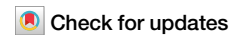


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International reliance on Brazil's water through soy and beef supply chains



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As commodities enter supply chains, consumers rely on distant freshwater sources to ensure continued supply. This information often lacks the traceability and granularity required to assess the reliance of supply chains on specific river basins and their level of water scarcity. Here, we quantify the volume and source of freshwater for the production and export of Brazilian soy and beef to China and the EU, together with deforestation and greenhouse gas emissions for the 2015–2017 period. Both sectors mainly rely on rainfed systems, but also soy irrigation and a combination of cattle drinking and evaporation from reservoirs serving as the drinking source. About 20% and 50% of the freshwater required for exports to China and the EU, respectively, rely on river basins with high or critical water scarcity. Our study further shows how a multi-indicator assessment is key to guiding decisions in commodity sectors towards sustainable production and supply chains.

Brazil is consistently one of the world's top producers of soy and beef¹, with a well-documented history of cropland and pasture expansion into natural vegetation². In addition to deforestation, biodiversity loss and greenhouse gas (GhG) emissions, agricultural land expansion also appropriates water resources, either as soil moisture in rainfed systems, or surface and groundwater for irrigation or cattle drinking. These resources have respectively been described as green and blue water to highlight trade-offs in land and water use³. In Brazil, these trade-offs affect moisture recycling and regional precipitation regimes, but also availability of downstream surface water⁴ with consequences to both hydro-geographies and supply chains.

Brazil is home to 16% of global renewable freshwater resources⁵, yet the use of water for agricultural commodity production and trade remains underappreciated compared to deforestation or GhG emissions, in part due to limitations in data availability and methodological development. Previous studies have provided nationwide and municipal-level assessments of water use for soy production and supply chains^{6–8}, but detailed and comprehensive estimates on irrigation have been lacking. Studies on water use for beef have mainly focused on feed⁹, with few regional or field studies^{10–12}, but often overlook water directly consumed by cattle as well as evaporation from farm reservoirs used as the main drinking water source for the sector¹³.

A municipal-level assessment of water use for Brazilian soy and beef production is essential for quantifying the geographic variability across biomes and river basins, but also for linking consumers to river basins and their levels of water scarcity¹⁴. Brazil is a net exporter of virtual water through the trade of its agricultural products⁸, and this use competes with household and industrial uses, energy and ecosystem needs. Moreover, as supply chains

adapt to new legislation aimed at regulating imports of commodities linked to deforestation, such as the EU Regulation on Deforestation-Free Products (EUDR)¹⁵, some sources of soy and beef exports may move from regions of high deforestation to regions of both low deforestation and high water scarcity, thereby shifting the environmental burden of production and trade from one impact category to another. Such a shift could be avoided by ensuring that multiple impacts are reported together in supply chain sustainability assessments.

Two key methodological advancements now allow for more spatially explicit estimates of water use in Brazilian soy and beef production and supply chains. First, new developments in remote sensing allow for improved mapping of water resources over several decades, including the detection of irrigated fields and surface water¹⁶. Second, spatially explicit soy and beef supply chain maps linking municipalities to international markets allow for more spatially explicit assessments of the environmental impacts of consuming countries and traders^{17,18}.

This study provides spatially explicit information on water use for Brazilian soy and beef to quantify the critical dependency of supply chains on water resources and water scarcity. We combine estimates of water use, deforestation and GhG emissions for soy and beef production in Brazilian municipalities with the spatially explicit supply chains of Trase (trase.earth) to link these impacts to China and the EU (as EU27 + UK), which respectively imported \$38 and \$8.8 billion of soy and beef products from Brazil in 2024¹⁹. We then link water use for soy and beef exports to Brazilian river basins to highlight China and the EU's reliance on Brazilian water resources, and the water scarcity risks to their

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supply chains, before comparing regional patterns of deforestation and water scarcity impacts.

Our results show that the amount of blue water consumed by the soy and beef sectors can be estimated at the municipality level and should not be overlooked. About 20% and 50% of soy and beef, respectively, imported into China and the EU, were linked to river basins that experience either high or critical water scarcity and could therefore be a source of conflict and pose risks to supply chains. Our multi-indicator assessment also reveals the limited overlap between deforestation and water scarcity impacts in supply chains, such that focusing on one specific metric could prevent a successful transition towards more sustainable production and supply chains.

Results and discussion

Water use for soy and beef production

We estimate the water use, deforestation and GhG emissions of soy and beef production to assess the environmental performance of each commodity sector (Table 1) for the 2015–2017 period. Almost all water (>99%) was consumed in rainfed systems (as green water), with the residual consumed by soy irrigation ($0.96\text{--}1.70\text{ km}^3\text{ y}^{-1}$), cattle consumption and reservoir evaporation ($10.1\text{--}10.4\text{ km}^3\text{ y}^{-1}$) (as blue water). The combined indicators show that the Brazilian beef sector, as the living cattle herd, appropriated >80% of total land and water resources, deforestation and GhG emissions associated with the soy and beef sectors (Table 1). Moreover, about 80% of GhG emissions for beef came from deforestation for pasture ($1422\text{--}1666\text{ Mt CO}_2\text{-eq y}^{-1}$ in the 2015–2017 period), while 70% of blue water use came from evaporation from reservoirs ($7.3\text{--}7.6\text{ km}^3\text{ y}^{-1}$). Omitting reservoir evaporation for beef production (median of 0.51 Mha y^{-1} , Table 1), therefore, greatly underestimates the amount of blue water consumed by the sector. Reservoir evaporation results should be considered as an underestimate due to interannual variability in surface water and needed improvements of open water evaporation estimates²⁰.

