1 **The global nexus of food-trade-water sustaining environmental flows by 2050**

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18 **Abstract**

19 In face of meeting Sustainable Development Goals (SDGs) for water-food-energy-ecosystems nexus,

20 integrated assessments are great means to measure the impact of global change on natural resources. In

21 this study, we evaluate the impact of future climate change scenarios (RCP8.5) and future shared-

22 socioeconomic Pathways (SSP2) on land use, water consumption and food trade under water

23 regulation policy scenarios (INVEST-EXPLOIT-ENVIRONMENT). We have used the land use

24 model GLOBIOM, and constrained it with water availability, environmental flow requirements

25 (EFRs) and water use from agriculture and industry and households (simulated with LPJml, EPIC and

26 WaterGap models). Here, we show that an increase in land use by 100Mha would be required to

27 double food production by 2050, in order to meet projected food demand. International trade would

28 need to nearly triple to meet future crop demand, with an additional 10-20% trade flow from water-

29 abundant regions to water-scarce regions to sustain EFRs on a global scale.

30 Keywords: food production, agricultural area, environmental flow requirements, international trade

1. Introduction

Global water resources are under increasing pressure due to large-scale water abstraction for human needs (Loh et al. 2010; WWF/ZSL 2016). About 70% of the water that is abstracted from freshwater systems is used for irrigation and about 40% of our food is produced on irrigated lands (Wada et al. 2013). By 2050, without major policy interventions, human water use and irrigated area are expected to increase rapidly due to population growth and an increase in food demand (Elliott et al. 2014; Molden 2007; Alexandratos and Bruinsma 2012). In addition, crop yields are projected to decrease by more than 80% in some areas under the highest-emission climate scenario (Elliott et al. 2014; Rosenzweig et al. 2014; Schlenker and Roberts 2009; Ray et al. 2013). Climate change could affect 10 to 45% of current cereal production while water scarcity is predicted to increase in the coming decades (Elliott et al. 2014; Osborne, Rose, and Wheeler 2013; Haddeland et al. 2014) However, CO_2 fertilization and optimized crop production could stabilize and/or increase future crop yields under climate change (de Vrese, Stacke, and Hagemann 2018; Tester and Langridge 2010). Freshwater abstraction and river fragmentation can be detrimental to freshwater ecosystems (Poff and Zimmerman 2010), and Jagermeyr et al. (2017 have shown that under current conditions, 30% of irrigated crop production comes at the expense of environmental flow requirements (EFRs). The use of trade and/or "climate-smart food systems" was proposed in order to address future challenges related to climate change and food security (Kummu et al. 2014; Qureshi, Hanjra, and Ward 2013; Wheeler and Von Braun 2013).

Rising demand for water is likely to increase the pressure on riverine ecosystems (Falkenmark, Rockström, and Karlberg 2009). To limit biodiversity loss in riverine ecosystems, EFRs have been defined for many river systems around the globe (Declaration 2007; Tharme 2003). EFRs are needed, *inter alia*, to preserve connectivity, supply sediments and nutrients for soil fertility, and replenish groundwater aquifers (Richter 2010). Until recently, on a global scale, most of the methods used to define EFRs were applied to single river basins or estimated with a "rule of thumb" (A. V Pastor et al. 2013). The recently developed Variable Monthly Flow Method (VMF) (A. V. Pastor et al. 2014) was designed with refined spatial and temporal scales to be applied globally. Using this method, the planetary boundary for freshwater resources was estimated at 2,800 km^3 yr^{-1}, equivalent to 7% of total runoff and much lower than in previous assessments (D. Gerten et al. 2013; Steffen et al. 2015).

