Queries by anonymous referee #3 & answers by the authors

Dear Referee,

thank you very much for providing us with your insightful comments, which helped us to further improve the manuscript. Your time and effort is much appreciated. Please find the answers (in black) to your queries (in blue) below.

Referee #3: I was very pleased to see the study from Multsch et al. who have taken on such an important challenge to assess the irrigation potential of Brazilian crops in the Cerrado region. The study looks specifically at agricultural practices in 2012 and then estimates blue water scarcity from irrigation expansion assuming that irrigation will be applied to current rainfed agriculture. While I applaud the goals of the study, I have some reservations on the methods and results which need further clarification and review.
My concerns mainly are:
-Concerns over the definition of irrigation expansion
-Concerns over modeling choices and water scarcity
-Lack of a sensitivity analysis and deeper insight into study limitations

Referee #3: Concerns over the definition of irrigation expansion
The definition of irrigation expansion is solely based on current practices (and I appreciate the reference to this assumption on L-175-176),

1) however the use of irrigation is only expected until the onset of the rainy season, particularly in central and south-western Cerrado.
2) We would expect the CONAB general planting dates and season to change to adapt to irrigation practices.
3) For instance, irrigation has been applied in the first month of soybean development as a means to anticipate the growing season, but also to include a third crop in the dry season (Lathuillière et al., 2018).
4) I also strongly suggest that the authors consider an interannual scarcity estimate, with a focus on the dry season when we would expect irrigation practices to kick-off. This additional piece of information would be more informative since more in line which the practices that we expect.

Authors: Thank you for these detailed observations. We have taken the liberty to split up the comment into four parts and would like to note the following:

1) In this study we postulate that full irrigation is desired, hence the algorithm to determine crop water requirements used here (Sections 3.1.2 and 3.2.1) does consider irrigation only if effective precipitation is not sufficient to meet demand.
2) We agree that planting dates will be adjusted from year to year, based on the onset of the rainy season. To reflect this, subregion-specific planting (and harvesting) dates have been considered in this study. These were obtained from CONAB and are listed in Table A2.
3) We would like to note that we have included 2nd and 3rd crops in our study as appropriate, i.e. a strong attempt has been made to reflect such practice of the study year 2012 throughout Brazil as realistically as possible.
4) We have aligned our choices with those of current practice in Brazil. Q95 and scarcity levels used in this paper have been suggested and are used by ANA, the National Water Agency of Brazil (ANA 2015). In light of this, we don't see that there is anything substantially wrong with the scarcity indicator that we have chosen. Additional scarcity

estimates (e.g. inter-annual) may be interesting, but they are not necessary in order to convey the points that we have conveyed in the manuscript.

Referee #3: Concerns over modeling choices and water scarcity
1) Despite great detail provided in the methodology, there are still many open questions on some important modeling choices. The region presents important seasonality in rainfall and hydrologic years are typically represented between September and August. Did the study consider calendar year 2012? I think the years should appear in Table A2 as key parameters into the model (this information would also improve the reproducibility of the study).
2) With respect to water scarcity, there seems to be a slight deviation from the typical consumption-to-availability ratio calculations in which availability is often defined including environmental flow requirements (Boulay et al., 2018; Mekonnen and Hoekstra, 2012) which was not mentioned in the study, other than Q95 already include all currently allocation blue water flows within the basins. This has typically been done by comparing Q50 and Q90 flows (previously unallocated) (Smakhtin et al., 2004).

Authors: Answers to the two parts of this query by referee#3 are provided below.
1) The question about year 2012 was raised also further below by referee#3. We have studied the production year 2012. We make reference to what we cover in terms of harvested area, production mass and production value on page 4, lines 104 to 107. This data is provided per year, and so are others that we use (e.g. extent of irrigated areas). Certainly, the cropping cycle is essential in the analysis. We have added the word 'production' so that it now reads 'production year' and we refer to Table A2 (planting and harvesting dates) in the text. We have changed the terminology throughout the manuscript. We feel that adjusting Tables 2 and 3, and referring to Table A2, rather than changing Table A2 has accomplished what the referee#3 points out.
   Furthermore, we use actual climate data (precipitation, maximum and minimum temperature, solar radiation, relative humidity, and wind speed), and we are hence uncertain why the referee#3 points out seasonality as an issue. Seasonality is certainly captured in our study.
2) We agree that considerations of environmental flow requirements are important. There are many ways to consider environmental flows apart from Hoekstra et al. (2012). We are using Q95 as considered by ANA (2015) in Brazil as a first step. The resulting scarcity levels are in line with the reporting that the Brazilian Water Agency ANA uses (ANA, 2015). We do not agree with the notion of 'typical'. We have provided reasons for our choices and we find that there is no obligation to utilise the definition of the papers that referee#3 cites. There are studies that are in line with the approach chosen here. See for example Flach et al. (2016), which we have now cited in our paper (p. 6, line 194). We have also provided references to support our choice (section 3.2.3). We have further expanded the discussion section to allude to this.

Referee #3: Lack of a sensitivity analysis and deeper insight into the study limitations There are some modeling choices that I expect would have quite a large impact on the results and would suggest that the authors consider a sensitivity analysis on at least the use of the factor of 2 used to derive water withdrawal from consumption (L-200) and the planting dates provided by CONAB. Planting dates are known to change based on the onset of the rainy season (Arvor et al., 2014) which is strong evidence for the use of a window of planting dates for the 2012/2013 season based on precipitation regimes in each basin. The study would also greatly benefit from self-criticism of the results, perhaps in a supplemental material, where all assumptions and limitations are described to offer the reader with a critical view of the results.

This information is somewhat described at the beginning of the Discussion section, but the information provided seem more like a justification of the modeling choices rather than an assessment of how these choices might affect the main conclusions of the study (and thus require more discussion).

Authors: We have expanded the discussion and further addressed limitations of the study therein. One specific comment here: we have used actual planting dates, not generic ones. While planting dates may change based on the onset of the rainy season, we used known planting dates from the past, as recorded in the annual reports provided by CONAB. We have included this point in the discussion section as well.

We would also like to point out that we have mentioned issues around dry spells and late planting in our text (section 5.3).

Some additional key points that merit mention are:

Referee #3: The lack of other water sources in the scarcity calculation; this is mentioned in the introduction (L-89), but this information can easily be forgotten as an important factor to be considered. In fact, I would expect the irrigation expansion to occur primarily as a function of groundwater availability and water available in small dams previously used for cattle drinking water (Rodrigues et al., 2012) rather than surface water availability.

Authors: Thank you for pointing out this complexity. We have opted to focus on surface water at first – as noted in the title of the paper (next to the introduction). We would argue that there is nothing wrong with working out one step at a time. We will consider other water sources in future work.

Referee #3: The importance of currently existing infrastructure and the most recent study from ANA on irrigation (https://www.ana.gov.br/noticias/ana-e-embrapa-identificam-forte-tendencia-de-crescimento-da-agricultura-irrigada-por-pivos-centrais-no-brasil/ana_levantamento-da-agricultura-irrigada-por-pivos-centrais_2019.pdf)

Authors: We have included these points in the now extended discussion section of the paper.

Referee #3: Some comparison of results to previous work on crop water use would be helpful, using global and regional studies

Authors: We already have included and discussed relevant studies (e.g. Lathuillière et al. (2016), Fachinelli and Pereira (2015) or Scarpare et al. (2016). We added further studies.

Specific comments Referee #3: P-2, L65: Please provide a reference for the terms "green" and "blue" water.

Authors: We have added the reference "Falkenmark (1995)".

Falkenmark, M.: Land-water linkages: a synopsis. In: FAO, Land and water integration and river basin management, Proceedings of an FAO informal workshop, Rome, Italy, 31 January–2 February 1993, FAO Land and Water Bulletin 1, Food and Agriculture Organization, Rome, pp. 15–16, 1995.

Referee #3: P-3, L.67: The authors should recognize the timely nature of water resources in Brazil as well given the wet and dry seasons, particularly in the Cerrado.

Authors: Thank you. We have adjusted this sentence, which now reads: "Hence, efficient, sustainable and equitable strategies must be developed, thereby considering the spatially and temporally varying water availability."

Referee #3: P3, L82: A definition of water consumption is warranted and its relation to water scarcity in this paragraph, particularly considering the definition from ANA related to water availability and water withdrawal.

Authors: Those definitions and relationships are provided in later sections (3.1 and 3.2). We feel that this brief description of the analysis steps would become rather lengthy if we copy all definitions and explanations of relationships over to this part. We would therefore ask the reviewer to allow us to keep things as they are.

Referee #3: P3, L83: Please confirm that you are considering an "irrigation" expansion scenario (it does appear on L87). Is the nature of the assumption needed here (instead of the methods)? In reality, irrigated cropland becomes rain-fed as soon as the rainy season begins, even in the case of crops that are not typically irrigated (Lathuillière et al., 2018).

Authors: Yes, we confirm that an irrigation expansion scenario has been investigated in this study. Please note that we are providing an analysis that includes a 'full irrigation' scenario. Rainfall is of course considered in the 'irrigation scenarios' studied here and irrigation is provided only to make up for a deficit. So our approach also considers dry spells.

Referee #3: P3, L91: a separate section called "Data" prior to the methods seems a little odd

Authors: This order has been chosen since reference to various data sets used in this study is made in the Methods section. We would hence like to leave the order as is.

Referee #3: P3, L94: What years were selected to derive ET based on the meteorological parameters? I understand that daily data is needed, but are you then using a 30-y average (from the 1980/2013 time series)? How is this data related to the year 2012, and how does it match discharge calculations from ANA described on P7, L188? This was answered by authors in response to R1, but why have a mismatch between consumption and availability?

Authors: We are using the data for the production year 2012, which encompasses the time periods that are provided in Table A2. The reason why we have chosen this year is provided in the text on p. 3, lines 78-79. We have revised the sentence in question to now read: "Precipitation, maximum and minimum temperature, solar radiation, relative humidity, and wind speed data for the production year 2012 were obtained from Xavier et al. (2016), who developed a daily gridded dataset for Brazil with a 0.25°×0.25° resolution of these meteorological variables based on 3,625 rain gauges and 735 weather stations."

Referee #3: P4, L103: please provide scientific names for all crops. All "beans" should be "bean"

Authors: Thank you for pointing this out. We have adjusted the text accordingly, i.e. changes all occurrences of 'beans' to 'bean'.

Referee #3: P4, L113: "demands", this term should be replaced by "consumption" as the study clearly does not look at demand, but consumption of water.

Authors: The text has been adjusted accordingly.

Referee #3: P4, L121-122: The link sends to a login page, not a download page to the model: is this correct?

Authors: Thank you for pointing this out. There was a change in servers and the link has since been changed. We have decided to remove the link and leave the reference to the original paper where the first version of SPARE:WATER has been introduced. We trust that interested readers will get in touch with the developers at University of Giessen in Germany to obtain a copy of the latest version of the software free of charge.

Referee #3: P6, L162: the symbols for water content at field capacity and wilting point are reversed. Also, equation (6) does not show water content at wilting point.
Authors: Thank you very much for spotting this. We have corrected the text.

Referee #3: P6, L185: If Q95 already includes all regulated flows, can you confirm that it does not include environmental flow requirements? This inclusion is an important component of deriving blue water scarcity following several methods such as (Hoekstra et al., 2012)
Authors: We agree that considerations of environmental flow requirements are important. You re referring to Hoekstra et al. (2012), But there are many other ways to consider environmental flows. We are using Q95 as considered by ANA (2016) in Brazil as a first step. We would also like to note that we present the resulting scarcity levels in line with the reporting that ANA uses (ANA, 2015). Others have followed the same approach that we apply here (see Flach et al., 2016).

Referee #3: P7, L187: It is important to mention that blue water availability does not take into account any environmental flow requirements, which have often been used to derive a blue water scarcity ratio as per (Boulay et al., 2018; Hoekstra et al., 2012).
Authors: Again, we agree that environmental flow requirements are important. We would like to re-iterate that we have made the intentional choice to use as much of the currently used indicators and nomenclature as possible, i.e. to use those that ANA uses. In a next step environmental flow requirements should be investigated. This will aggravate the results. We note this in a newly added part of the discussion section, based on the comments received by Referee #3.

Referee #3: P7, L200: I am unsure I fully understand where the ratio of 2 comes from. I understand the need to factor in non-crop water uses, but how is this factor applied? And applied to what? The water scarcity level? The blue water consumption estimate? The response to previous comments for Reviewer 1 does not help in understanding this factor.
Authors: Please note that the factor of 2 was applied to adjust the scarcity levels, because the original levels were related to gross water consumption (i.e. no consideration of losses). No such factor has been applied to the crop water requirements (equation 4). Water scarcity is calculated on the basis of water availability in the catchments and blue water consumption (equation 2). A detailed description can be found in the manuscript (page 7, 205-211): *"In this paper, net water withdrawal (or blue water consumption) rather than gross water withdrawal is compared to water availability, often termed consumption-to-availability ratio (Vanham et al., 2018). Therefore, the scarcity levels described above were adjusted to reflect that withdrawals also include non-consumptive losses at field scale and losses during transport of water to the field, which are not considered when calculating blue water consumption. To account for this a factor of 2 was applied, which is a central estimate of the ratio between withdrawal and consumptive blue water use reported in Wriedt et al. (2008). The resulting scarcity levels represent the same classes of water scarcity from acceptable to very critical, but are adapted to the threshold values of 2.5, 5, 10 and 20%."*
We would ask the reviewer to acknowledge that we are making a strong effort to account for aspects that other authors do in fact neglect. The factor of 2 is based on published work by Wriedt et al. (2008). Certainly, to utilize Brazil-specific and spatially differentiated factors would be even better. We added a note to a newly added part of the discussion section.