Our results confirm the importance of green water to sustain the soy and beef sectors in Brazil^{6–9}, such that precipitation variability can greatly affect crop yields and pasture productivity^{21,22}. Our results also provide additional details on the variation in water use and production practices across the country. Soy water use was greater at the intersection of the Northern (N), Northeastern (NE) and Central Western (CWe) regions (> $2000\text{ m}^3\text{ t}^{-1}$, especially in 2016) which includes the region known as Matopiba (Fig. 1 and Supplementary Figs. 4 and 5), while soy irrigation was concentrated in the Southeastern (SE) and NE regions, respectively producing 8.6 Mt and 9.5 Mt of soy in 2017 (Fig. 1). Blue water use for beef was mostly $<250\text{ m}^3\text{ (t liveweight (LW))}^{-1}$, while green water use was $>10,000\text{ m}^3\text{ (t LW)}^{-1}$ (Fig. 2 and Supplementary Figs. 6 and 7). Variability in green water use was due to a combination of pasture evapotranspiration (ET) and area (Supplementary Fig. 18 and Supplementary Table 15). We note greater blue water footprints for beef in the N and NE regions, producing 14 Mt LW and 8.2 Mt LW in 2017 (Fig. 2), especially in areas that did not produce soy. Our results rely on monthly and annual responses of soy and pasture landscapes to meteorological variables. While these results can describe the geographic variability of water use across Brazil, our short temporal resolution does not allow for a trend analysis (Supplementary Note 1).

The role of blue water in the soy and beef sectors shows specific regions susceptible to conflict over water uses, especially in the NE. Surface and groundwater use for agriculture competes with downstream household or industrial uses, energy and ecosystem needs. Irrigation and farm reservoirs are key strategies to adapt to dry spells and longer dry seasons. Soy irrigation can help maintain crop yields or increase crop intensity to three crops per year²³ while reservoirs allow for an extended drinking water source for cattle over the dry season. Between 2015 and 2017, soy irrigation area increased from 0.81 to 0.95 Mha with a concentration in the states of Minas Gerais, Goiás, Bahia and São Paulo (each $>100,000\text{ ha}$ in 2017) (Supplementary Table 12). The extent to which irrigation can expand sustainably in Brazil has been verified within the context of the country's irrigation law, with a large portion of existing irrigated and rainfed cropland already in water-

scarce basins²⁴. However, the role and magnitude of groundwater use for irrigation expansion is still a major unknown. Farm reservoir area increased from 0.49 Mha to 0.51 Mha between 2015 and 2017 (Supplementary Table 12) with larger blue water footprints found in the NE due to a combination of large reservoir area and smaller cattle herds (Fig. 2). These reservoirs are often constructed by damming small streams without a permit with effects on downstream water availability, stream temperature and water quality^{25,26}.

International reliance on water-scarce Brazilian river basins

We link municipal-level water use for soy and beef production to China and the EU's supply chains to quantify their appropriation of water resources and their dependencies on Brazilian river basins. This information was then combined with deforestation and GhG emissions for a multi-dimensional assessment of resources and impacts related to production and supply chains (Fig. 3). In the 2015–2017 period, China's imports required $300\text{--}461\text{ km}^3\text{ y}^{-1}$ of water through the combined $34\text{--}48\text{ Mt}$ of soy and $0.411\text{--}0.720\text{ Mt}$ of beef (as carcass weight (CW)). Over the same period, EU imports of $12\text{--}13\text{ Mt}$ of soy and $0.163\text{--}0.182\text{ Mt CW}$ of beef were attributed a combined $75\text{--}88\text{ km}^3\text{ y}^{-1}$ of water for commodity production (Fig. 3 and Supplementary Figs. 8 and 9). The majority (>99%) of water used for imports relied on green water resources, with a total volume of blue water for soy and beef ranging from 1.9 to $3.1\text{ km}^3\text{ y}^{-1}$ for China and 0.8 to $1.0\text{ km}^3\text{ y}^{-1}$ for the EU. Brazilian domestic consumption of $26\text{--}31\text{ Mt}$ of soy and $8.5\text{--}8.6\text{ Mt}$ of beef products, respectively, required $51\text{--}57\text{ km}^3\text{ y}^{-1}$ and $5190\text{--}5574\text{ km}^3\text{ y}^{-1}$ of water over the 2015–2017 period (Fig. 3 and Supplementary Figs. 8 and 9). Total volumes linked to imports were close to China's $380\text{ km}^3\text{ y}^{-1}$, but exceeded the EU's $60\text{ km}^3\text{ y}^{-1}$ of agricultural water withdrawals reported for the 2015–2017 period⁵. This comparison emphasises the importance of outsourcing water to Brazilian river basins with volumes typically not included in each of the blocs' domestic water demand²⁷.

Almost half of the blue water used for exports to the EU was sourced in river basins with high (mean of 35% of total volume for 2015–2017) or critical (13%) water scarcity according to classification by the Brazilian National Water and Sanitation Agency²⁸, compared to average (45%) and low scarcity (7%) (Fig. 4 and Supplementary Figs. 10 and 11). About 20% of blue water use for exports to China was sourced from basins experiencing high (a mean of 7%) or critical (11%) water scarcity compared to average (65%) and low scarcity (17%). Imports relied on a similar set of river basins, such as the São Francisco or Parnaíba (critical scarcity), Atlântico Sul or Uruguai (high scarcity), showing that the water use associated with any one country (e.g., the EU) could affect the supply chains of others (e.g., China) with effects on economies²⁹, as well as Brazilian domestic supplies. China and the EU's soy and beef supply chains are therefore not only at risk but also contribute to water scarcity in Brazilian basins.

Revealing connections among supply chains and specific river basins can guide strategies to ensure a secure and fair supply of water for all, including local communities and sectors, as well as ecosystems. Such strategies may include reducing the water footprint of production, thereby also affecting the amount of water linked to supply chains, especially in river basins with critical and high water scarcity. We calculate these potential water savings for China and the EU's imports, considering reductions of the largest soy and beef water footprints in municipalities of production (>80th percentile of production, see next section) to median values over the 2015–2017 period. Water savings ranged from 2 to $3.8\text{ km}^3\text{ y}^{-1}$ for China and 0.96 to $2.1\text{ km}^3\text{ y}^{-1}$ for the EU, with greater relative savings in the beef supply chain for which we only considered blue water (Table 2). Reducing the water footprint of production has previously been shown to lead to global water savings³⁰ and reduce the critical water dependency and risks to supply chains. Our results, however, show only minor changes to China and the EU's dependency on Brazilian river basins following strategies that could reduce the water footprint of soy and beef across the country.