Integrated Assessment (IA) models have been developed to evaluate the interactions between socioeconomic developments, climate change and bioenergy scenarios and their effects on land-use dynamics (Lampe et al. 2014; Verburg et al. 2004). IA models are classified into computable general equilibrium (CGE) models and partial equilibrium (PE) models (Robinson et al. 2014). CGE models require general production/cost functions for all sectors, whereas PE models involve a more

65   comprehensive description of agricultural technologies. In this study, we used the PE integrated

66   assessment model GLOBIOM (Global Biosphere Management Model) to optimize the allocation of

67   future cropland and water withdrawals and find trade-offs between future crop production and

68   sustainable water withdrawals. We evaluate how a redistribution of cropland could result in more

69   sustainable water use (Fig. 1). This is the first integrated global assessment that evaluates the impact of

70   climate change, socioeconomic change and the implementation of EFRs on the future distribution of

71   cropland and food production.

72   In this study, we show that crop production needs to be doubled by 2050 under any of the water

73   management policy scenarios (Fig. 3 and Supplementary Table 8). Table 1 shows that water use for

74   irrigation increases by 20% between 2000 and 2050 in the INVEST scenario (the less water restrictive

75   scenario), while water use decreases by 30-38% by 2050 in the ENV and ENV+ scenarios (under

76   EFRs restrictions). Under the INVEST scenario, the increase in crop production comes from a large

77   expansion of cropland (50% irrigated/50% rainfed), assuming large scale investments in water

78   infrastructure. The INVEST scenario results in the highest water use and the lowest international trade

79   (Table 1, Fig. 2). Under the EXPLOIT scenario (local water restrictions), the increase in crop

80   production comes mainly from an increase in rainfed area in Latin America and in South-East Asia

81   (SEA; Figs. 4 and 5). The EXPLOIT scenario results in the largest increase in land use, with

82   intermediate trade and water use. To comply with EFRs, the ENV and ENV+ scenarios result in a

83   reduction of irrigated areas in China and India by 2050 with a reallocation of cropland in the tropics

84   (Fig. 4 - Supplementary Fig. 3-4-5). Between 2000 and 2050, international trade would need to nearly

85   triple to meet future crop demand, with an additional 15% to compensate for water restrictions from

86   EFRs (Table A5). Crop area would expand from 17% to 20% in all scenarios, with an increase of

87   high-input rainfed cropping systems by up to 25% (Fig. 3; Supplementary Figure 9). In the ENV

88   scenarios, a conversion of up to 60 Mha of irrigated cropland to rainfed cropland would be required to

89   meet EFRs (Supplementary Figure 2).

90   *Future regional changes in land use under water restrictions*

91   In 2050, the increase in agricultural crop production under the INVEST scenario would be mostly

92   achieved by a 20% expansion of total irrigated and rainfed crop area (Fig. 4 and Table A5), while

93   implementing EFRs (ENVIRONMENT scenario) would imply a regional increase in rainfed area and

94   a large reduction in irrigated area, especially in Asia (Fig. 4). For example, we show that under the

95   INVEST scenario, irrigated area could expand from about 220 Mha in 2000 to 300 Mha in 2050,

96   mainly in East of Asia (EAS, e.g. China) and South Asia (SA, e.g. India), while under the ENV and

97   ENV+ scenarios, by 2050, irrigated area could be reduced from 220 Mha to 161 Mha, mainly in EAS

98   and SA (Fig. 3, Table A5). Climate change alone would lead to an increase in irrigated land in North

99   America (NAM) and Southeast Asia (SEA), including Indonesia, and to a decrease in irrigated land in

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100   the Mediterranean and North-African (MENA) region and to an expansion of rainfed area in Latin

101   America (LAM; Fig. 4, Table A5).

102   *Consequences for future crop production*

103   At present, 40% of crop production comes from irrigated areas (Fig.3, Supplementary Table 6). We

104   show that by 2050, under EFRs restrictions, only 20% of crops could be produced on irrigated land,

105   compared to 38% for the INVEST scenario (Supplementary Table 7). Under the EXPLOIT and

106   INVEST scenarios, part of the irrigated production comes at the expense of EFRs, especially in the

107   MENA and in China and India, while, under the ENV scenarios, irrigated area would be reduced by

108   about 50% in these regions representing more than 30 Mha (Fig. 4, Supplementary Tables 7-8).