Referee #3: P7, L214: It is unclear how the allocation of available blue water and water consumptive use was carried out for municipalities that are contained in two different basins. Please clarify your choices.

Authors: Please see Figure A1, where the spatial aggregation steps have been summarized. See also the text (page 5, line 136 to line 143). *"First, the daily crop water balance was calculated at 0.25°x0.25° grid-level for each crop per growing season, utilising the gridded climate and soils data (see Table 1). Second, the contribution of crop production to the regional water balance at the level of municipalities was derived by multiplying crop water consumption per growing season, averaged over the grids in the municipality, with the respective municipal cropping area [ha a-1]. Note that the information regarding irrigated areas and the fraction of irrigated area per crop was also available at municipality level (Table 1). Thirdly, the total water consumption was determined per sub-catchment, which was then contrasted with water supply in each one of the 166,842 sub-catchments and aggregated to municipality level. These steps are shown in Figure A1."*

Referee #3: P11, L338: "parameter" typo

Authors: Thank you very much for spotting this. It has been corrected in the text.

Referee #3: P14, L418: I suggest you call this "moisture recycling"

Authors: We agree, using 'moisture recycling' would be well suited. However, we did use the wording used in the original paper by Spera et al. (2016) and we feel that we should in fact do so, in order to avoid confusion.

Referee #3: Figure 4: I am a little confused with the data presented here. Do you mean that the information in d, e and f (which are labeled as rainfed, please consider re-labeling) is the scarcity should irrigation be applied to rain-fed agriculture only? I take that these area are basically those where crop ET < ETc for the existing mix of crops in each municipality.

Authors: The information provided refers to the potentially irrigated areas (all rainfed areas are irrigated, as described on p. 3, lines 84-86). The method that has been applied is described in detail in part 3 ('Methods').

Regarding the comment on re-labeling:

Authors: We would prefer to keep the labels, as the Figure caption clearly states what the Figure show. Additional note: We found a typo in the text (line 333 on page 11), which has been corrected. We referred to Figure 4b, while it is in fact Figure 4a that we discuss.

Referee #3: Table A2: There are many acronyms in this table that need to be defined (IRR, Corn 1st, etc.): Please confirm that these results represent an average of the entire Brazilian Cerrado following the spatial variability in planting dates, precipitation and soil texture described in the methods. Why is ET in mm and Green water in m3/y? In fact, the time component should be expressed per crop cycle (which is shorter than a year). This table would benefit also from additional information on planting dates and total development cycle to better understand ET (or at least reference Table A1 and A2).

Regarding the comment on the acronyms:

Authors: We were not able to find 'IRR' in Table A2. However, IRR (which appears in Table 2) and such acronyms (ET_{act}, P_{eff}) are described in the 'Methods' section of the manuscript. We have added the following sentence to the Table caption of Table A2: *"Note that "2nd" and "3rd" are the second and third planting dates for double- and triple-cropping within one growing season, i.e. a successive multiple cropping practice."*

We also added the following sentence to the Table caption of Table 2: *"1ˢᵗ", 2ⁿᵈ" and "3ʳᵈ" are the first, second and third planting dates for successive multiple cropping practice within one growing season.*

Regarding the comment 'results represent an average of the entire Brazilian Cerrado':

Authors: Table 2 shows the results for all of Brazil, whereas Table 3 shows the result for the Cerrado only. We have extended the Table caption of Table 3 (added the study year, and also added the sentence that we added to Table 2, as described above). And yes, the results presented are averages, thereby considering the spatial variability in planting dates, single-, double- and triple-cropping, spatially varying climate and soils, etc.

Regarding the comment 'Why is ET in mm and green and blue water in volume per year'?

Authors: There is no particular reason.

Regarding the comment on the year information:

Authors: We make reference to what we cover in terms of harvested area, production mass and production value on page 4, lines 104 to 107. The relevant sentences are reproduced here for convenience: *"The crops considered are cotton, rice, sugarcane, Vigna spp. and Phaseolus spp. bean, cassava, corn, soybean and wheat. Combined those nine crops account for 96% of harvested area [ha], 98% of production mass [ton] and 90% of production value [Brazilian Real] in Brazil in the year 2012 (IBGE, 2012)."* This data is provided per year, and so are others that we use (e.g. extent of irrigated areas). We of course agree that the cropping cycle is essential in the analysis. We have added the word 'production' so that it now reads 'production year' and we refer to Table A2 (planting and harvesting dates)

Regarding the comment on the planting date etc.

Authors: Since this Tables 2 and 3 already rather sizeable we would like to keep the initial information in Tables A1 and A2. We refer to these tables in Table 1 in the text. We have added the following text to the captions of Tables 2 and 3: *"Crop development stages are provided in Table A1 and planting/harvesting dates are provided in Table A2."*

References

ANA: Conjuntura dos recursos hídricos no Brasil, Informe 2015, Agência Nacional de Águas, Brasília, Brazil, 88 p., ISBN: 978-85-8210-030-1, 2015.

Arvor, D., Dubreuil, V., Ronchail, J., Simões, M., Funatsu, B.M., 2014. Spatial patterns of rainfall regimes related to levels of double cropping agriculture systems in Mato Grosso (Brazil). Int. J. Climatol. 34, 2622–2633. doi:10.1002/joc.3863

Boulay, A., Bare, J., Benini, L., Berger, M., Lathuillière, M.J., Manzardo, A., Margni, M., Motoshita, M., Núñez, M., Pastor, A.V., Ridoutt, B., Oki, T., Worbe, S., Pfister, S., 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, 368–378. doi:10.1007/s11367-017-1333-8

Falkenmark, M.: Land-water linkages: a synopsis. In: FAO, Land and water integration and river basin management, Proceedings of an FAO informal workshop, Rome, Italy, 31 January–2 February 1993, FAO Land and Water Bulletin 1, Food and Agriculture Organization, Rome, pp. 15–16, 1995.

Fachinelli, N. P. and Pereira Jr., A. O.: Impacts of sugarcane ethanol production in the Paranaiba basin water resources, Biomass Bioenerg., 83, 8-16, https://doi.org/10.1016/j.biombioe.2015.08.015, 2015.

Flach, R.; Ran, Y.; Godar, J.; Karlberg, L.; Suavet, C. Towards more spatially explicit assessments of virtual water flows: Linking local water use and scarcity to global demand of Brazilian farming commodities. Environ. Res. Lett. 2016, 11, 075003.

Hoekstra, A.Y., Mekonnen, M.M., Chapagain, A.K., Mathews, R.E., Richter, B.D., 2012. Global Monthly Water Scarcity: Blue Water Footprints versus Blue Water Availability. PLoS One 7, e32688. doi:10.1371/journal.pone.0032688

IBGE: Produção Agrícola Municipal. Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro, Brazil. Available at: http://www.sidra.ibge.gov.br/, 2012.

Lathuillière, M. J., Coe, M. T., and Johnson, M. S.: A review of green- and 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, 2179-2194, 2016.

Lathuillière, M.J., Dalmagro, H.J., Black, T.A., Arruda, P.H.Z. de, Hawthorne, I., Couto, E.G., Johnson, M.S., 2018. Rain-fed and irrigated cropland-atmosphere water fluxes and their implications for agricultural production in Southern Amazonia. Agric. For. Meteorol. 256–257, 407–419. doi:10.1016/j.agrformet.2018.03.023

Mekonnen, M.M., Hoekstra, A.Y., 2012. A Global Assessment of the Water Footprint of Farm Animal Products. Ecosystems 15, 401–415. doi:10.1007/s10021-011-9517-8

Rodrigues, L.N., Sano, E.E., Steenhuis, T.S., Passo, D.P., 2012. Estimation of small reservoir storage capacities with remote sensing in the Brazilian Savannah region. Water Resour. Manag. 26, 873–882. doi:10.1007/s11269-011-9941-8

Scarpare, F. V., Hernandes, T. A. D., Ruiz-Corrêa, S. T., Picoli, M. C. A., Scanlon, B. R., Chagas, M. F., Duft, D.G., de Fatima Cardoso, T.: Sugarcane land use and water resources assessment in the expansion area in Brazil, J. Clean. Prod., 133, 1318-1327, 2016.

Smakhtin, V., Revenga, C., Doll, P., 2004. A Pilot Global Assessment of Environmental Water Requirements and Scarcity. Water Int. 29, 307–317. doi:10.1080/02508060408691785

Spera, S. A., Galford, G. L., Coe, M. T., Macedo, M. N., and Mustard, J. F.: Land-use change affects water recycling in Brazil's last agricultural frontier, Glob. Change Biol., 22, 3405-3413, https://doi.org/10.1111/gcb.13298, 2016.

Vanham, D., Hoekstra, A. Y., Wada, Y., Bouraoui, F., de Roo, A., Mekonnen, M. M., van de Bund, W.J., Batelaan, O., Pavelic, P., Bastiaanssen, W.G.M., Kummu, M., Rockström, J., Liu, J., Bisselink, B., Ronco, P., Pistocchi, A., and Bidoglio, G.: Physical water scarcity metrics for monitoring progress towards SDG target 6.4: An evaluation of indicator 6.4.2 "Level of water stress", Sci. Total Environ., 613-614, 218-232, https://doi.org/10.1016/j.scitotenv.2017.09.056, 2018.

Wriedt, G., Van der Velde, M., Aloe, A., and Bouraoui, F.: Estimating irrigation water requirements in Europe, J. Hydrol., 373, 527-544, 2009.

Xavier, A. C., King, C. W., and Scanlon, B. R.: Daily gridded meteorological variables in Brazil (1980–2013), Int. J. Climatol., 36, 2644-2659, https://doi:10.1002/joc.4518, 2016.

Assessment of potential implications of agricultural irrigation policy on surface water scarcity in Brazil

Sebastian Multsch[1,*], Maarten S. Krol[2], Markus Pahlow[3], André L. C. Assunção[4], Alberto G. O. P. Barretto[4], Quirijn de Jong van Lier[5], Lutz Breuer[1,6]

[1]Institute for Landscape Ecology and Resources Management (ILR), Research Centre for BioSystems, Land Use and Nutrition (iFZ), Justus Liebig University Giessen, Giessen, Germany
[2]Water Engineering and Management, University of Twente, Enschede, The Netherlands
[3]Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand
[4]Luiz de Queiroz College of Agriculture (ESALQ), University of São Paulo, Brazil
[5]Center for Nuclear Energy in Agriculture (CENA), University of São Paulo, Brazil
[6]Centre for International Development and Environmental Research (ZEU), Justus Liebig University Giessen, Giessen, Germany
[*]Current address: knoell Germany GmbH, Mannheim, Germany

Correspondence to: Lutz Breuer (Lutz.Breuer@umwelt.uni-giessen.de)

Abstract. Expanding irrigated cropping areas is one of Brazil's strategies to increase agricultural production. This expansion is constrained by water policy goals to restrict water scarcity to acceptable levels. We therefore analysed the trade-off between levels of acceptable water scarcity, and feasible expansion of irrigation. The appropriateness of water use in agricultural production was assessed in categories ranging from acceptable to very critical based on the river flow that is equalled or exceeded for 95% of the time (Q95) as indicator for physical water availability. The crop water balance components were determined for 166,842 sub-catchments covering all of Brazil. The crops considered were cotton, rice, sugarcane, beans, cassava, corn, soybean and wheat, together accounting for 96% of the harvested area of irrigated and rainfed agriculture. On currently irrigated land irrigation must be discontinued on 54% (2.3 Mha) for an acceptable water scarcity level, on 45% (1.9 Mha) for a comfortable water scarcity level and on 35% (1.5 Mha) for a worrying water scarcity level, in order to avoid critical water scarcity. An expansion of irrigated areas by irrigating all 45.6 Mha of rainfed area would strongly impact surface water resources, resulting in 26.0 Mha experiencing critical and very critical water scarcity. The results show in a spatially differentiated manner that potential future decisions regarding expanding irrigated cropping areas in Brazil must, while pursuing to intensify production practices, consider the likely regional effects on water scarcity levels, in order to reach sustainable agricultural production.

1 Introduction

In 2013 the Brazilian government took a step towards the consolidation of a national irrigation policy through the enactment of Law 12,787 (www.planalto.gov.br/CCIVIL_03/_Ato2011-2014/2013/Lei/L12787.htm), with two of the objectives being to encourage the expansion of irrigated areas and to increase productivity on an environmentally sustainable basis. According to

Law 12,787, policy implementation would have to be based on regional and national plans estimating expansion potential and indicating suitable areas for prioritisation of public investments. However, to date, a national plan has not yet been developed and the official study available to support the plan is expected to be fully reviewed in 2019 (FEALQ-IICA-MI, 2015). Underlying policy goals include to strive for equitable socio-economic development (VanWey et al., 2016), for a continued large role of biofuels in national energy production and for a strong agricultural sector serving national and international demands of commodities such as soybean (Dalin et al., 2012). One of the governing principles in this policy is the sustainable use and management of land and water resources for irrigation, thereby not negatively affecting communities or sacrificing water resources, unique ecosystems and the services they provide (Alkimim et al., 2015; Castello and Macedo, 2016; Lathuillière et al., 2016).