Water scarcity and deforestation impacts

We carry out a benchmark analysis of production by ranking the municipalities that produce soy and beef according to their deforestation, water footprints and water scarcity footprints (as defined in Boulay et al.³¹) (Supplementary Figs. 12 and 13). Soy produced in municipalities with the largest deforestation footprints (>80th percentile of production with largest

Table 1 | Total resources use, impacts and environmental footprints of the soy and beef (as liveweight) sector and product in Brazil are shown as medians and ranges (in brackets) for the 2015–2017 period

	Unit	Soy	Beef
Resource use and impacts per sector (median (range))			
Production	Mt y ⁻¹	97.5 (96–115)	65.6 (65.6–66.5)
Land use	Mha y ⁻¹	33.3 (32–34)	156 (155–157)
Deforestation	Mha y ⁻¹	0.92 (0.76–0.93)	4.5 (4.2–4.7)
GhG emissions	Mt CO ₂ -eq y ⁻¹	138 (113–145)	2010* (1835–2078)
Total water use	km ³ y ⁻¹	192 (189–207)	1284 (1202–1285)
From rainfed systems (green water)	km ³ y ⁻¹	191 (188–206)	1274 (1192–1274)
From surface and groundwater sources (blue water)	km ³ y ⁻¹	1.0 (0.96–1.70)	10.4 (10.1–10.4)
Water source area	Mha y ⁻¹	0.88 (0.81–0.95) (irrigation)	0.51 (0.49–0.52) (reservoirs)
Environmental footprints per product (median of annual means (range))			
Yield	t or head ha ⁻¹	3.03 (2.89–3.37)	1.51**
Deforestation	ha kt ⁻¹	8.1 (7.9–9.4)	68.6 (64.0–70.7)
GhG emissions	t CO ₂ -eq t ⁻¹	1.3 (1.2–1.4)	30.1* (28.0–31.7)
Water	m ³ t ⁻¹	1938 (1805–1992)	19,356 (18,354–19,559)
From rainfed systems (green water)	m ³ t ⁻¹	1928 (1796–1981)	19,100 (18,200–19,400)
From surface and groundwater sources (blue water)	m ³ t ⁻¹	10 (9–18)	156 (154–159)

*As mean of estimates from enteric CH₄ using C_a = 0.17 and C_a = 0.34 (see “Methods” section).

**2017 only from IBGE census³⁶.

deforestation footprints, e.g., >0.00736 ha t⁻¹ in 2017, Supplementary Fig. 12 and Supplementary Table 13) were concentrated in the Matopiba region and the Southern (S) region (Fig. 5 and Supplementary Figs. 14 and 15). In 2017, municipalities within, and surrounding Matopiba, also exhibited a range of water footprints above and below 1962 m³ t⁻¹ (as the 80th percentile cutoff), as well as a mix of soy produced with and without irrigation. The municipalities with the largest beef deforestation footprint in 2017 (>0.104 ha (t LW)⁻¹, as 80th percentile cutoff) took place in the northern half of Brazil with a mix of values above and below 187 m³ (t LW)⁻¹ (80th percentile cutoff) and greater impacts to water scarcity near the coast in the SE and NE regions (Fig. 6 and Supplementary Figs. 16 and 17).

China and the EU may seek to minimise their impacts to water scarcity purely based on the performance of their product supply chains. We carry out a benchmark analysis of consumption focused on the 80th percentile of imported products having the largest water scarcity footprints. A total of 2.6–2.9 Mt and 0.76–1.1 Mt of soy imported respectively into China and the EU in 2015–2017 had the largest water scarcity footprints (Fig. 5 and Supplementary Table 14). These imports were associated with 19,100–42,000 ha and 15,200–18,300 ha of deforestation in respective supply chains (or 7–13% and 9–15% of total deforestation associated with imports in 2015–2017). For beef, import volumes were 0.0822–0.144 Mt CW for China and 0.0327–0.0365 Mt CW for the EU and were respectively associated with 31,900–64,800 ha (34–36%) and 1660–3370 ha (8–16%) of deforestation in the supply chain (Fig. 6 and Supplementary Table 14). These results show some level of overlap between deforestation and water scarcity impacts which can help reporting and due diligence requirements, particularly the EU’s Corporate Sustainability Due Diligence Directive³² with which companies could focus efforts on a few jurisdictions to ensure environmental compliance, including biodiversity loss from deforestation and scope 3 GhG emissions of land use change in addition to water scarcity. However, soy and beef supply chain interventions focused first and foremost on reducing water use impacts can also miss municipalities associated with a large portion of deforestation in the supply chain and on the ground.

We overlap municipalities of production showing the largest deforestation, soy irrigation and beef with the largest water scarcity footprints of production (>80th percentile) with China and the EU’s supply chains to gauge how supply chains coincide with impacts on the ground. In the 2015–2017 period, 3.1–3.4 Mt of soy was exported to China and 1.1–2.1 Mt of soy to the EU were produced in fewer than 79 municipalities with both irrigation and the largest deforestation footprints. These volumes were respectively associated with 70,900–118,200 ha (17–32%) and 27,300–69,500 ha (24–35%) of deforestation in China and the EU’s soy supply chains (Supplementary Table 14). Municipalities that produced beef with the largest deforestation and water scarcity footprints supplied 0.0035–0.0147 Mt CW to China and 0.000592–0.0011 Mt CW to the EU from fewer than 151 municipalities. These exports were associated with

Fig. 1 | Soy production water footprint in Brazilian municipalities in 2017. Sum of green and blue water footprints (A) and blue water footprint (B) (both in m³ t⁻¹) across the country’s regions (N North, NE Northeast, CWe Central West, SE Southeast, S South). See Supplementary Figs. 4 and 5 for 2015 and 2016.

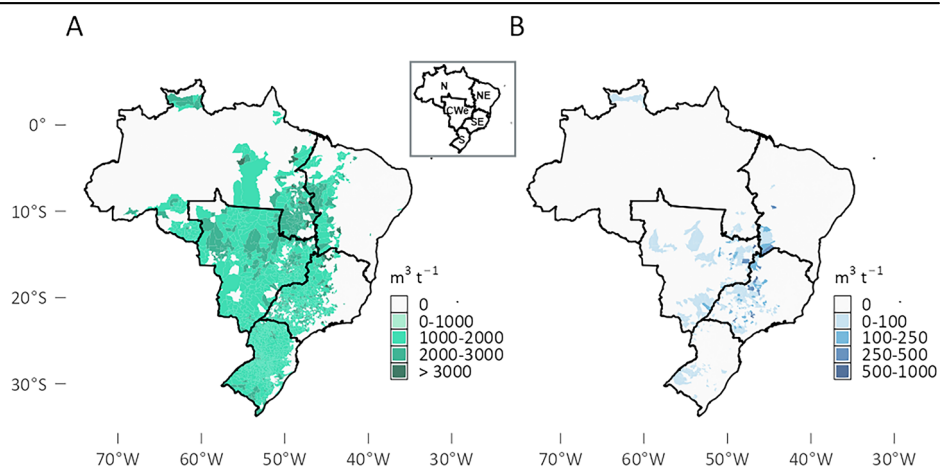


Fig. 2 | Beef production water footprints in Brazilian municipalities in 2017. Blue water footprint (A) and green water footprint (B) (both in $\text{m}^3 (\text{t LW})^{-1}$) across the country's regions (N North, NE Northeast, CWe Central West, SE Southeast, S South). See Supplementary Figs. 6 and 7 for 2015 and 2016.

