoria C D, Huang C, Gibbs K H and Bolle L E 2017 Forest carbon emissions from cropland expansion in the Brazilian Cerrado biome Environ. Res. Lett. 12 025001 Novo R M, Brando M P, Caleo J R, Rosa R A and Morais J O 2014 Estimating 20–year land-use change and derived CO2 emissions associated with crops, pasture and forestry in Brazil and each of its 27 states Glob. Change Biol. 23 3716–28 Núñez M, Bouchard C R, Bulle C, Boulay A M and Margni M 2016 Critical analysis of life cycle impact assessment methods addressing consequences of freshwater use on ecosystems and recommendations for future method development Int. J. Life Cycle Assess. 21 1799–815 Palhares J C P, Morelli M and Junior C C 2017 Impact of roughage-concentrate ratio on the water footprints of beef feedlots Agric. Syst. 155 126–35 Persson U M, Henders S and Cederberg C 2014 A method for calculating a land-use change carbon footprint (LUC–CFP) for agricultural commodities – applications to Brazilian beef and soy, Indonesian palm oil Glob. Change Biol. 20 3482–91 Pfister S, Koehler A and Hellweg S 2009 Assessing the environmental impacts of freshwater consumption in LCA Environ. Res. Lett. 43 4098–104 Phalan B, Ripple W J and Smith P 2016 Increasing beef production won’t reduce emissions Glob. Change Biol. 22 3255–65 Ran Y, van Middelaar C E, Lannerstad M, Herrero M and de Boer I J M 2017 Freshwater use in livestock production—to be used for food crops or livestock feed! Agric. Syst. 155 1–8 Ridoutt B G, Page G, Opie K, Huang J and Bellotti W 2014 Carbon, water and land use footprints of beef cattle production systems in southern Australia J. Clean. Prod. 73 24–30 Ridoutt B G and Pfister S 2010 A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity Glob. Environ. Change 20 113–20 Ridoutt B G, Sanguansri P, Freer M and Harper G S 2012 Water footprint of livestock: comparison of six geographically defined beef production systems Int. J. Life Cycle Assess. 17 165–75 Rockström J 2003 Water for food and nature in drought–prone tropics: vapour shift in rain–fed agriculture Phil. Trans. R. Soc. B 358 1997–2009 Rodrigues L N, Sano E E, Steenhuis T S and Passo D P 2012 Estimation of small reservoir storage capacities with remote sensing in the Brazilian Savannah region Water Resour. Manage. 26 873–82 Silva R D O, Barioni L G, Hall J A, Matsurra M F, Albertini T Z, Fernandes F A and Moran D 2016 Increasing beef production could lower greenhouse gas emissions in Brazil if decoupled from deforestation Nature Clim. Change 6 493–7 Soares-Filho B, Rajão R, Macedo M, Carneiro A, Costa W, Coe M, Rodrigues H and Alencar A 2014 Cracking Brazil’s forest code Science 344 363–4 Spera S A, Galford G L, Coe M T, Macedo M N and Mustard J F 2016 Land-use change affects water recycling in Brazil’s last agricultural frontier Glob. Change Biol. 22 3405–13 Talamin E, Ruviaro C F, Florindo T J and Florindo G I B D M 2017 Improving feed efficiency as a strategy to reduce beef carbon footprint in the Brazilian Midwest region Int. J. Environ. Sustain. Dev. 16 579 Thiago L R L Silva and Sil M 2016 Aspectos práticos da suplementação alimentar de bovinos de corte (Campo Grande, MS: Embrapa Gado de Corte) (https://www.embrapa.br/gado-de-corte/busca-de-publicacoes//publicacao/326990/aspectos-praticos-da-suplementacao-alimentar-de-bovinos-de-corte) Vanham D, Mekonnen M M and Hoekstra A Y 2013 The water footprint of the EU for different diets Ecol. Induc. 32 1–8 Xavier A C, King C W and Scanlon B R 2015 Daily gridded meteorological variables in Brazil (1980–2013) Int. J. Climatol. 36 2644–59 Zaks D P M, Barford C C, Ramankutty N and Foley J A 2009 Producer and consumer responsibility for greenhouse gas emissions from agricultural production—a perspective from the Brazilian Amazon Environ. Res. Lett. 40 044010 Zalles V et al 2019 Near doubling of Brazil’s intensive row crop area since 2000 Proc. Natl Acad. Sci. 116 428–35 Zhang L, Dawes W R and Walker G R 2001 Response of mean annual evapotranspiration to vegetation changes at catchment scale Water Resour. Res. 37 701–8