The extent to which irrigation is a suitable measure to achieve these goals is debated in the literature. Both Fachinelli and Pereira (2015) and Scarpare et al. (2016) find that in the Paranaíba river basin, covering about 25% of the Brazilian Cerrado biome, irrigation increases sugarcane yield, in particular in projected expansion areas, but also in the central region of the basin where sugarcane production is already established. Irrigation shows potential to reduce costs, thereby enhancing the economic viability of sugarcane expansion. Yet both studies caution not to compromise available water resources and hence to restrict irrigation practices to areas where water is sufficiently available, which, according to Scarpare et al. (2016), generally corresponds to most of the central and western portions of that basin. In a study on the Amazon region Lathuillière et al. (2016) identify that the best land-water management would be one that intensifies agricultural production by expanding cropland into pasture and considering irrigation, while avoiding conflicts with downstream users such as electricity production and reducing pressure on aquatic ecosystems in the Amazon Basin. The expansion of rain-fed agriculture in Southern Amazonia is known to reduce water vapour supply to the atmosphere (Lathuillière et al., 2018). Lathuillière et al. (2018) note that this effect could slow down or be reversed by an increase in vapour supply to the atmosphere following widespread irrigation, but not without consequences on surface or groundwater resources.

The Cerrado in central Brazil with a savannah climate is a region with both a strong trend over the last several years of advancing large-scale agribusinesses for agriculture and livestock, and potential for more sustainable land management (Dickie et al., 2016). For example, Alkimim et al. (2015) propose that it is possible to expand sugarcane production in Brazil by converting existing pasturelands into cropland without further environmental losses, whereby they estimate that an area of 50 Mha is moderately or highly suitable for sugarcane production. In another study, Strassburg et al. (2014) assess that current productivity of Brazilian cultivated pasturelands is one third of its potential, and that increasing the productivity to one half of the potential would suffice to meet national demands for meat, crops, wood products and biofuels until at least 2040, thereby avoiding additional conversion of natural ecosystems. Sparovek et al. (2015) analyse comprehensive scenarios with a spatially explicit land-use model for Brazilian agriculture production and nature conservation. They find that a substantial increase in crop production, using an area 1.5-2.7 times the current cropland area, is feasible with much of the new cropland being located on current pastureland.

Land use and land management affect the utilisation of water resources, so every strategy and decision with respect to land is also a strategy and decision with respect to water. This holds for both the precipitation-supplied water stored in the soil matrix (termed green water) and the water in streams, lakes, wetlands and aquifers (termed blue water) (Falkenmark, 1995). While Brazil may be considered well endowed with water resources, these resources are unevenly distributed across the country.

70 Hence, efficient, sustainable and equitable strategies must be developed, thereby considering the spatially and temporally varying water availability. To that end, Getirana (2016) points out that ineffective energy development and water management policies in Brazil have magnified the impacts of recent severe droughts, which include massive agricultural losses, water supply restrictions, and energy rationing.

Metrics of water scarcity and stress have evolved from simple threshold indicators to holistic measures characterising human

75 environments and freshwater sustainability (Damkjaer and Taylor, 2017). The Brazilian national water agency ANA (Agência Nacional de Águas) uses blue surface water availability in operational management, whereby the river discharge, partly delivered by regulated reservoir flows, is compared to water withdrawals. ANA distinguishes water scarcity classes based on the risk of river flow to fail to support environmental services (ANA, 2015).

In studying possible expansion of irrigated areas, as encouraged by the Brazilian Government under Law 12,787, this paper

80 addresses the trade-off between the choice of the level of blue water scarcity that is deemed acceptable, and the feasible expansion of the irrigated area complying with that limitation. In addressing this issue, we restrict the analysis to irrigation expansion on cropping areas in the production year 2012, representing the situation just before law 12,787 came into effect in 2013.

Our assessment entails the following steps:

85   i.   the spatially explicit calculation of green and blue water consumption for the main crops cultivated in Brazil for both rainfed and irrigated production systems,

    ii.   the estimation of blue water scarcity due to the blue water consumption of a reference scenario (irrigated areas in 2012) and an expansion scenario, i.e. under the assumption that all rainfed areas are irrigated, thereby considering surface water availability, and

90   iii.   the spatially explicit analysis to what extent expansion of irrigation areas is sustainable.

Our overall objective is to evaluate the feasibility of irrigation expansions in Brazil. We thereby investigate the following research question: Is expansion of irrigated areas, as encouraged by the Brazilian government, environmentally sustainable from a surface water resources point of view? The Cerrado biome, a region of significant agricultural expansion and a biodiversity hotspot (Mittermeier et al., 2005; Strassburg et al., 2017), is considered in particular detail.

95 **2 Data**

Precipitation, maximum and minimum temperature, solar radiation, relative humidity, and wind speed data for the production year 2012 were obtained from Xavier et al. (2016), who developed a daily gridded dataset for Brazil with a 0.25°×0.25°

resolution of these meteorological variables based on 3,625 rain gauges and 735 weather stations ~~for the time period 1980-2013~~. In order to determine the required soil properties, data on bulk density, organic carbon content, and fractions of sand,

100   silt, clay have been extracted from the ISRIC SoilGrids1km database (Hengl et al., 2014).

Saturation and residual water content θ_s and θ_r [m^3 m^{-3}] and the parameters α and n of the van Genuchten function (van Genuchten, 1980) were estimated using the level 3 pedotransfer function of Tomasella et al. (2000) for Brazilian soils, under the assumption that coarse and fine sand fraction have an equal share of the total sand content. Field capacity and wilting point were determined as soil water content at -33 kPa and -1,500 kPa, respectively, following van Genuchten (1980). Soil types

105   were determined using the nomenclature of the United States Department of Agriculture (USDA). Data on harvested area and yield of nine main crops for the ~~study~~ production year 2012 as provided by IBGE were utilised in this study. The crops considered are cotton, rice, sugarcane, *Vigna* spp. and *Phaseolus* spp. bean~~s~~, cassava, corn, soybean and wheat. Combined those nine crops account for 96% of harvested area [ha], 98% of production mass [ton] and 90% of production value [Brazilian Real] in Brazil in the year 2012 (IBGE, 2012). Planting and harvesting dates for the sub-regions considered were taken from

110   Conab (2015). For some crops, multiple harvests per year are considered, following information provided by IBGE. Catchment-scale data on surface water supply were obtained from the ANA Geonetwork (http://metadados.ana.gov.br/geonetwork/srv/pt/main.home). An overview of the underlying data is given in Table 1.

Table 1 here

115

3 Methods

In order to assess water ~~demands~~ consumption of potential expansion of irrigation, impacts on water scarcity, and limits to irrigation expansion under scarcity thresholds, we applied a site-specific crop water balance model at the catchment scale. To this end, high-resolution gridded data on climate and soil were combined with statistical information on irrigation management

120   to run a countrywide daily crop water balance model for 166,842 sub-catchments in Brazil to determine rainfed and irrigated water requirements. The crops considered were cotton, rice, sugarcane, Vigna spp. and Phaseolus spp. bean~~s~~, cassava, corn, soybean and wheat.

3.1 SPARE:WATER

125   ### 3.1.1 Calculation of green and blue water consumption

The open source crop water balance and footprint model SPARE:WATER (Multsch et al., 2013~~; available at http://www.uni-giessen.de/faculties/f09/institutes/ilr/hydro/download~~) was used to determine green and blue water consumption in crop production. The tool was applied to investigate several topics related to water resources management in recent years, e.g. the

predicted future irrigation demands and impact of technology in the Nile river basin (Multsch et al., 2017a), managing desalinated seawater use in agriculture in Saudi Arabia (Multsch et al., 2017b), and characterising groundwater scarcity caused by large scale irrigation in the USA (Multsch et al., 2016).

First, the daily crop water balance was calculated at 0.25°x0.25° grid-level for each crop per growing season, utilising the gridded climate and soils data (see Table 1). Second, the contribution of crop production to the regional water balance at the level of municipalities was derived by multiplying crop water consumption per growing season, averaged over the grids in the municipality, with the respective municipal cropping area [ha a^{-1}]. Note that the information regarding irrigated areas and the fraction of irrigated area per crop was also available at municipality level (Table 1). Thirdly, the total water consumption was determined per sub-catchment, which was then contrasted with water supply in each one of the 166,842 sub-catchments, and aggregated to municipality level. These steps are shown in Figure A1.

Consumptive water use was separated into green (CW_g) and blue (CW_b) crop water consumption in [m^3 ha^{-1}] at grid level. To achieve this simulations were carried out twice for the entire country, once for purely rainfed conditions (fraction irrigated f=0), to determine green water consumption CW_g, and once for purely irrigated conditions (fraction irrigated f=1) CW_b, in order to determine additional blue water consumption, following earlier work by Mekonnen and Hoekstra (2010) and Siebert and Döll (2010). The blue water consumption was estimated as the difference between the two simulations:

$$CW_g = ET_{f=0} \tag{1}$$

$$CW_b = ET_{f=1} - ET_{f=0} \tag{2}$$

3.1.2 Calculation of crop water balance

In SPARE:WATER, the crop water balance is calculated based on the crop water balance model proposed by Allen et al. (1998). Reference evapotranspiration (ET_o) [mm d^{-1}] was derived as

$$ET_o = \frac{0.408\Delta(R_n-G)+\gamma\frac{900}{T+273}u_2(e_s-e_a)}{\Delta+\gamma(1+0.34u_2)} \ , \tag{3}$$

with net radiation R_n [MJ m^{-2} d^{-1}], soil heat flux density G [MJ m^{-2} d^{-1}], air temperature T at 2 m height [°C], wind speed at 2 m height u_2 [m s^{-1}], saturated vapour pressure e_s [kPa], actual vapour pressure e_a [kPa], slope of the vapour pressure curve Δ [kPa °C^{-1}] and the psychrometric constant γ [kPa °C^{-1}]. ET_o is adapted to specific field crops by a crop coefficient (K_c), which varies over time and is adjusted to field conditions by a water stress coefficient (K_s) resulting in ET_{act} [mm d^{-1}] according to:

$$ET_{act} = ET_o \times K_c \times K_s \tag{4}$$

whereby K_c and K_s are dimensionless values. K_c reflects canopy development and changes over the course of the growing period, as measured by the number of days after sowing (DAS). The growing period was divided into the four periods initial period (L_{ini}), growth period (L_{dev}), mid period (L_{mid}) and late period (L_{end}). A crop coefficient is related to three of the periods:

$K_{c,ini}$, $K_{c,mid}$ and $K_{c,end}$. The crop coefficient of L_{dev} was interpolated in relation to the respective DAS and the values of L_{ini} and L_{mid}.

160   The water stress coefficient K_s was derived on the basis of a simple water balance approach from the total available soil water (TAW), the actual root zone depletion (D_r) and a crop specific water extraction coefficient (p) [-] following Allen et al. (1998):

$$K_s = \frac{TAW - D_r}{(1-p)TAW} \tag{5}$$

with the TAW and D_r in [mm]. TAW was derived from the wilting point, field capacity and the actual rooting depth (Z_r) according to Allen et al. (1998):

165    $$TAW = 1000\left(\theta_{FC} - \theta_{\cancel{\theta}WP}\right)z_r \tag{6}$$

with the water content at field capacity ($\theta_{WP}\theta_{FC}$) and wilting point ($\theta_{FC}\theta_{WP}$) in [m³ m⁻³] and the rooting depth z_r in [m]. The daily soil water depletion D_r [mm] at day i was derived for soil layer r from the water balance components:

$$D_{r,i} = D_{r,i-1} - P_{eff,i} - Irr_i - CR_i + ET_{act,i} + DP_i \tag{7}$$

with daily effective precipitation (P_{eff}), irrigation (Irr), capillary rise (CR) and deep percolation DP in [mm]. In order to account
170   for the case f=1 (full irrigation) the daily irrigation depth Irr_i was calculated to fill up the soil water compartment to field capacity when the critical depletion was reached, i.e. any water stress is avoided. This approach reflects full irrigation practices. P_{eff} was computed as P–RO, where precipitation P is taken from the meteorological input data and surface runoff RO was estimated on the basis of the curve number method according to Bosznay (1989), while CR was neglected.

3.2 Blue water scarcity

175   ### 3.2.1 Calculation of current and potential blue water consumption

The expansion area, i.e. the rainfed areas to be converted to irrigated land, was assessed considering and contrasting water consumption and water availability. The potential blue water consumption for full expansion of irrigation was calculated based on the irrigation required of all rainfed areas. Blue water consumption was derived for two scenarios. First, for the irrigated areas in 2012, which is subsequently denoted as reference scenario. Second, for an expansion scenario under the assumption
180   that all rainfed areas are irrigated.

Knowing the potential consumption, the expansion of irrigated areas was then assessed with respect to the available blue water resources. Water available for expansion was determined by subtracting the available blue water from the water consumption under the reference scenario (actually irrigated areas). The remainder is available to expand irrigation to rainfed areas.