109   *Pathways to sustain environmental flows*

110   Our results show that there are three main mechanisms that compensate for the loss of irrigated

111   agriculture in order to meet EFRs (Fig. 2). The first is a conversion of irrigated and natural areas to

112   rainfed areas (Figs. 3 & 4, Supplementary Figure 2 and Table 5-6), the second is an increase in global

113   crop trade (Fig. 5, Supplementary Figures 3-4-5), and the third is a shift to more intensive cropping

114   systems and less water-demanding crops (Supplementary Figure 9, Supplementary Data). In 2050, the

115   difference between scenarios in total crop area remains relatively small (Fig. 2). The additional crop

116   production would come from regional shifts in land use, cropping systems and modes of production.

117   Conversion of irrigated area to rainfed area takes place in productive croplands with sufficient rainfall

118   (Supplementary Figure 2). To compensate for this loss of cropland area in China, India and in the

119   MENA, our results show that an expansion of cropland area by up to 20 Mha in Latin America, Africa

120   and Russia would be required (Fig. 4, Supplementary Table 2).

121   *International trade by region*

122   Results indicate that bilateral trade needs to increase by 5% to compensate for climate change alone,

123   by 10-13% to compensate for EFRs alone and by 17-20% to compensate for combined climate change

124   and EFRs (Fig. 5, Supplementary Figure Fig. A5). In general, trade flow increases from water-

125   abundant regions such as Latin America and Southeast Asia to water-scarce regions such as China and

126   MENA (Fig. 5). Water-scarce regions need to import more agricultural products under the

127   ENVIRONMENT scenarios than under the EXPLOIT and INVEST scenarios (Fig. 5, Supplementary

128   Figure 3-4-5). Climate change further increases imports of agricultural products to China and South

129   Asia (including India), though the impact of climate change on global crop trade remains lower than

130   the effect of implementing EFRs.

131   *Changes in land use and expansion*

132   Under climate change and water limitations, part of the additional crop production would come from

133   converting grasslands, forests and other natural vegetation into productive rainfed cropland

134   (Supplementary Table 7 and Figure 2). Globally, agricultural expansion into natural land and primary

135   forest is expected to be about 300 Mha (100 Mha cropland and 200 Mha grassland) between 2000 and

136   2050 due to increase in food demand, with more than 60% of the increase coming at the expense of

137   forests. Fifty to sixty percent of this conversion would occur in Latin America, where managed land

138   would expand into forest and other natural land. On a global scale, the impact of EFRs alone could

139   lead to 15% more conversion of grassland to cropland, 12 to 21% more conversion of natural land to

140   cropland and up to 9% more conversion of forest to cropland (Supplementary Table 7). Additional

141   results on cropping system shifts, agriculture intensification and sensitivity analyses on crop yields,

142   crop area and water supply are available in supplementary results (Supplementary Figures 2 to 9,

143   Supplementary Data).

144   Discussion

145   Our results indicate that in order to protect freshwater by meeting EFRs and supply sufficient food for

146   future generations, irrigated areas should be reduced by 30% relative to the current situation, which

147   correspond to the compromised EFRs found in Jägermeyr et al. (2017). In addition to the change in

148   land use, increased interregional trade in agricultural products is needed to supply the world's

149   population with sufficient food (three times more than in 2000). Interestingly, our results indicate that

150   the primary cause of land use expansion is the increase in food demand, whereas, to meet EFRs, our

151   assessment shows that what is needed is a large-scale conversion of irrigated land to intensive rainfed

152   land and a regional reallocation of rainfed area, especially in Latin America and the Pacific Islands.