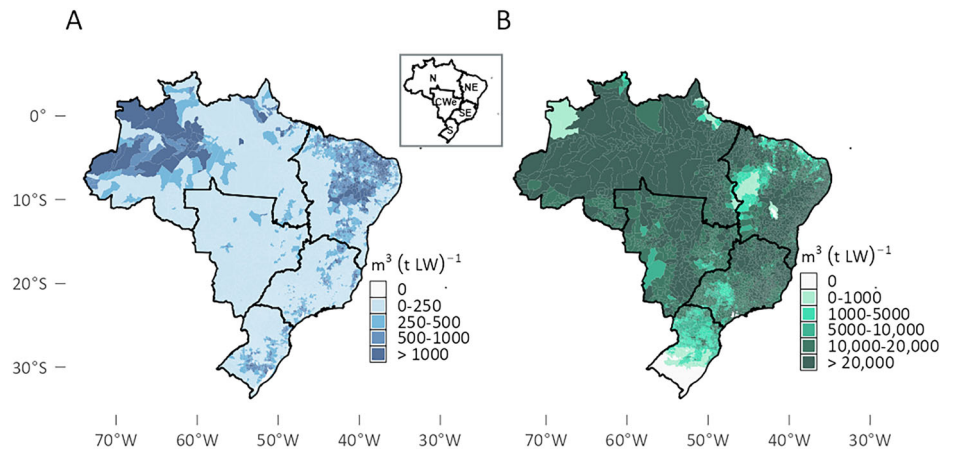
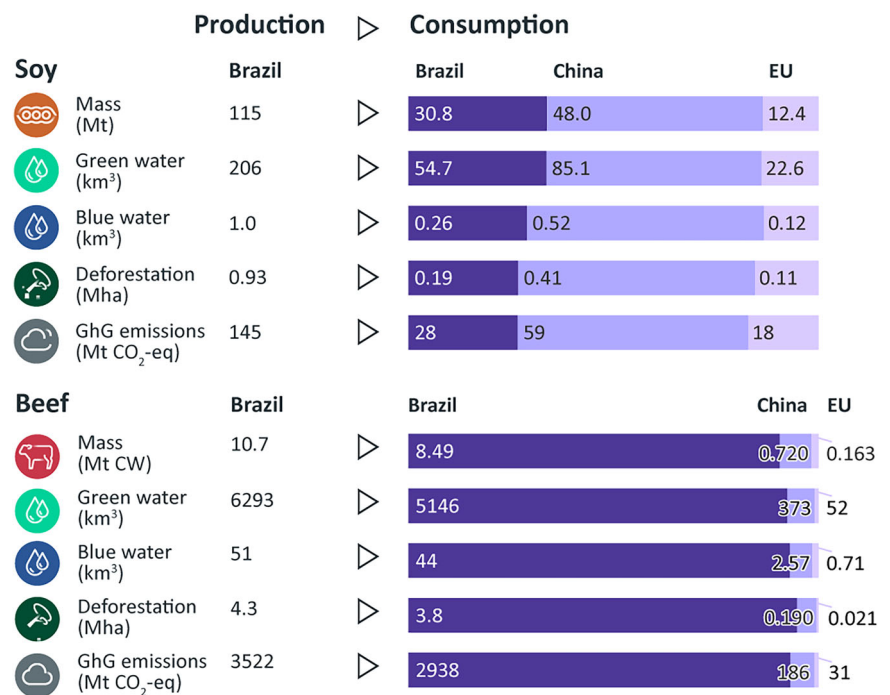


Fig. 3 | Resource use and impacts of Brazilian soy and beef production and consumption domestically and via trade to China and the EU in 2017. See Supplementary Figs. 8 and 9 for 2015 and 2016.



3600–16,500 ha (4–9%) and 570–1150 ha (3–5%) of deforestation in the respective supply chains (Supplementary Table 14). These results show much more coincidence of impacts among supply chains and production in the soy sector compared to the beef sector, given the larger size of the export market (Fig. 3), and therefore an opportunity to target collaboration among actors in a subset of municipalities.

Changes to supply chain environmental performance could be achieved through collaboration within river basins and improvements in agricultural production practices, but also a shift in sourcing to municipalities with lower deforestation or water use impacts. Cropland and cattle intensification are often presented as solutions to avert further deforestation and degradation, while also abating GhG emissions^{33,34}. Most cattle herding in Brazil takes place in non-intensive systems with a potential for intensification on existing pastureland³⁵, then allowing for soy and maize to be planted on degraded pasture and avoiding further deforestation³⁶. However, this process can carry additional water use, either through irrigation processes to increase productivity to three crops per year and allow early soy planting²³ as well as increased water use from a larger cattle herd, which in turn can increase hydrological

fragmentation, loss of freshwater ecosystem services and reduced provisioning to local communities³⁷.

Shifting sourcing based on environmental performance is already on the agenda ahead of upcoming legislation, such as the EUDR, with the creation of a multi-tiered system where producers and traders segregate commodity supply chains based on traceability and deforestation due diligence requirements³⁸. Without including water use together with deforestation in supply chains, a change in sourcing could shift the environmental burden of soy and beef imports from areas of high deforestation to areas of high water scarcity (e.g. beyond Matopiba and the NE region) or favour more intense production systems, which may push the need for more water resources.