For each municipality the allocation of expansion of irrigated area for the crops was assumed proportional to the ratio of the
185   crops grown in the reference case. If the volume of available blue water is insufficient to meet the reference blue water consumption of formerly rainfed areas, the expansion areas for each crop are reduced proportionally to the cropping fractions in the municipality.

3.2.2 Blue water availability

Following Flach et al. (2016), Aavailability of blue water was taken from the national Brazilian water resources inventory
(ANA, 2016). There, Q95, i.e. the river flow that is equalled or exceeded 95% of the time, and increased by regulated flow
from reservoirs, is taken as an indicator of physical availability of water. In essence, Q95 is a measure for discharge in the
low-flow season, thereby including regulated flows. Note that ANA provides the Q95 values as averages over the time period
2008 to 2016. The study production year 2012 studied here is at the centre of this average.

3.2.3 Scarcity levels

The ratio of gross water withdrawal to physical water availability is often called withdrawal-to-availability ratio (Vanham et
al., 2018), and is used as an indicator of water scarcity. Using the Q95 indicator for water availability, Brazilian water
authorities consider the appropriateness of the water withdrawal, as a fraction of water availability (i.e. scarcity levels), to be
acceptable when it remains below 5%, comfortable between 5 and 10%, worrying between 10 and 20%, critical between 20
and 40% and very critical above 40% (ANA, 2015). This classification is inspired by threshold values for water exploitation
suggested by Raskin et al. (1997), and also used by the United Nations (UN, 1997).

In this paper, net water withdrawal (or blue water consumption) rather than gross water withdrawal is compared to water
availability, often termed consumption-to-availability ratio (Vanham et al., 2018). Therefore, the scarcity levels described
above were adjusted to reflect that withdrawals also include non-consumptive losses at field scale and losses during transport
of water to the field, which are not considered when calculating blue water consumption. To account for this a factor of 2 was
applied, which is a central estimate of the ratio between withdrawal and consumptive blue water use reported in Wriedt et al.
(2008). The resulting scarcity levels represent the same classes of water scarcity from acceptable to very critical, but are
adapted to the threshold values of 2.5, 5, 10 and 20%.

Using these thresholds for consumptive blue water use, blue water scarcity was analysed both for the reference situation and
for a complete expansion of irrigation on the rainfed cropping area. Note that in the case of expansion of irrigation on the
rainfed cropping areas the approach applied here does not account for dynamic changes in regional water availability due to
increased upstream water consumption and hence an altered water availability downstream. The results provided here
summarise the scarcity assessment with respect to the pre-defined scarcity levels.

3.3 Calculation of the extent of sustainable irrigation areas

The sustainable expansion of irrigated areas on rainfed cropping areas was assessed through the water consumption-to-
availability ratio. Three management strategies are presented by limiting the available water under the assumption of scarcity
levels acceptable, moderate and worrying. Each management strategy has been mapped spatially for reference and expansion
scenarios. The volume of water available for consumptive blue water use in irrigation was calculated at the level of
municipalities for the different threshold levels of water scarcity. If this volume of blue water exceeds the consumptive blue

water requirement in the reference situation, the excess volume was allocated to irrigation expansion. For the irrigation
220   expansion scenario the growing areas of the crops considered have been upscaled using the proportion of crops grown in the
reference scenario. The overall extent of the expansion is chosen to either use all of the excess volume of blue water assumed
to be available, or to use all of the rainfed cropping area. If the volume of available blue water (depending on the threshold for
scarcity chosen) is insufficient to meet the reference blue water requirement, the irrigated areas for each crop were reduced
proportionally to achieve the chosen level of scarcity. Viable expansions at municipal level were aggregated to regions for
225   each of the threshold levels of water scarcity.

4 Results

4.1 Spatial explicit modelling using SPARE:WATER

4.1.1 Crop water balance modelling

The crop water balance components show significant differences between crops, partly due to differences in cropping locations
230   within Brazil, different growing seasons, and between rainfed and irrigated production systems (see Table 2). Average ET_{act}
values vary between 154 mm (3rd *Vigna* spp. and *Phaseolus* spp.) and 925 mm (sugarcane) on rainfed areas. ET_{act} is consistently
higher on irrigated areas with average values between 260 mm (3rd *Vigna* spp. and *Phaseolus* spp.), i.e. 69% higher than
rainfed, and 1,508 mm (sugarcane), i.e. 63% higher than rainfed. Effective precipitation P_{eff} varies between 229 mm (3rd *Vigna*
and *Phaseolus* spp.) and 1,574 mm (sugarcane), with high values relating to crops with comparably long growing periods.
235   Crops with a high Irrigation IRR are wheat (291 mm) and particularly sugarcane (644 mm), mainly due to the growing periods
extending into the dry seasons. Another important fact is that even if effective rainfall could often cover potential ET in total,
the rainfall was not available at the time of high crop water demands and could not be stored by the soil in sufficient quantity,
making it unavailable to the crop. Thus, irrigation is often required even if total rainfall is enough.

240   **Table 2 here**

In Table 3 the results for ET_{act}, P_{eff}, IRR, cropping area, green and blue water consumption are summarized for the Cerrado
region, one of the main areas of agricultural development and a biodiversity hotspot. ET_{act} is below the Brazilian average
values in the cases of cotton (6%), wheat (47%) and sugarcane (14%), as well as for beans for the first sowing date (51%).
245   Other crops show an ET_{act} that is higher by 4% to 14%. P_{eff} is lower in the Cerrado for all crops by 7% to 65%. A slightly
higher ET_{act} (by 1 to 6%) is estimated for irrigated production in the Cerrado region for all crops when compared to the average
of Brazil. The irrigation depths in the Cerrado are found to exceed the Brazilian averages, e.g. +17% for cotton, +20% for
sugarcane, +23% for the 2nd sowing date for corn, +30% for wheat as well as +7% and +26% for the 2nd and 3rd sowing date
of beans.

Table 3 here

4.1.2 Green and blue water consumption

The total water consumption of the nine crops considered in this study is 285.5 km³ in the production year 2012 (Table 2).
Green water is dominating with 95% of the total consumption. The majority (91%) of the green water consumption was
consumed on rainfed areas (53.8 Mha, including double/triple cropping) and only a minor fraction on irrigated areas (4.9 Mha).
The spatial distribution of the total, green and blue water consumption in crop production is shown in Figure 1. The North of
Brazil (States: Acre, Amapá, Amazonas, Pará, Rondônia, Roraima, Tocantins) consumes only a minor fraction (3%) of the
national total volume. Agriculture is not intensive in this area and many regions are not cultivated because of climate
conditions, non-suitability of soils and nature protection in the Amazonas region. The highest percentage of green water
consumption is found in the Centre-West (34%) (States: Goiás, Mato Grosso, Mato Grosso do Sul, Distrito Federal) and the
highest percentage of blue water consumption occurs the North-East (States: Alagoas, Bahia, Ceará, Maranhão, Paraíba,
Pernambuco, Piauí, Rio Grande do Norte, Sergipe) and the South-East (States: Espírito Santo, Minas Gerais, Rio de Janeiro,
São Paulo) with 31% and 39%, respectively. Water consumption displays a distinct change in pattern from West to East
(western areas: rainfed; eastern areas: irrigated) . The majority of green water is consumed by soybeans, sugarcane and corn
with 37.8%, 28.6% and 21.5%, respectively. Regarding blue water, sugarcane (10.0 km³ a^{-1}), rice (2.3 km³ a^{-1}), corn (1.1 km³
a^{-1}) and soybeans (0.9 km³ a^{-1}) consume with 92.9% the highest fraction.

The Cerrado (Figure 1, delimited by black line) is one of the most sensitive landscapes and is comprised of about half of both
irrigated and rainfed areas in Brazil with 46% and 47%. The large extent of agricultural areas comes with a high green and
blue water consumption of 132 km³ a^{-1} and 5.7 km³ a^{-1} (together 48% of the total across Brazil). The average field scale water
consumption [mm a^{-1}] shows a higher green (~5%) and lower blue (~19%) water consumption when compared to Brazil's
average.

Figure 1 here

4.2 Blue water scarcity

Blue water availability and scarcity are shown in Figure 2. The available water flows have been classified according to seven
groups between 80 mm a^{-1} and greater than 2,560 mm a^{-1} related to water scarcity levels of 2.5, 5, 10 and 20%. The highest
values are located in the North near the Amazonas River with a median Q95 of 765 mm a^{-1}. Q95 decreases in particular in the
eastern areas with 26 mm a^{-1} and 197 mm a^{-1} in the North East and South East. The Cerrado area has also comparable low
values with a median of 177 mm a^{-1}.

The blue water scarcity for current irrigated areas (Figure 2b) shows a specific regional pattern. Most of the agricultural areas are classified as to either meet acceptable (35%) or very critical (38%) water scarcity. In the Cerrado region 44% of the area are in the category acceptable and 23% of the area are in the category very critical. The highest quantity of very critical catchments is located in the North East and South with 64% and 49%, respectively. The largest percentages of areas in the category acceptable lie in the North (94%) and Center-West (65%).

The situation would change significantly when also rainfed areas are irrigated as shown in Figure 2c, with an increase of the category very critical with 48% and a lower fraction in the class acceptable with 24%. A similar change can be observed for the Cerrado region with 38% of very critical catchments. The catchments with a higher scarcity are located in the southern and eastern area of Brazil, as well as in the eastern part of the Cerrado itself.

Figure 2 here

The higher scarcity for the potentially irrigated area can be caused by two additive impacts, i.e. a low Q95 and a high additional water demand. Two regions stand out regarding water availability: the northern and north-eastern parts with comparably high availability, and the eastern regions with low availability. The other parts of the country show mixed water availability, with regions of higher and lower values (Figure 2a). The maximum and minimum quantities of water availability and consumption are heavily skewed to the blue water scarcity classes acceptable and very critical. For example, water scarcity in most catchments is classified as acceptable or very critical for current irrigated areas (Fig 3a). In this case, the class acceptable is dominated by agriculture fields with an average blue water consumption below 80 mm a^{-1}. The catchments classified as very critical are dominated by agriculture fields consuming more than 640 mm a^{-1}. The highest water availability (often larger than 1,280 mm a^{-1}) is attributed to catchments classified as acceptable (Figure 3b). Catchments with a lower water availability (<160 mm a^{-1}) are mostly characterized as very critical. This distribution is similar for current (Figure 3a,b) and rainfed (Figure 3c,d), i.e. potentially irrigated, areas.

Figure 3 here

4.3 Extent of sustainable irrigation areas

Three scarcity levels were analysed in detail, namely acceptable, comfortable and worrying (Table 4). Current irrigated areas add up to 4.29 Mha without accounting for multiple cropping. Only 1.99 Mha of this area, i.e. 46.4%, should be irrigated when an acceptable blue water scarcity level is to be realised. The areas that do not meet the threshold of acceptable water scarcity (1.57 Mha) lie in catchments that are currently classified as very critical. Allowing higher scarcity levels (comfortable, worrying) would allow 2.38 Mha and 2.78 Mha of the current irrigation areas to remain irrigated. Note that worrying water

scarcity is the highest level of scarcity that avoids critical conditions. Expanding irrigation in order to irrigate all rainfed fields would result in an additional irrigated area of 45.56 Mha (i.e. the rainfed area without the multiple cropping areas listed in Table 1), with 22.00 Mha of the additional area in catchments with very critical and 4.02 Mha with critical water scarcity. Expansion of irrigation area by 16.68 Mha (36.6%), 20.68 Mha (45.4%) or 24.89 Mha (54.6%) would be achievable for the blue water scarcity levels acceptable, comfortable and worrying.

Table 4 here

The extent of sustainable irrigation areas is shown in Figure 4 in classes ranging from 20% to 100% for each catchment. The classes represent the percentage change needed to reach a certain level of water scarcity. For example, a countrywide acceptable scarcity level for the reference scenario (Figure 4ab) is only achievable if the currently irrigated areas in large parts of eastern Brazil as well as in the south and west are reduced to 20% of the actual extent. The sustainable irrigation area for scarcity levels comfortable and worrying are shown in Figure 4b and 4c, respectively. The highest reductions are required in the North-East, the eastern part of the Cerrado, and in southern regions of Brazil. A similar calculation has been conducted for potentially irrigated areas (Figure 4d-f). Only a modest fraction of the currently rainfed areas should be irrigated, while keeping blue water scarcity at acceptable, comfortable or worrying levels, as shown in Figure 4d, 4e and 4f, with expansions mainly feasible in the South-East, the western part of the Cerrado and in the Amazon basin.

Figure 4 here

5 Discussion

In the present study the biophysical boundaries of said strategy have been specified in a quantitative manner by comparing the potential water demand to fully cover the water demand of rainfed areas by irrigation with the available river flows. The underlying environmental and agronomic data were carefully selected to account for the high spatial variation of hydrological conditions across Brazil. A few choices and the resulting implications require further attention.

With respect to the choice of a water availability indicator, Q95 as has been selected in order to provide a conservative water availability scenario. This is important due to the high variability of hydrological conditions in Brazil and to account for dry periods over time. Moreover, choosing Q95 complies with the indices utilised by the Brazilian Water Agency and decision makers.