153   The combined impact of climate change and EFRs would increase net trade by up to 15% globally

154   compared to a business-as usual scenario (INVEST). The main increase in exports could come from

155   Latin America (+70%) and Southeast Asia, e.g. Indonesia (+22%), while increased dependency on

156   imports would take place mainly in China (+38%), India (+33%) and MENA countries (+19%). In

157   addition, with climate change, we observe that water use for irrigation is lower than without climate

158   change (Table 1), this is mainly due to a low water availability in water-scarce countries and due to a

159   combined increase in water demand for agriculture, industry and households and EFRs (for ENV and

160   ENV+ scenarios). Therefore, in water scarce regions such as MENA, the rise in marginal water price

161   leads to a partial abandonment of irrigated area. Stricter EFRs would not entirely be a win-win

162   scenario for the world, since regional reallocation of agricultural land would have consequences such

163   as the loss of agricultural area and expansion into natural lands and forests up to 9% (Supplementary

164   Table 7). As it is shown in Dalin et al. (2016), the environmental impact of water trade is beneficial as

165   long as the exporter's water productivity is higher than that of the importer, however, this latter should

166   not deplete non-renewable water, pollute freshwater and/or lead to the collapse of other terrestrial

167   ecosystems. In addition, it is important to consider that the expansion of agricultural area to natural

168   areas can release stored carbon, fragment species habitat, and alter the hydrological cycle.

169   Our results show that it is possible to double agricultural production with a 20% increase in cropland.

170   This assumes a significant reduction in the crop yield gap through intensification, technological

171   improvements and a rapid uptake of improved technologies, especially in Africa, Asia and Latin

172   America (Supplementary Figures 8-9). Tilman et al. (2011) provided similar estimates and found that

173   crop production can be doubled with a relatively small rise in agricultural area if a number of

174   adaptation measures are implemented to intensify agricultural production. However, a study by

175   Wirsenius et al. (2010) estimated a required increase in agricultural area of 1,600 Mha by 2030, which

176   is much higher than our projections. This difference is partly due to less-flexible trade flows between

177   regions and a less-flexible scheme for change in land use with respect to our study. Agricultural

178   intensification can also have major effects on the environment, including freshwater ecosystems, due

179   to increased use of agrochemicals. Our study explicitly focuses on the water quantity aspects of

180   protecting freshwater habitats, but this should not come at the expense of water quality (e.g. by using

181   extra nutrients and/or pesticides), which can also have a large impact on freshwater biodiversity

182   (Turner and Rabalais 2003).

183   Our results indicate that increase in trade is necessary to adapt to global change and allocate more

184   water to the environment. Similarly, a study from Dalin and Rodríguez-Iturbe (2016) showed that

185   trade can reduce global agricultural water use. In addition, a study from Martinez et al. (2017) shows

186   that agricultural trade market reduces the impact of climate change and crop yield reduction on food

187   provision. Therefore, it is important to include infrastructures and water trade flows in future

188   freshwater planetary boundary assessments (Konar et al. 2016). However, at present, trade in

189   agriculture is still limited with respect to other commodities due to high freight cost and protective

190   laws and regulations (Turner and Rabalais 2003; Dalin and Rodríguez-Iturbe 2016). Dalin and

191   Rodríguez-Iturbe (2016) also show that increased trade can have other negative consequences, such as

192   decreased terrestrial biodiversity and local socioeconomic changes. Trade liberalization can potentially

193   increase the environmental impact in countries where environmental protection laws are less

194   restrictive and should be used with caution. Trade can also be a risky tool in times of food crisis or

195   drought, such as in 2007, increasing food insecurity for the poor and malnourished (Suweis et al.

196   2015). Although international trade can help supply food in times of regional shortages, there are also

197   environmental tradeoffs such as increasing deforestation and/or agricultural land expansion in LAM

198   and SEA. For example, DeFries et al. (2012) reveal a direct, positive linear relationship between forest

199   loss in Asia and Latin America and net agricultural trade. To reduce the negative effects of agricultural

200   expansion policies, exporting countries could establish expansion limits for agricultural land dedicated

201   to export crops, intensification policies (in order to avoid expansion), and subsidies to sell crops

202   locally at a lesser price and thus reduce exports.