This study presented a spatially explicit analysis of water use for Brazilian soy and beef production and supply chains to complement deforestation and GhG emissions assessments. Our water-specific results can be used in three ways. First, as an indication of China and EU's reliance on Brazilian water resources to ensure the supply of commodities consumed by each market. Brazilian water management not only affects other water uses (e.g. household, industry, energy, and ecosystems), but also domestic and

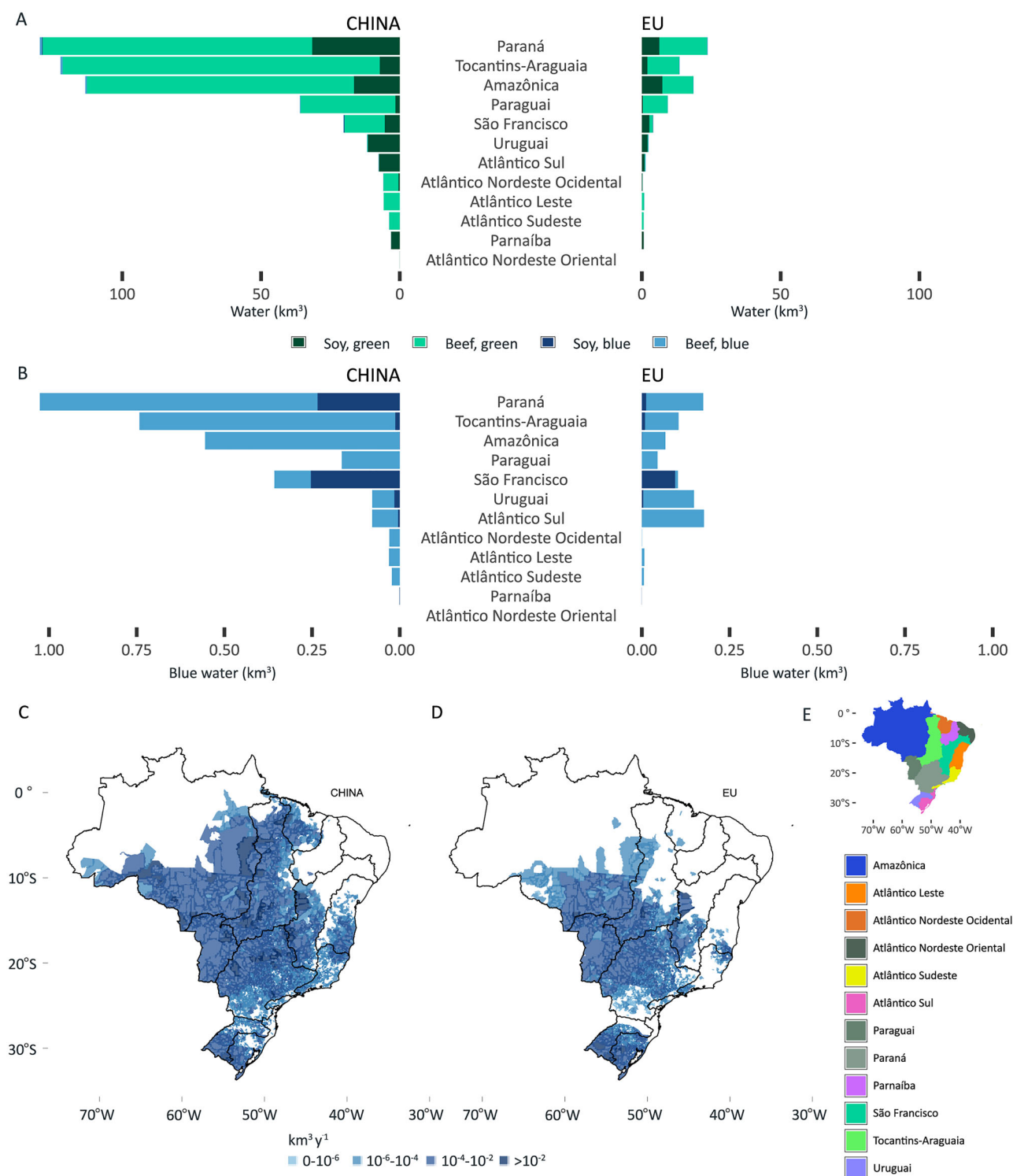


Fig. 4 | China and the EU's reliance on Brazilian river basins for soy and beef imports in 2017. Total (A) and blue water use (B) for soy and beef exports according to Brazil's river basins (E) (note the differences in scales between the bar graphs).

Map of total blue water use for soy and beef exported to China (C) and the EU (D). Values are provided per municipality of export contained within the river basins. See Supplementary Figs. 10 and 11 for 2015 and 2016.

international markets. Second, as an indication of potential supply chain disruption from the overlap of international reliance and water scarcity in each river basin that supplies the Chinese, EU and domestic markets. Water scarcity is affected by both water consumption activities and water availability in these basins, such that the production of commodities exported to the EU may affect the supply to Chinese and domestic markets, and vice versa. Finally, as an indication of the impact of water scarcity, allowing for

each individual supply chain to focus actions on specific river basins and municipalities. However, the level of overlap between international supply chain and production impacts can differ based on the size of the export market.

Combining water use with deforestation impacts in supply chains can prevent supply chain actors from shifting environmental impacts from one category to another and create opportunities to improve the

sustainability of production and supply chains beyond a single indicator. Given the interdependencies of water use for production and trade, including an assessment of water use in supply chains, can foster collaboration among actors in new ways that can also be complementary to the zero deforestation agenda.

Table 2 | Median national soy and beef water footprints and potential water savings in China and the EU's supply chains as a result of reducing Brazil's largest municipal water footprints (>80th percentile production) to median values over the 2015–2017 period

		2015	2016	2017
Soy				
Median national water footprint (green + blue)	$\text{m}^3 \text{ t}^{-1}$	1928	1918	1803
China	$\text{km}^3 \text{ y}^{-1} (\%)^*$	1.8 (3)	3.7 (5)	2.2 (3)
EU		0.77 (3)	1.9 (7)	0.86 (4)
Beef				
Median national water footprint (blue)	$\text{m}^3 (\text{t CW})^{-1}$	4456	4503	4410
China	$\text{km}^3 \text{ y}^{-1} (\%)^*$	0.21 (13)	0.26 (13)	0.32 (12)
EU		0.19 (25)	0.21 (27)	0.21 (30)

*As percent of total water (for soy) and blue water (for beef) in the supply chain.