The selection of crop-specific parameter sets was an important aspect in the design of such a study. Crop coefficients and length of growing seasons of the individual crops studied here have been assembled from a well-recognised source (Allen et al., 1998, i.e. parameters implemented in the FAO CROPWAT model), a Brazilian study (Hernandes et al., 2014) and regional information for Brazil, as provided by Companhia National de Abastecimento (Conab) (https://www.conab.gov.br/). We

acknowledge that further spatial differentiation is desirable, should reliable data be available. We have chosen the procedures put forth by Allen et al. (1998), as their high level of robustness, transferability and ~~repeatabilty~~repeatability have been shown (Pereira et al., 2015). Moreover, in a large-scale irrigation requirement study for the Murray-Darling basin, Multsch et al. (2013) report that the choice of the potential evapotranspiration calculation method outweighs the role of the local refinement of crop coefficients. Lastly, planting dates are known to change based on the onset of the rainy season (Arvor et al., 2014), which is strong evidence for the use of a window of planting dates based on precipitation regimes different regions. To address this, the actual and region-specific crop calendars (Conab, 2015) were utilised for the determination of crop water requirements to account for varying conditions in different parts of Brazil.

The blue soil water content and the blue water fluxes could be further separated into blue water originating from irrigation water and blue water originating from capillary rise, as for example in Chukalla et al. (2015), to track which fractions of ET originate from rainwater, irrigation water and capillary rise, respectively.

An important aspect when assessing water scarcity caused by agricultural water consumption are return flows, e.g. due to evapotranspiration recycling (Berger et al., 2014) or water losses in irrigation systems (Pereira et al., 2002; Jägermeyr et al., 2015). We neglect evapotranspiration recycling effects in the present study, since great care has been taken to subdivide the study area into sub-catchments with sizes where this effect does not play a significant role. The calculated blue water consumption represents net water requirements, which only includes evapotranspiration by crops and from soils.

Determination of water scarcity was carried out here using the consumption-to-availability ratio. Two aspects require further discussion: the effect of environmental flow requirements and of non-consumptive losses. Environmental flow requirements (EFR) were not included here. Considering EFR results in a reduction of blue water availability (Boulay et al., 2018; Hoekstra et al., 2011) and hence the water scarcity levels determined here would increase. It is challenging to determine the level of environmental flow requirements for a given region (Hoekstra et al., 2011). Such an analysis is beyond the scope of the current study. A broad range of methods is available in the literature (e.g. Abdi and Yasi, 2015; Hoekstra et al., 2012; Książek et al., 2019; Richter et al., 2012; Smakhtin et al., 2004; Tennant, 1976). In future work it is recommended to select an adequate method to determine EFR and to include such EFRs to carry out a detailed assessment of the impacts of different potential cropping systems on the water cycle, thereby including a quantification of land and water resources trade-offs in the context of agricultural intensification, as suggested by Lathuillière et al. (2018). Losses, e.g. at field scale and during transport, were considered by adjusting the scarcity levels. The adjustment was based on the work by Wriedt et al. (2008), who estimated gross irrigation demands in the European Union and Switzerland to be 1.3-2.5 times higher than field requirements, depending on the efficiency of transport and irrigation management. To consider these non-consumptive losses, the scarcity levels in the current study were adjusted from those originally used by ANA (2015) (acceptable below 5%, comfortable between 5 and 10%, worrying between 10 and 20%, critical between 20 and 40% and very critical above 40%) using a central factor of 2. Applying the lower (1.3) or higher (2.5) bound found by Wriedt et al (2008) would result in higher (3.8, 7.7, 15.4 and 30.1%)

and lower (2, 4, 8 and 16%) scarcity thresholds, respectively, than those employed here using the factor of 2 (2.5, 5, 10 and 20%).

380   It is critical to note that pumping river water for irrigation, as investigated here, has likely impacts on natural systems and should be carefully evaluated, thereby considering water management measures. In addition, the effect of land conversion requires attention. Recent studies show the potential effects of future land use and land cover change scenarios in the Amazonian region of Brazil on the hydrological regime in the region (Abe et al., 2018; Dos Santos et al., 2018). The results of the spatially explicit quantification regarding water resources of this study add information on several aspects as explained
385   below.

5.1 Expansion and intensification of irrigation areas

The agricultural policy of Brazil has been investigated with a focus on water resources. By using a spatially explicit and process-oriented modelling approach the extent of sustainable irrigation areas was quantified. Future policy will need to decide on the level of the expansion and intensification of agricultural areas. Others (Alkimim et al., 2015; Sparovek et al., 2015;
390   Spera, 2017; Strassburg et al., 2014) made a strong case that agricultural expansion into currently uncultivated areas can be avoided through efficient utilisation of currently cultivated areas, mainly those allocated to extensive grazing. The quantification of sustainable irrigation areas has shown that the use of irrigation as a large scale intensification strategy is limited. On the one hand, even actual irrigated areas (reference scenario) must be reduced in order to achieve an acceptable scarcity level. Thus, intensification would be in some areas highly unfavourable and current mechanisms of water use
395   monitoring and control need to be improved. On the other hand, some rainfed areas (expansion scenario) maybe irrigated in the future without resulting in higher scarcity due to adequate blue water availability. Thus, this spatial explicit analysis can inform agricultural policy making with regard to water resources management in order to implement likely agricultural expansion in the future in a sustainable manner. This in turn can be linked to trade of agricultural commodities. For example, da Silva et al. (2016) determined that the northeast region of Brazil, with low water availability (see Figure 2), shows substantial
400   import of agricultural commodities.

Regarding intensification, employing state of the art irrigation technology and further development of such technology would be in line with an objective of Brazil's irrigation policy through Law No. 12,787, i.e. to train human resources and foster the creation and transfer of technologies related to irrigation. Fachinelli and Pereira (2015) point out the potential yield increase through irrigation, and hence an opportunity to reduce related land requirements for sugarcane expansion. Future work should
405   assess the potential of efficient use of water resources regarding irrigation technology to further refine the quantification of sustainable irrigation areas, including not only biophysical variables but also infrastructure availability (ANA, 2019) and socioeconomic conditions. Needless to say that in future work groundwater availability and water available in small dams previously used for cattle drinking water (Rodrigues et al., 2012) should be considered in addition to surface water availability, as was done in the current work.

5.2 Protecting the Cerrado

The Brazilian government has identified new areas for agricultural development in the northeastern part of the Cerrado, which became an agricultural frontier since the early 2000s. How would such a policy impact water resources? To answer this question, some knowledge regarding the landscape level development must be provided. On May 6, 2015, Brazilian Decree no. 8447 officially committed government support for the agriculture and livestock development plan PDA MATOPIBA for the 'MATOPIBA' region, i.e. 337 municipalities that span the states of Maranhão (MA), Tocantins (TO), southern Piauí (PI), and western Bahia (BA) (Spera et al., 2016). It must be noted that around 90% of MATOPIBA lies within the Cerrado biome. Spera et al. (2016) point out that unlike most of the Cerrado, MATOPIBA does not have a history of large-scale cattle ranching. As a result, cropland expansion in MATOPIBA is advancing primarily through clearing native vegetation rather than by using previously cleared pasturelands. It has been pointed by others that careful planning for the region should allow for large-scale agriculture to grow and contribute to rural economic development in a way that harmonises with other uses of the landscape and other economic development pathways (Dickie et al., 2016).

A further policy evaluation is feasible now that the blue water scarcity levels as presented in the current study are available. Nearly the half of Brazil's irrigated and rainfed area is located in the Cerrado area and requires a similar fraction for water consumption. Thus, policy strategies for Brazil regarding agricultural expansion will have a significant impact on that region, in particular on water resources. Currently, the scarcity levels of the area are mostly acceptable and comfortable and most areas under worrying and critical scarcity lie outside of the Cerrado area. Irrigation of rainfed areas would tremendously change this situation and increase blue water scarcity to a worst-case situation. In order to maintain sustainability with respect to surface water resources, less than 20% of rainfed areas should be irrigated.

5.3 Green water management

In addition to the spatial aspects regarding expansion, the temporal variability of water availability and consumption is crucial to support policymaking. The high evaporative deficit on rainfed areas as shown by the crop water balance model deserves special attention. Although rainfall rates can potentially cover the crop ET in many regions, the plant available soil moisture is not sufficient to store and provide enough water, especially in lighter-textured (sandy or sandy loam) soils. Additionally, a low infiltration capacity makes soils classified as clay or clay loam soils unable to store high-intensity rainfall.

Measures focusing on managing green water resources as proposed elsewhere (e.g. Multsch et al., 2016; Rockström et al., 2010; Rost et al., 2009) for agriculture systems worldwide can potentially improve the water holding capacity. While restricting water use of irrigated crops to green water may lead to substantial production losses (Siebert and Döll, 2010), improved irrigation practices can support reduction of non-beneficial water consumption, without compromising yield levels (Jägermeyr et al., 2015). Different measures to improve green water management have been evaluated by Jägermeyr et al. (2016) on the global scale showing that the kilocalories derived from agricultural production could be enhanced by 3-14% by soil moisture conservation and by 7-24% by water harvesting. In order to store the high surface run-off which occurs in Brazil's agricultural

systems, in-situ rainfall harvesting by conservation tillage and mulching may be helpful measures in order to improve agricultural productivity in a sustainable manner.

Based on the work shown here specific scenarios can be evaluated, such as cultivation of a 2nd and/or 3rd cropping cycle for selected crops, using water resources for bridging dry spells during the growing season only (supplemental irrigation), or utilisation of water resources to avoid late planting due to unfavourable climatic conditions. Thus, this study provides a basis to further investigate specific measures, thereby considering various agriculture management strategies in space and time.

5.4 Water recycling

Another important aspect of sustainable irrigation is the effect on the amount of water recycled to the atmosphere via evapotranspiration. Spera et al. (2016) find by analysis of remote sensing data that the conversion of Cerrado vegetation into cropland resulted in changes in water recycling that show dependency on the cropping frequency, with double cropping behaving more akin to the natural system. Future investigations of this kind should include the additional effect of various irrigation strategies, combined with the effect of cropping frequency and area response to climate variability, whereby the importance of the latter has been highlighted by Cohn et al. (2016).

6 Conclusions

Based on the assessment of crop water consumption as fraction of water availability (in terms of Q95) and classifying the results regarding water scarcity for Brazil the following can be concluded:

- *Avoiding critical water scarcity on currently irrigated land:* In order to avoid critical water scarcity, irrigation must be discontinued on 54% of the area (2.3 Mha) for an acceptable water scarcity level, on 45% (1.9 Mha) for a comfortable water scarcity level and on 35% (1.5 Mha) for a worrying water scarcity level of 4.3 Mha currently irrigated land (not considering multiple cropping).
- *Avoiding critical water scarcity on currently rainfed land*: For 37% (16.7 Mha) of the currently 45.6 Mha rainfed land the blue water scarcity level would remain acceptable, for 45% (20.7 Mha) comfortable and 55% (24.9 Mha) worrying under irrigation (not considering multiple cropping).
- *Expansion of agriculture into currently uncultivated areas*: Given that there is potential for additional irrigation areas and taking into account estimates by FAO, which estimates that a cropping intensity of 120% can be achieved on irrigated land (www.fao.org/nr/water/aquastat/countries_regions/BRA/), production on currently cultivated land can overall be made more efficient through investment in irrigation infrastructure. This lends support to the statement made in other work that an expansion into currently uncultivated land is not required in order to increase agricultural productivity.

- *Decision support for stakeholders and decision-makers*: The results cover different water scarcity categories, which allows for a trade-off analysis among stakeholders and decision makers as to which level of water scarcity and the related consequences are acceptable to reach a given goal.

475
- *Global virtual water flows*: The agricultural policy will affect local farmers, but also global markets, given the global dimension of Brazil's agriculture. Brazil is a country, which imports blue water resources and exports its green water resources (Fader et al., 2011). The vast green water exports have been attributed to soybeans, which are strongly requested on the world market, in particular by China (Dalin et al., 2012), to sustain human diet and livestock nutrition. A similar picture applies to sugarcane, since Brazil has a share of 30% of global production (Gerbens-Leenes and Hoekstra, 2012). An expansion of irrigated areas would therefore significantly alter global virtual water

480
flows.

In studying possible expansion of irrigated areas, as encouraged by the Brazilian Government under Law 12,787, this paper addresses the trade-off between the choice of the level of blue water scarcity that is deemed acceptable, and the feasible expansion of the irrigated area complying with that limitation. In addressing this issue, we restrict the analysis to irrigation expansion on cropping areas in 2012, representing the situation just before law 12,787 came into effect in 2013.

485 Expanding irrigation can be an effective measure to increase agricultural production. Using a spatial explicit modelling tool sensible, forward-looking and sustainable planning of expansion areas can be achieved by avoiding an expansion in areas where high water scarcity would be the consequence. This applies in particular to the Cerrado biome. Moreover, the temporal variations regarding crop water requirements have been addressed by process-oriented modelling with respect to the local cropping calendar. This work provides a sound basis for further assessment of water management strategies in order to achieve

490 nation-wide development and implementation of sustainable agricultural policies.

495

Code availability. The code written for this analysis can be made available by the first author upon request.

Data availability. Data used in this study are available from the following sources: Climate data (Xavier et al., 2016) from http://careyking.com/data-downloads/, soils data (Hengl et al., 2014) from https://www.isric.org/explore/soilgrids, crop data

500 (IBGE, 2012) from http://www.sidra.ibge.gov.br/, extent of irrigted areas (IBGE, 2012) from http://www.sidra.ibge.gov.br/, fraction of irrigated area per crop (IBGE, 2006) from http://www.sidra.ibge.gov.br/ and surface water supply (ANA, 2016) from http://metadados.ana.gov.br/geonetwork/srv/pt/metadata.show?id=307. Other data used here, but not accessible online, can be accessed via the references listed in the references section.

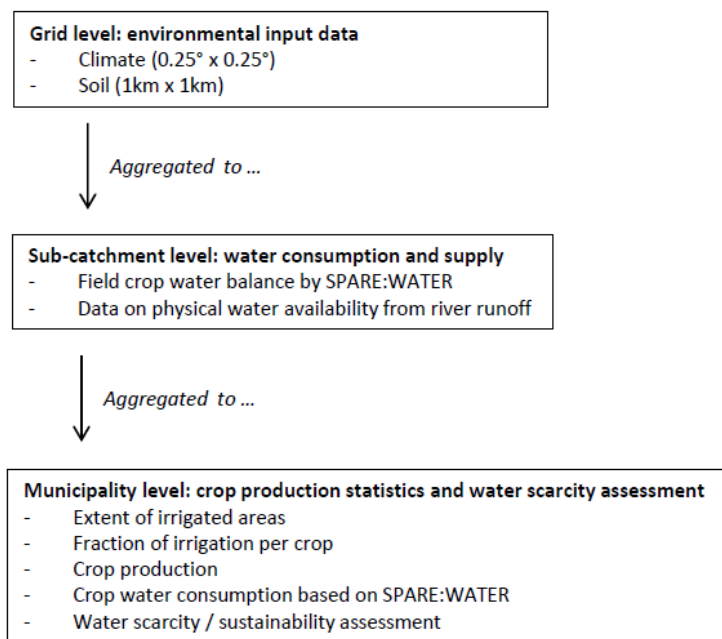
 Appendices.

Table A1. Crop coefficients K_c [-] and lengths L [days] of crop development stages of the crops considered in this study.

Crop	$K_{c,ini}$	$K_{c,mid}$	$K_{c,end}$	L_{ini}	L_{dev}	L_{mid}	L_{late}
Corn[1]	0.65	1.1	0.6	30	40	50	30
Soybean[1]	0.6	1.05	0.6	10	40	50	20
Sugarcane[1]	0.5	1.25	0.8	30	60	180	95
Cassava[2]	0.3	0.8	0.3	20	40	90	60
Rice[2]	1.05	1.2	0.75	30	30	60	30
Cotton[2]	0.35	1.2	0.6	30	50	55	45
Wheat[2]	0.7	1.15	0.25	15	30	65	40
Phaseolus[2]	0.5	1.05	0.9	20	30	30	10
Vigna[2]	0.5	1.05	0.9	20	30	30	10

[1] Source: Hernandes et al. (2013), [2] Source: Allen et al. (1998)

510 Table A2. Planting and harvesting dates of the different crops and the five sub-regions considered in this study (Source: Conab, 2015). Note that "2nd" and "3rd" are the second and third planting dates for double- and triple-cropping within one growing season, i.e. a successive multiple cropping practice.

	North		North-East		Center-West		South-East		South	
Crop	Sowing	Harvest	Sowing	Harvest	Sowing	Harvest	Sowing	Harvest	Sowing	Harvest
Cassava	01.09.	29.03.	01.09.	29.03.	01.09.	29.03.	01.09.	29.03.	01.09.	29.03.
Corn	01.12.	29.04.	15.01.	13.06.	15.11.	13.04.	15.11.	13.04.	15.10.	13.03.
2nd Corn	10.04.	06.09.	01.05.	27.09.	15.02.	14.07.	15.03.	11.08.	15.02.	14.07.
Cotton	15.01.	13.07.	15.02.	13.08.	15.12.	12.06.	01.12.	29.05.	15.11.	13.05.
Phaseolus	15.12.	14.03.	15.11.	12.02.	15.11.	12.02.	01.11.	29.01.	01.10.	29.12.
2nd Phaseolus	01.04.	29.06.	01.03.	29.05.	15.02.	15.05.	01.03.	29.05.	01.02.	01.05.
3rd Phaseolus	15.05.	12.08.	15.05.	12.08.	15.05.	12.08.	01.05.	29.07.	01.05.	29.07.
Rice	15.11.	13.04.	01.01.	30.05.	15.11.	13.04.	15.11.	13.04.	01.11.	30.03.
Soybean	01.12.	30.03.	01.12.	30.03.	15.11.	14.03.	15.11.	14.03.	15.11.	14.03.
Sugarcane	01.10.	30.09.	01.10.	30.09.	01.07.	30.06.	01.07.	30.06.	01.07.	30.06.
Vigna	15.12.	14.03.	15.11.	12.02.	15.11.	12.02.	01.11.	29.01.	01.10.	29.12.
2nd Vigna	01.04.	29.06.	01.03.	29.05.	15.02.	15.05.	01.03.	29.05.	01.02.	01.05.
3rd Vigna	15.05.	12.08.	15.05.	12.08.	15.05.	12.08.	01.05.	29.07.	01.05.	29.07.
Wheat	15.04.	11.09.	15.04.	11.09.	15.04.	11.09.	01.05.	27.09.	15.06.	11.11.

515 Figure A1. Spatial aggregation steps in the analysis.

Author contribution. MP, QL and MK initiated the study. SM and MP jointly developed the concept and methodology, with contributions by MK and LB. SM, MP, AA and AB pre-processed the input data for the analysis. SM carried out the calculations and prepared the figures. SM, MP, MK and LB analysed the results. SM, MP and MK wrote the first draft of the
520 manuscript. The final version of the manuscript has been prepared based on revisions that have been contributed by all authors.

Competing interests. The authors declare no competing interests.

Acknowledgements. Markus Pahlow, Maarten Krol and Quirijn de Jong van Lier gratefully acknowledge financial support
525 from the National Council of Technological and Scientific Development (CNPq - Brazil) and Netherlands Organisation for Scientific Research (NWO – Netherlands) (joint research programme Biobased Economy - project number: CNPq 456387/2013-7 and NWO 729.004.014).

References

Abdi, R., and Yasi, M.: Evaluation of environmental flow requirements using eco-hydrologic–hydraulic methods in perennial
530 rivers. Water Sci. Technol., 72(3), 354-363, https://doi.org/10.2166/wst.2015.200, 2015.

Abe, C. A., Lobo, F. L., Dibike, Y. B., Costa, M. P. F., Dos Santos, V., and Novo, E. M. L. M.: Modelling the effects of historical and future land cover changes on the hydrology of an Amazonian Basin, Water, 10(7): 932, https://doi.org/10.3390/w10070932, 2018.

Alkimim, A., Sparovek, G., and Clarke, K. C.: Converting Brazil's pastures to cropland: an alternative way to meet sugarcane demand and to spare forestlands, Appl. Geogr., 62, 75-84, https://doi.org/10.1016/j.apgeog.2015.04.008, 2015.

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapotranspiration-guidelines for computing crop water requirements, FAO Irrigation and drainage paper 56, Food and Agriculture Organization of the United Nations, Rome, Italy, 1998.

ANA: Conjuntura dos recursos hídricos no Brasil, Informe 2015, Agência Nacional de Águas, Brasília, Brazil, ~~pp.~~ 88 p., ISBN: 978-85-8210-030-1, 2015.

ANA: Disponibilidade Hídrica Superficial, Agência Nacional de Águas, Brasília, Brazil, available at: http://metadados.ana.gov.br/geonetwork/srv/pt/metadata.show?id=307, 2016.

ANA: Levantamento da agricultura irrigada por pivôs centrais no Brasil, Agência Nacional de Águas, Embrapa Milho e Sorgo, 2nd ed., Brasília, Brazil, 47 p.: ISBN: 978-85-8210-060-8, 2019.

Arvor, D., Dubreuil, V., Ronchail, J., Simões, M., and Funatsu, B.M.: Spatial patterns of rainfall regimes related to levels of double cropping agriculture systems in Mato Grosso (Brazil), Int. J. Climatol. 34, 2622-2633. doi:10.1002/joc.3863, 2014.

Boulay, A., Bare, J., Benini, L., Berger, M., Lathuillière, M. J., Manzardo, A., Margni, M., Motoshita, M., Núñez, M., Pastor, A. V., Ridoutt, B., Oki, T., Worbe, S., and Pfister, S.: 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, 368-378, doi:10.1007/s11367-017-1333-8, 2018.

Bosznay, M.: Generalization of SCS curve number method, J. Irrig. Drain. Eng., 115, 139-144, 1989.

Castello, L. and Macedo, M. N.: Large-scale degradation of Amazonian freshwater ecosystems, Glob. Change Biol., 22, 990-1007, 2016.

Chukalla, A. D., Krol, M. S., and Hoekstra, A. Y.: Green and blue water footprint reduction in irrigated agriculture: effect of irrigation techniques, irrigation strategies and mulching, Hydrol. Earth Syst. Sci., 19, 4877-4891, https://doi.org/10.5194/hess-19-4877-2015, 2015.

Cohn, A. S., VanWey, L. K., Spera, S. S, and Mustard, J. F.: Cropping frequency and area response to climate variability can exceed yield response, Nat. Clim. Change, 6, 601-604, 2016.

Conab: Acomp. Safra bras. grãos, v. 2 – Safra 2014/15, n. 10 – Décimo levantamento, Brasília, p. 1-109, Companhia Nacional de Abastecimento, Observatório Agrícola, ISSN: 2318-6852, 2015.

da Silva, V. D. P. R., De Oliveira, S. D., Hoekstra, A. Y., Dantas Neto, J., Campos, J. H. B. C., Braga, C. C., De Araújo, L. E., Aleixo, D. D. O., De Brito, J. I. B., De Souza, M. D., and De Holanda, R. M.: Water footprint and virtual water trade of Brazil, Water, 8, 517, 2016.

Dalin, C., Konar, M., Hanasaki, N., Rinaldo, A., and Rodriguez-Iturbe, I.: Evolution of the global virtual water trade network, Proc. Natl. Acad. Sci. U.S.A., 109, 5989-5994, https://doi.org/10.1073/pnas.1203176109, 2012.

Damkjaer, S. and Taylor, R.: The measurement of water scarcity: Defining a meaningful indicator, Ambio, 46(5), 513-531, 2017.

Dickie, A., Magno, I., Giampietro, J., and Dolginow, A.: Challenges and opportunities for conservation, agricultural production, and social inclusion in the Cerrado biome, CEA Consulting, San Francisco, USA, 54 pp., 2016.

Dos Santos, V., Laurent, F., Abe, C., and Messner, F.: Hydrologic response to land use change in a large basin in Eastern Amazon, Water, 10(4): 429. https://doi.org/10.3390/w10040429, 2018.

Fachinelli, N. P. and Pereira Jr., A. O.: Impacts of sugarcane ethanol production in the Paranaiba basin water resources, Biomass Bioenerg., 83, 8-16, https://doi.org/10.1016/j.biombioe.2015.08.015, 2015.

Fader, M., Gerten, D., Thammer, M., Heinke, J., Lotze-Campen, H., Lucht, W., and Cramer, W.: Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade, Hydrol. Earth Syst. Sci., 15, 1641-1660, 2011.

Falkenmark, M.: Land-water linkages: a synopsis. In: FAO, Land and water integration and river basin management, Proceedings of an FAO informal workshop, Rome, Italy, 31 January–2 February 1993, FAO Land and Water Bulletin 1, Food and Agriculture Organization, Rome, pp. 15–16, 1995.

FEALQ/IICA/MI: Integrated spatial analysis for development of irrigated agriculture in Brazil. Luiz de Queiroz Agricultural Studies Foundation / Inter-American Institute for Cooperation on Agriculture / Ministry of National Integration, Technical Cooperation Program PCT BRA/IICA/08/002, available at http://www.mi.gov.br/analise-territorial-para-o-desenvolvimento-da-agricultura-irrigada (in Portuguese), 2015.

Flach, R., Ran, Y., Godar, J., Karlberg, L., and Suavet, C.: Towards more spatially explicit assessments of virtual water flows: Linking local water use and scarcity to global demand of Brazilian farming commodities, Environ. Res. Lett., 11, 075003, 2016.

Getirana, A. (2016).: Extreme water deficit in Brazil detected from space, J. Hydrometeorol., 17, 591-599, 2016.

Gerbens-Leenes, W. and Hoekstra, A. Y.: The water footprint of sweeteners and bio-ethanol, Environ. Int., 40, 202-211, 2012.

Hernandes, T. A., Bufon, V. B., and Seabra, J. E.: Water footprint of biofuels in Brazil: assessing regional differences, Biofuel. Bioprod. Bior., 8, 241-252, https://doi.org/10.1002/bbb.1454, 2014.