Methods

Soy and beef production and consumption

We separated soy and beef production and consumption according to product type and geographic centres (Brazil, EU, China) (see below). Soy production was quantified as beans produced in Brazilian municipalities, as reported in national statistics³⁹. Soy consumption was expressed in soybean equivalents derived from the mass of beans needed to meet the volume of soy products consumed domestically and exported to the EU and China (Supplementary Methods). Soy is consumed as bean, oil or cake as identified by the harmonised system (HS) codes of each export (see below) and consumed domestically (as bean). Beef production and consumption were differentiated respectively as the living cattle herd (tonnes (t) liveweight (LW) y^{-1}) and the carcass weight (CW) equivalents produced from animal slaughter (t CW y^{-1}) that is subsequently exported to the EU and China under different HS codes (Supplementary Table 1) and consumed domestically. The living cattle herd was derived for each municipality using a detailed breakdown of animal age, sex, and confinement status, as well as regional LW from MCTI⁴⁰ (Supplementary Tables 2 and 3). The municipal living cattle herd was then used to derive the mass of CW produced per municipality using offtake rates corrected for animal movement as per zu Ermgassen et al.¹⁷ (Supplementary Methods).

Deforestation for soy and beef

Deforestation was allocated to soy and beef (as live cattle in pasture) following existing methods^{17,18,41}. Deforestation data were obtained from PRODES⁴² in the Amazon and Cerrado, and from MapBiomass⁴³ (Collection 6) for all other Brazilian biomes and overlaid in space and time with soy maps from Song et al.⁴⁴ and pasture maps from MapBiomass⁴³. To allocate deforestation to either soy or pastureland, a Landsat (30 m) pixel of land use in the year of production had to overlap with a pixel of deforestation up to

Fig. 5 | Soy production and supply chain performance in 2017. Soy production performance below (A) and above (B) the 80th percentile of production in municipalities with the largest soy deforestation footprint in 2017 and their corresponding water use and performance above (labelled as “above”) and below (labelled as “below”) the 80th percentile of production in municipalities with the largest water footprint. Soy water scarcity footprint in 2017 with hotspot municipalities supplying 2.6 Mt of soy to China (C) and 0.76 Mt to the EU (D) (with blue outline). See Supplementary Figs. 14 and 15 for 2015 and 2016. See Fig. 4 for river basin boundaries.

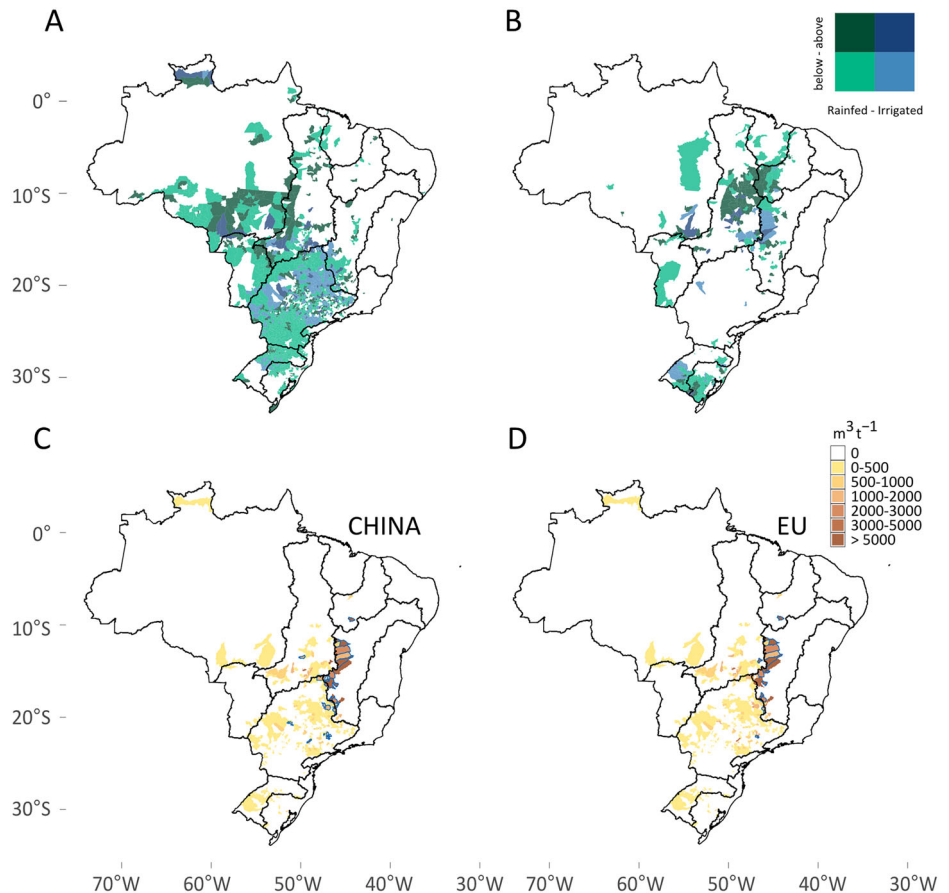
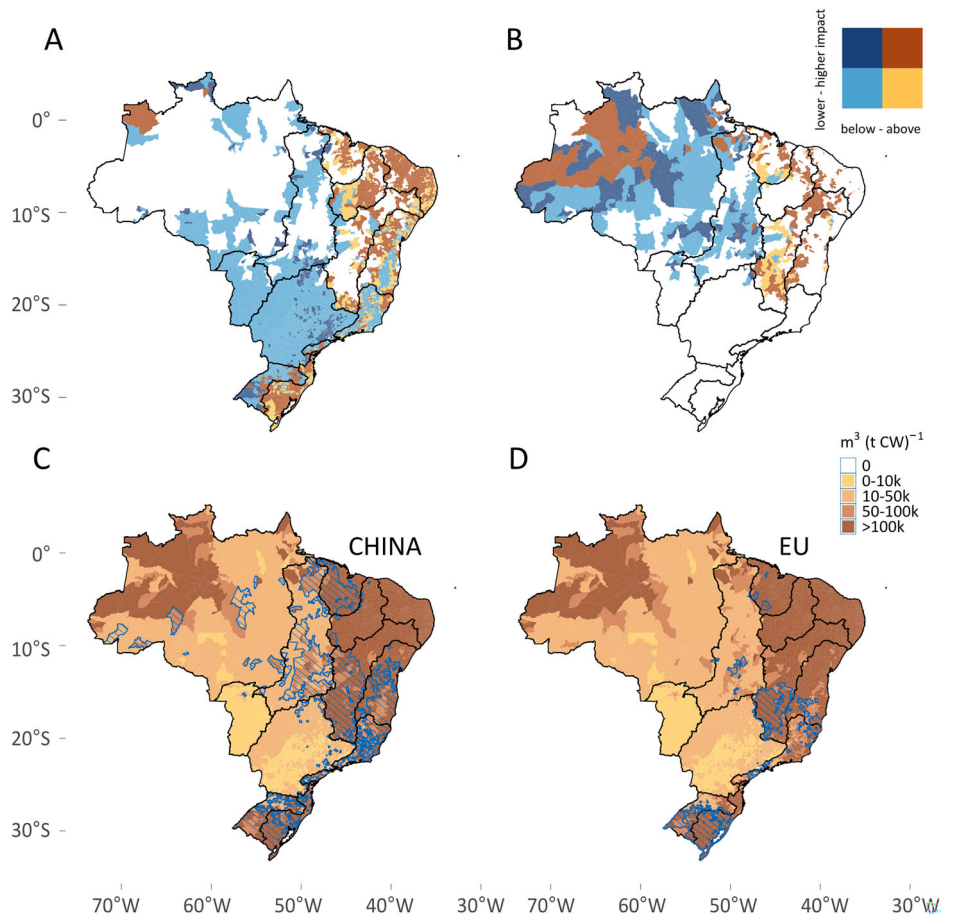