Hengl, T., de Jesus, J. M., MacMillan, R. A., Batjes, N. H., Heuvelink, G. B. M., Ribeiro, E., Samuel-,osa, A., Kempen, B.,Leenaars, J.G.B., Walsh, M.G., and Ruiperez Gonzalez, M.: SoilGrids1km - Global Soil Information Based on Automated Mapping PLoS ONE, 9(8): e105992, https://doi:10.1371/journal.pone.0105992, 2014.

Hoekstra, A. Y., Mekonnen, M. M., Chapagain, A. K., Mathews, R. E., and Richter, B. D.: Global monthly water scarcity: Blue water footprints versus blue water availability, PLoS One 7, e32688. doi:10.1371/journal.pone.0032688, 2012.

IBGE: Censo Agropecuário 2006. Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro, Brazil. Available at: http://www.sidra.ibge.gov.br/, 2006.

IBGE: Produção Agrícola Municipal. Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro, Brazil. Available at: http://www.sidra.ibge.gov.br/, 2012.

600 Jägermeyr, J., Gerten, D., Heinke, J., Schaphoff, S., Kummu, M., and Lucht, W.: Water savings potentials of irrigation systems: global simulation of processes and linkages, Hydrol. Earth Syst. Sci., 19, 3073-3091, 2015.

Jägermeyr, J., Gerten, D., Schaphoff, S., Heinke, J., Lucht, W., and Rockström, J.: Integrated crop water management might sustainably halve the global food gap, Environ. Res. Lett., 11: 25002, https://doi.org/10.1088/1748-9326/11/2/025002, 2016.

Książek, L., Woś, A., Florek, J., Wyrębek, M., Młyński, D., and Wałęga, A.: Combined use of the hydraulic and hydrological
605 methods to calculate the environmental flow: Wisloka river, Poland: case study, Environ. Monit. Assess., 191(4), 254. https://doi.org/10.1007/s10661-019-7402-7, 2019.

Lathuillière, M. J., Coe, M. T., and Johnson, M. S.: A review of green- and 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, 2179-2194, 2016.

610 Lathuillière, M. J., Dalmagro, H. J., Black, T. A., Arruda, P. H. Z. d., Hawthorne, I., Couto, E. G., and Johnson, M. S.: Rain-fed and irrigated cropland-atmosphere water fluxes and their implications for agricultural production in Southern Amazonia, Agric. For. Meteorol., 256-257, 407-419, https://doi.org/https://doi.org/10.1016/j.agrformet.2018.03.023, 2018.

Mekonnen, M. M. and Hoekstra, A. Y.: A global and high-resolution assessment of the green, blue and grey water footprint of wheat, Hydrol. Earth Syst. Sci., 14, 1259-1276, 2010.

615 Mittermeier, R. A., Gil, P. R.; Hoffman, M.; Pilgrim, J., Brooks, T., Mittermeier, C. G., Lamoreux, J., and da Fonseca, G.A.B.: Hotspots revisited-Earth's biologically richest and most endangered terrestrial ecoregions, University of Chicago Press, Chicago, IL, USA, 2005.

Multsch, S., Al-Rumaikhani, Y. A., Frede, H.-G., and Breuer, L.: A site-specific agricultural water requirement and footprint estimator (SPARE: WATER 1.0), Geosci. Model Dev., 6, 1043-1059, 2013.

620 Multsch, S., Pahlow, M., Ellensohn, J., Michalik, T., Frede, H.-G., and Breuer, L.: A hotspot analysis of water footprints and groundwater decline in the High Plains aquifer region, USA, Reg. Environ. Change, 16(8), 2419-2428, https://doi:10.1007/s10113-016-0968-5, 2016.

Multsch, S., Elshamy, M. E., Batarseh, S., Seid, A. H., Frede, H.-G., and Breuer, L.: Improving irrigation efficiency will be insufficient to meet future water demand in the Nile Basin. J. Hydrol.: Regional Studies, 12, 315-30, 2017a.

625 Multsch, S., Grabowski, D., Lüdering, J., Alquwaizany, A. S., Lehnert, K., Frede, H.-G., P. Winker, and L. Breuer: A practical planning software program for desalination in agriculture - SPARE:WATERopt, Desalination, 404, 121-131, https://doi.org/10.1016/j.desal.2016.11.012, 2017b.

Raskin, P., Gleick, P. H., Kirshen, P., Pontius, R. G. Jr, and Strzepek, K.: Comprehensive assessment of the freshwater resources of the world, Stockholm Environmental Institute, Sweden, pp. 51, 1997.

630 Richter, B. D., Davis, M. M., Apse, C., and Konrad, C.: A presumptive standard for environmental flow protection, River Res. Appl., 28(8), 1312-1321. https://doi.org/10.1002/rra.1511, 2012.

Rockström, J., Karlberg, L., Wani, S. P., Barron, J., Hatibu, N., Oweis, T., Bruggeman, A., Farahani, J., and Qiang, Z.: Managing water in rainfed agriculture - The need for a paradigm shift, Agr. Water Manage., 97, 543-550, https://doi.org/10.1016/j.agwat.2009.09.009, 2010.

635 Rodrigues, L. N., Sano, E. E., Steenhuis, T. S., and Passo, D. P.: Estimation of small reservoir storage capacities with remote sensing in the Brazilian Savannah region, Water Resour. Manag., 26, 873–882. doi:10.1007/s11269-011-9941-8, 2012.

Rost, S., Gerten, D., Hoff, H., Lucht, W., Falkenmark, M., and Rockström, J.: Global potential to increase crop production through water management in rainfed agriculture, Environ. Res. Lett., 4: 44002, https:// doi:10.1088/1748-9326/4/4/044002, 2009.

640 Scarpare, F. V., Hernandes, T. A. D., Ruiz-Corrêa, S. T., Picoli, M. C. A., Scanlon, B. R., Chagas, M. F., Duft, D.G., de Fatima Cardoso, T.: Sugarcane land use and water resources assessment in the expansion area in Brazil, J. Clean. Prod., 133, 1318-1327, 2016.

Siebert, S. and Döll, P.: Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation, J. Hydrol., 384,198-217, 2010.

645 Smakhtin, V., Revenga, C., and Döll, P.: A pilot global assessment of environmental water requirements and scarcity. Water International, 29(3), 307-317, https://doi.org/10.1080/02508060408691785, 2004.

Sparovek, G., Barretto, A. G. O. P., Matsumoto, M., and Berndes, G.: Effects of governance on availability of land for agriculture and conservation in Brazil, Environ. Sci. Technol., 49, 10285-10293, 2015.

Spera, S. A., Galford, G. L., Coe, M. T., Macedo, M. N., and Mustard, J. F.: Land-use change affects water recycling in Brazil's
650 last agricultural frontier, Glob. Change Biol., 22, 3405-3413, https://doi.org/10.1111/gcb.13298, 2016.

Spera, S. A.: Agricultural intensification can preserve the Brazilian Cerrado: Applying lessons from Mato Grosso and Goiás to Brazil's last agricultural frontier, Trop. Conserv. Sci., 10, 1-7, https://doi.org/10.1177/1940082917720662, 2017.

Strassburg, B. B. N, Latawiec, A. E., Barioni, L. G., Nobre, C. A., da Silva, V. P., Valentim, J. F., Vianna, M., and Assad, E.D.: When enough should be enough: Improving the use of current agricultural lands could meet production demands and
655 spare natural habitats in Brazil, Global Environ. Chang., 28, 84-97, 2014.

Strassburg, B. B. N., Brooks T., Feltran-Barbieri R., Iribarrem A., Crouzeilles R., Loyola R., Latawiec A.E., Oliveira Filho F.J., de M. Scaramuzza, C.A., Scarano, F.R., Soares-Filho, B., and Balmford, A.: Moment of truth for the Cerrado hotspot, Nat. Ecol. Evol., 1(4): 0099, DOI:10.1038/s41559-017-0099, 2017.

Tennant D. L.: Instream flow regimens for fish, wildlife, recreation and related environmental resources, Fisheries 1, 6-10,
660 1976.

Tomasella, J., Hodnett, M. G., and Rossato, L.: Pedotransfer functions for the estimation of soil water retention in Brazilian soils, Soil Sci. Soc. Am. J., 64, 327-38, 2000.

UN: Comprehensive assessment of the freshwater resources of the world. Report of the Secretary General, Report E/CN.17/1997/9, New York, NY, United Nations, 1997.

665 Van Genuchten, M.T.: A closed form equation for predicting the hydraulic conductivity of unsaturated soils, Soil Sci. Soc. Am. J., 44, 892-898, 1980.

Vanham, D., Hoekstra, A. Y., Wada, Y., Bouraoui, F., de Roo, A., Mekonnen, M. M., van de Bund, W.J., Batelaan, O., Pavelic, P., Bastiaanssen, W.G.M., Kummu, M., Rockström, J., Liu, J., Bisselink, B., Ronco, P., Pistocchi, A., and Bidoglio, G.: Physical water scarcity metrics for monitoring progress towards SDG target 6.4: An evaluation of indicator 6.4.2 "Level of

670 water stress", Sci. Total Environ., 613-614, 218-232, https://doi.org/10.1016/j.scitotenv.2017.09.056, 2018.

VanWey, L. K., Spera, S., de Sa, R., Mahr, D., and Mustard, J. F.: Socioeconomic development and agricultural intensification in Mato Grosso, Philos. T. R. Soc. A, 368: 20120168, https://doi.org/10.1098/rstb.2012.0168, 2013.

Wriedt, G., Van der Velde, M., Aloe, A., and Bouraoui, F.: Estimating irrigation water requirements in Europe, J. Hydrol., 373, 527-544, 2009.

675 Xavier, A. C., King, C. W., and Scanlon, B. R.: Daily gridded meteorological variables in Brazil (1980–2013), Int. J. Climatol., 36, 2644-2659, https://doi:10.1002/joc.4518, 2016.

680 **Table 1. Data used in this study and respective sources (Note: *Brazil is administratively divided into 5,565 municipalities; **For hydrological analyses, Brazil is subdivided into 166,842 catchments).**

Data type	Source	Spatial scale
Climate data	Xavier et al. (2016)	0.25°x0.25°
Soil data	Hengl et al. (2014)	1 km
Crop production	IBGE (2012) Produção Agrícola Municipal (PAM)	Municipality*
Crop coefficients (see Table A1)	Allen et al. (1998); Hernandes et al. (2014)	-
Planting and harvesting date (see Table A2)	Conab (2015)	-
Surface water supply	ANA (2016)	Catchment**
Extent of irrigated areas	IBGE (2012) Produção Agrícola Municipal (PAM)	Municipality*
Fraction of irrigated area per crop	IBGE (2006) Censo Agropecuário	Municipality*

Table 2. Crop water balance and water consumption of rainfed and irrigated crops in Brazil for the production year 2012. "1st", 2nd" and "3rd" are the first, second and third planting dates for successive multiple cropping practice within one growing season. Crop development stages are provided in Table A1 and planting/harvesting dates are provided in Table A2.

	Crop	ET_{act} [mm]	P_{eff} [mm]	IRR [mm]	Cropping area [ha]	Green water [km³ a⁻¹]	Blue water [km³ a⁻¹]
rainfed	*Vigna* spp. 1st	244	648		6,097	0.010	
	Phaseolus spp. 1st	244	648		799,232	1.824	
	Cotton	447	954		1,315,585	5.643	
	Cassava	443	1,114		1,491,520	5.864	
	Corn 1st	438	975		6,613,805	31.076	
	Soybean	355	823		23,692,402	92.524	
	Vigna spp. 2nd	214	389		6,097	0.009	
	Phaseolus spp. 2nd	214	389		799,232	1.593	
	Corn 2nd	328	477		6,613,805	21.534	
	Wheat	310	406		1,827,587	6.066	
	Vigna spp. 3rd	154	229		6,097	0.008	
	Phaseolus spp. 3rd	154	229		799,232	0.913	
	Rice	462	956		1,652,877	7.754	
	Sugarcane	925	1,574		8,143,700	70.145	
	Subtotal				**53,767,270**	**244.963**	
irrigated	*Vigna* spp. 1st	299	648	138	770	0.001	0.002
	Phaseolus spp. 1st	299	648	138	99,053	0.218	0.124
	Cotton	592	954	216	66,322	0.248	0.175
	Cassava	565	1,114	183	189,305	0.684	0.489
	Corn 1st	532	975	206	438,283	2.041	0.459
	Soybean	432	823	180	1,176,186	4.630	0.875
	Vigna spp. 2nd	276	389	106	770	0.001	0.001
	Phaseolus spp. 2nd	276	389	106	99,053	0.174	0.115
	Corn 2nd	494	477	245	438,283	1.272	0.619
	Wheat	514	406	291	58,916	0.193	0.036
	Vigna spp. 3rd	260	229	159	770	0.001	0.001
	Phaseolus spp. 3rd	260	229	159	99,053	0.111	0.143
	Rice	623	956	236	753,691	3.220	2.342
	Sugarcane	1,508	1,574	644	1,507,080	12.386	9.979
	Subtotal				**4,927,531**	**25.181**	**15.360**
	Total				**58,694,801**	**270.145**	**15.360**

Table 3. Crop water balance and water consumption of rainfed and irrigated crops in the Cerrado region of Brazil for the production year 2012. "1st", 2nd" and "3rd" are the first, second and third planting dates for successive multiple cropping practice within one growing season. Crop development stages are provided in Table A1 and planting/harvesting dates are provided in Table A2.