Fig. 6 | Beef production and supply chain performance in 2017. Beef production performance below (A) and above (B) the 80th percentile of municipalities producing beef with the largest deforestation footprint in 2017 and their corresponding water use performance above and below the 80th percentile of municipalities with the largest water footprints (as “below” and “above”) together with their relative water scarcity footprint (“lower impact”, “higher impact”). Beef water scarcity footprint in 2017 with hotspot municipalities supplying 0.144 Mt CW to China (C) and 0.0327 Mt CW to the EU (D) (with striped, blue outline). See Supplementary Figs. 16 and 17 for 2015 and 2016. See Fig. 4 for river basin boundaries.



five years prior to the year of production, assuming that pasture can be grown in the same year as the deforestation event, while the first soy harvest is assigned a one-year lag. As a result, soy and pasture produced in 2017 were allocated deforestation from the 2012 to 2016 and 2013 to 2017 periods, respectively. This pixel-level allocation was then summed at the municipality level to provide soy and pasture deforestation for municipality m and year y , following the method of Trase⁴¹. Deforestation per municipality was then allocated to the amount of municipal production to provide a deforestation footprint for soy (ha of deforestation per tonne of soy produced), and live cattle, considering deforestation for pasture (in ha of deforestation per tonne LW). To assign deforestation for pasture to beef produced (in ha of deforestation per tonne CW), a five-year allocation period was used to account for the fact that cattle live multiple years (Supplementary Methods).

Water use for soy and beef

Green and blue water use for soy and beef production (as a living herd) was calculated at the municipality level as water consumption⁴⁵. Falkenmark and Rockström³ contrast green and blue water resources based on the water source consumed. Soil water regenerated by rainfall, as green water, is consumed through crop or pasture ET, while surface or groundwater, as blue water, is consumed through irrigated crop ET and cattle drinking. Evaporation from farm reservoirs used for cattle drinking was also accounted as blue water following Lathuillière et al.¹³.

Total soy water use from ET (WU_{ET} , $m^3 t^{-1}$, as the sum of green and blue water use) in municipality m and year y was estimated from yield following Rockström⁴⁶ (Eq. 1):

$$WU_{ET,m,y} = \frac{WU_{T,s}}{1 - e^{bY_{m,y}}} \quad (1)$$

where $WU_{T,s}$ ($m^3 t^{-1}$) is the soy water use from transpiration and $Y_{m,y}$ is the soy yield ($t ha^{-1}$). Values of b were obtained by plotting $WU_{ET,m,y}$ estimates from Flach et al.⁷ with their corresponding $Y_{m,y}$ from IBGE³⁹ for the 2003–2013 period. Median state-level $WU_{T,s}$ was assumed to be median state-level $0.5WU_{ET,m,y}$ following Lathuillière et al.²³, leading to state-level median values of b that approached the value of -0.3 reported by Rockström⁴⁶ (Supplementary Table 5). Each state-level model was then used with 2015–2017 municipal yield data from IBGE³⁹ to derive the corresponding $WU_{ET,m,y}$.

Total soy water use for the 2015–2017 period was disaggregated into green and blue water use (details on study limitations are in Supplementary Note 1). First, we used the ratio of soil water deficit to crop water requirements from ANA⁴⁷ to estimate the amount of irrigation needed for soy in a municipality m and year y . These ratios were then applied to the total soy water use to estimate the potential soy blue water use in the municipality. Both green and blue water uses were then recalculated for the municipality as weighted by the irrigated soy area from MapBiomass Água⁴⁸, considering annual yields in the municipality. We assumed that soy was irrigated when the ratio of soil water deficit was >10% of the crop water requirement (Supplementary Figs. 1 and 2). In cases where no irrigation data were available from ANA⁴⁷, we assumed that the total soy water use was exclusively made of green water.

Blue water use for cattle per municipality m and year y is the sum of the blue water consumptive use of the living animal ($W_{animal,m,y}$) and the evaporation from farm reservoirs ($W_{res,m,y}$) from which unconfined cattle source water on the landscape¹³ (Eq. 2):

$$W_{cattle,m,y} = W_{animal,m,y} + W_{res,m,y} \quad (2)$$

Values of $W_{animal,m,y}$ ($m^3 y^{-1}$) were obtained per head of cattle within each category (age, sex, (un)confinement) following Ridoutt et al.⁴⁹ as the

sum of drinking water (W_{drink}), water in feed (W_{feed}) and metabolic water (W_{met}) (Supplementary Eqs. 4–6). To estimate W_{drink} , we used a Brazil-specific estimate from Zanetti et al.⁵⁰ (Supplementary Equation 4) together with state-average meteorological conditions for the 2010–2019 period⁵¹ (Supplementary Table 7). Values of $W_{\text{res},m,y}$ ($\text{m}^3 \text{y}^{-1}$) were estimated using 2010–2019 mean municipality reference ET from Xavier et al.⁵¹ as a proxy. The dam and reservoir area in each municipality was obtained from MapBiomass Águia⁴⁸ in which anthropic reservoirs were filtered in Google Earth Engine⁵² and assigned to the cattle sector, considering area (0.5–50 ha) and proximity to pasture (>10% coverage). Green water use for cattle was obtained as pasture ET using the model from Zhang et al.⁵³ (Supplementary Eq. 7), together with the mean municipality reference ET and precipitation⁵¹ (Supplementary Methods). Details on the allocation of blue and green water use to beef (in m^3 per tonne CW) are described in the Supplementary Methods.

Water scarcity and water scarcity footprint

River basin blue water scarcity was derived as the area-weighted sum of the micro-basin blue water scarcity values of ANA²⁸ contained within each of the 12 macro-basins of interest. ANA²⁸ obtained blue water scarcity as the ratio of water demand to water availability (as Q95) and provided six categories based on the result percentages: low (<5%), average (5–30%), high (30–70%), very high (70–100%), critical (>100%), and periodic (null). Blue water impacts on water scarcity were expressed as a water scarcity footprint following the method of Boulay et al.³¹ in which the blue water footprint is multiplied by a river basin impact factor representing the relative level of available water remaining per area once human and aquatic ecosystem demands have been met³¹. We used the Brazil-specific river basin impact factors from Andrade et al.⁵⁴ applied to the blue water footprint of soy and beef (Supplementary Table 11).

Soy and beef GhG emissions

GhG emissions from land use change for soy and beef production were obtained by converting the pixel-level deforestation (type of vegetation and area) allocated to soy and pastureland (see above) with the carbon stock information of SEEG⁵⁵ on above- and below-ground biomass and necromass. This pixel-level allocation was then summed at the municipality level to provide soy and pasture GhG emissions from deforestation for municipality m and year y . We then derived a municipal carbon footprint from deforestation for soy (in tonnes $\text{CO}_2\text{-eq}$ from deforestation per tonne of soy produced), and live cattle, considering deforestation for pasture (in tonnes $\text{CO}_2\text{-eq}$ per tonne LW). Enteric and manure CH_4 emissions, and manure N_2O (direct and indirect) emissions were calculated following the procedure and parameters of MCTI^{40,56} based on IPCC guidelines⁵⁷ (Supplementary Methods). All emissions were converted to $\text{CO}_2\text{-eq}$, considering a 100-year global warming potential ($28 \text{ kg } \text{CO}_2\text{-eq} (\text{kg } \text{CH}_4)^{-1}$, $265 \text{ kg } \text{CO}_2\text{-eq} (\text{kg } \text{N}_2\text{O})^{-1}$)⁵⁸. To assign deforestation for pasture to beef produced (in tonnes of $\text{CO}_2\text{-eq}$ per tonne CW), a five-year allocation period was used to account for the fact that cattle live multiple years (Supplementary Methods). Emissions from fertiliser application, as well as truck and vessel transport, were not included in our sector GhG emissions estimate (Supplementary Note 1).

Brazilian soy and beef supply chain mapping

Our study focuses on the 2015–2017 trade period as it represents the window with the best overlap of trade data with the inputs needed to quantify the environmental indicators (Supplementary Methods). Supply chain maps were obtained from Trase (trase.earth) for Brazilian soy (v.2.6.1)⁵⁹ and beef (v.2.2.0)⁶⁰ which link a municipality of production to a country of import, including the traders involved (exporters and importers) through an improvement in the method described in Godar et al.⁶¹ and zu Ermgassen et al.¹⁷. These supply chains were constructed from the combination of per-shipment trade data, trader tax registration, and company facilities and ownership information to link each trade flow to the most probable municipality containing a silo or slaughterhouse through a logic-based decision tree. Soy and beef trade volumes were obtained by selecting

representative products and sub-products as they are identified as soy bean (HS 1201), oil (1507, 2304) and cake (1208), or beef as fresh or frozen (0201, 0202), offals (0206, 0210), processed or canned (1602) or live cattle (0102), normalized to soybean equivalents and beef CW equivalents using product-specific equivalence factors (Supplementary Table 1). Silo facility information was obtained from the Brazilian National Supply Company (CONAB), which lists a National Registry of Storage Facilities (SICARM), combined with sanitary permissions from SICASQ. Crushing facilities were obtained from the Brazilian Association of Vegetable and Oil Industries (ABIOVE) combined with market research by JJ Hinrichsen (<https://jotajota.com.ar/>). Slaughterhouses were obtained from MAPA⁶². Volumes of soy and beef aggregated in municipalities containing facilities were then allocated to municipalities of production following distinct methods for soy and beef. Municipalities producing soy for a municipality containing a silo were assigned using linear programming optimization for cost of soy transport (as time of travel using an OSRM transportation matrix) with four constraints: export demand, soybean production (as per IBGE³⁹), soybean consumption (as crushing capacity) and the oil to cake mass ratio resulting from the crushing of bean⁶³. Municipalities supplying cattle to slaughterhouses were identified using animal movement records as described by zu Ermgassen et al.¹⁷.

All calculations and data manipulations were carried out using statistical software R (v.4.4.1)⁶⁴ in RStudio (v.2024.9.1.394)⁶⁵ and packages (Supplementary Note 2).

Reporting Summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All data that support the findings of this study are available in Zenodo (<https://zenodo.org/records/14921618>) and include: Brazilian state-level water use and GhG emission factors for cattle, Brazilian municipal-level soy, cattle and beef production information, Brazilian municipal-level benchmarks for soy, cattle and beef production, Brazilian municipal-level soy and beef supply chains from Trase with deforestation, water and GhG emissions.

Code availability

R code used for analysis is available in Github (https://github.com/mlathuilliere/Lathuilliere_et_al_2025).

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Conceptualisation: M.J.L. Data generation and analysis: M.J.L., R.F., V.R., C.M.S. Writing—original draft: M.J.L. and R.F. Writing—review and editing: M.J.L., R.F., L.W.-E., V.R., E.K.H.J.z.E., and C.M.S.

Competing interests

The authors declare no competing interests.

Additional information

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