	Crop	ET_{act} [mm]	P_{eff} [mm]	IRR [mm]	Cropping area [ha]	Green water [km³ a⁻¹]	Blue water [km³ a⁻¹]
rainfed	*Vigna* spp. 1st	285	607		534	0.001	
	Phaseolus spp. 1st	285	607		240,816	0.681	
	Cotton	419	700		1,232,061	5.226	
	Cassava	498	997		228,505	0.980	
	Corn 1st	477	793		2,854,404	14.000	
	Soybean	402	724		12,081,675	49.685	
	Vigna spp. 2nd	204	265		534	0.001	
	Phaseolus spp. 2nd	204	265		240,816	0.493	
	Corn 2nd	274	273		2,854,404	9.456	
	Wheat	211	144		95,376	0.270	
	Vigna spp. 3rd	102	82		534	0.000	
	Phaseolus spp. 3rd	102	82		240,816	0.249	
	Rice	483	816		533,050	2.560	
	Sugarcane	813	1,179		4,136,773	35.580	
					24,740,298	**119.182**	
irrigated	*Vigna* spp. 1st	312	607	553	95	0.000	0.000
	Phaseolus spp. 1st	312	607	553	39,378	0.110	0.016
	Cotton	624	700	2,606	60,942	0.231	0.156
	Cassava	591	997	1,175	29,508	0.135	0.047
	Corn 1st	565	793	1,349	237,558	1.164	0.167
	Soybean	454	724	892	759,294	3.145	0.216
	Vigna 2nd	285	265	1,149	95	0.000	0.000
	Phaseolus spp. 2nd	285	265	1,149	39,378	0.074	0.035
	Corn 2nd	507	273	3,170	237,558	0.703	0.359
	Wheat	530	144	4,165	13,109	0.033	0.020
	Vigna spp. 3rd	268	82	2,149	95	0.000	0.000
	Phaseolus spp. 3rd	268	82	2,149	39,378	0.041	0.056
	Rice	627	816	1,703	72,836	0.389	0.050
	Sugarcane	1,577	1,179	8,040	783,690	6.575	4.530
					2,312,915	**12.60**	**5.65**
				Total	**27,053,214**	**131.78**	**5.65**

Table 4. Extent of current and potential irrigated areas under various scarcity levels for the reference and expansion scenario.

	Reference scenario Irrigated areas - target blue water scarcity				Expansion scenario Potentially irrigated areas - target blue water scarcity			
	Without	Acceptable	Comfortable	Worrying	Without	Acceptable	Comfortable	Worrying
				Mha				
Acceptable	1.49	1.49	1.49	1.49	11.69	11.69	11.69	11.69
Comfortable	0.32	0.23	0.32	0.32	3.71	2.62	3.71	3.71
Worrying	0.38	0.13	0.27	0.38	4.14	1.35	2.89	4.14
Critical	0.47	0.08	0.17	0.34	4.02	0.58	1.32	2.87
Very critical	1.63	0.06	0.13	0.25	22.00	0.44	1.07	2.5
Total	4.29	1.99	2.38	2.78	45.56	16.68	20.68	24.89

695

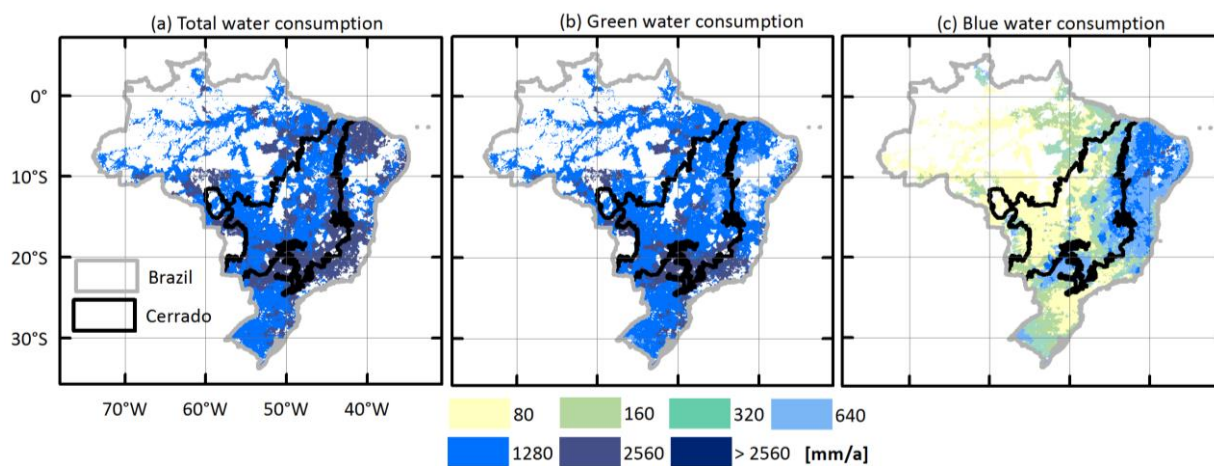



Figure 1. Spatial distribution of the water consumption in crop production in Brazil for the crops considered in this study: (a) total, (b) green and (c) blue water consumption. The black line delimits the Cerrado region.

705

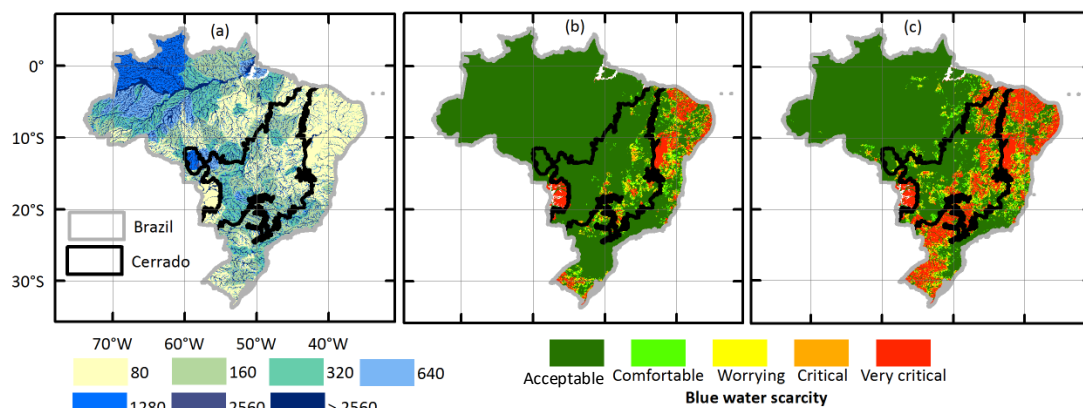
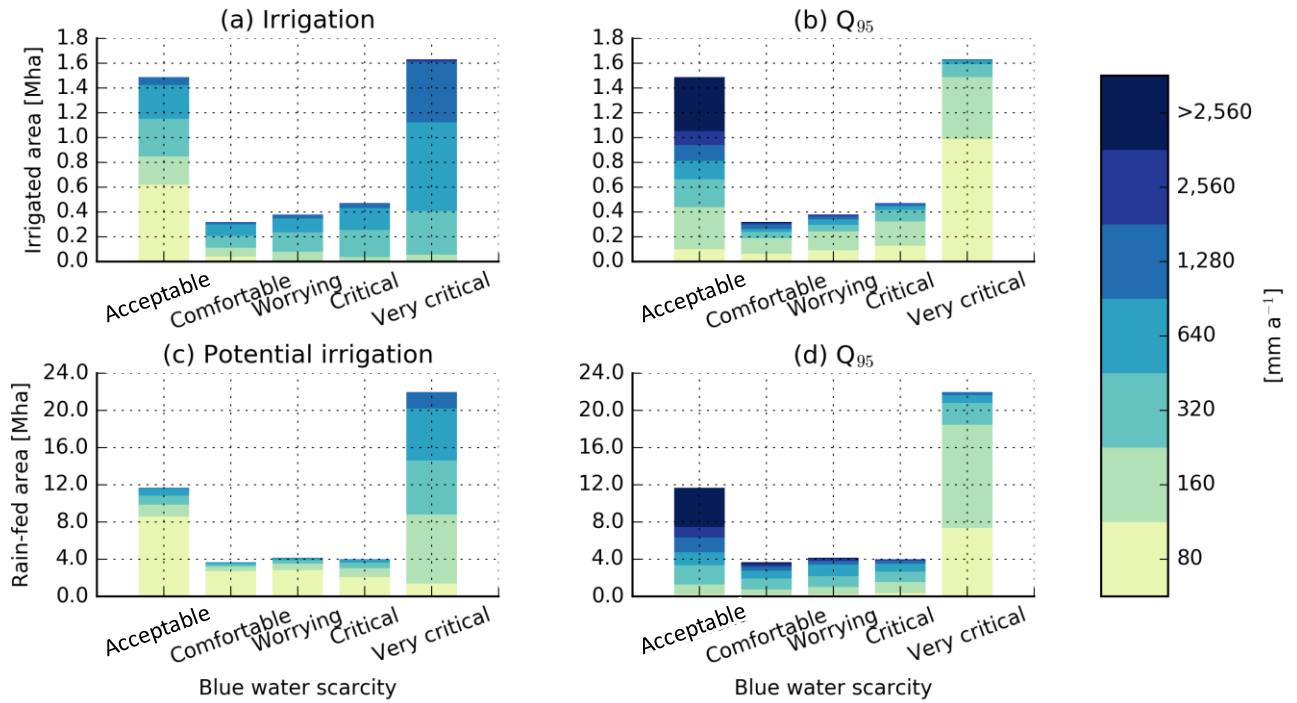



Figure 2. Water scarcity of 166,844 catchments across Brazil. (a) Annual average water availability Q95. (b) Blue water scarcity classification of irrigated areas. (c) Blue water scarcity classification of rainfed areas when irrigated. The black line delimits the Cerrado region.

715 **Figure 3. Classification of blue water consumption (a, c) and blue water availability (b,d) for irrigated areas (a,b; 4.29 Mha) and potential irrigated areas (c,d; 45.56 Mha) according to blue water scarcity levels.**

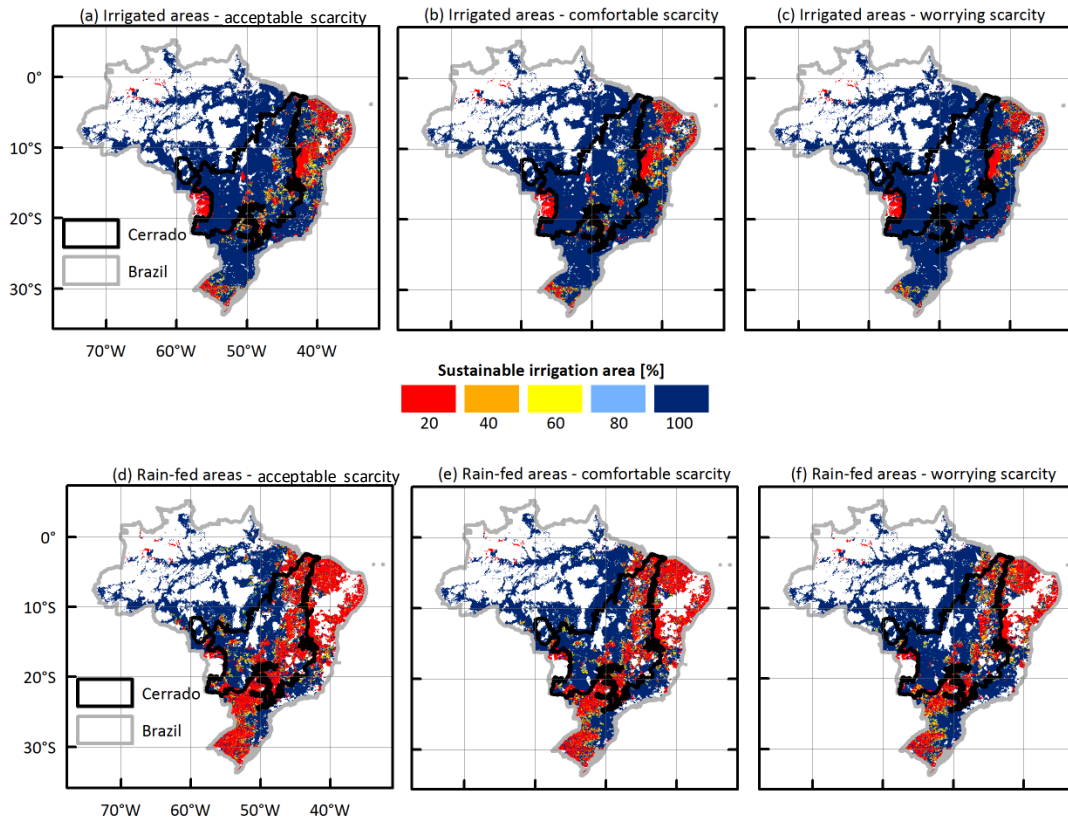



Figure 4. Fraction of current irrigated areas (a,b,c) and potentially irrigated areas (d,e,f) which can be sustablye irrigated according to a target blue water scarcity level of acceptable (a,d), comfortable (b,e) and worrying (c,f).