203 Our results show the trade-offs between land use, water use and crop production versus trade. Increase
204 in food demand reduces national self-sufficiency ratios especially in Asia and the MENA region, and
205 this result is worsened by EFRs and climate change (Fig. 5, Supplementary Figure 5). Currently, both
206 India and China have developed policies for securing food supply through high self-sufficiency ratios
207 (Yu and Lu 2006). Our analyses show that it is possible on a macroeconomic scale to provide food and
208 water for all, However, on a regional scale, reducing regional irrigation water use would have
209 significant consequences for regional crop production leading to increased imports and this could have
210 negative consequences for food security (Margulis 2013) in the importing countries and for
211 environment in the exporting countries. It is important for a regime with more agricultural trade to be
212 combined with policies guaranteeing food access and affordability because sufficient production does
213 not guarantee access to food for all. Importing more food into a country that is limited in natural
214 resources (land and/or water) can have a negative impact on local agriculture production, local natural
215 resources and on the rural economy. In addition, preserving EFRs can on one side favor ecosystems,
216 replenish groundwater, provide downstream populations with sufficient water and prevent
217 desalinization. However, this should not come with too many compromises on population habits and
218 reallocation and loss of terrestrial ecosystems. Alternative solutions must be proposed to compensate
219 the reduction in irrigation water use such as crop diversification in semi-arid areas (this study) and the
220 introduction of drought-resistant crops and aquaculture such as in Romo-leon et al., (2014).

221 The results show that reaching SDGs on a global scale remains a challenge, especially in the context
222 of the Water-Food-Energy-Ecosystem Nexus, in which each component has a target to be respected
223 without compromising the environment (Bazilian et al. 2011). For example, on a regional level,
224 finding trade-offs between water, food and energy remains a challenge in Southeast Asia, where
225 conflicts between downstream and upstream water users may exist and where increasing the water use
226 efficiency remains a priority (Rasul 2014). This study highlights how land-use systems could be
227 adapted to meet water and food demand for humans and ecosystems in the face of global change. The
228 reallocation of crops to the most productive and water-abundant regions, intensification of cropping
229 systems, conversion of irrigated land to rainfed land are suggested, mainly in Asia and shifting to less
230 water-intensive crops in water scarce regions would ease plant growth and crop production.

231 To make our results more robust, we performed a sensitivity analysis of model parameters and
232 decreased the uncertainty of our results by using multiples models and scenarios. The Supplementary
233 Figure 1 shows the different sources of uncertainty that were tackled in previous studies. In this study,
234 we mainly performed parametric uncertainty analysis by testing the limits of our system to the impact
235 of climate change (using the highest emission scenario: RCP8.5), the impact of two different climate
236 models (structural uncertainty, Fig. 3), the impact of three levels of water restrictions for
237 environmental flows: no restriction, medium and high restrictions (Fig. 3), and the impact of two

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238   different trade scenarios: constrained and unconstrained (Supplementary Table 6). For socio-economic

239   scenarios, we used SSP2 which is the average scenario. Uncertainties and ranges of socioeconomic

240   scenarios (SSPs) are addressed in the previous studies showing the impact of different SSPs on future

241   land use (Fujimori et al. 2017; Schmitz et al. 2013). However, in Schmitz et al. (2014), it is shown that

242   the shift from SSP2 to SSP3 would imply a change of less than 1% in total agricultural area in

243   GLOBIOM. From a global perspective, our results show a higher impact of EFRs on food production

244   than the sole impact of climate change and climate models (Fig. 2). We also show that a constrained

245   trade could reduce food production from -6 to -12% (with increasing water restrictions). We

246   performed a sensitivity analysis to examine the effects of our crop-yield growth assumptions, water

247   demand for other users (domestic and industrial), groundwater resources and irrigation use efficiency

248   (Supplementary Figure Figs. 4-6) on land use. Complementary to Leclère et al. (2014) and Fuss et al.

249   (2011), our results show that crop area is sensitive to crop yield volatility (SSP2 crop-yield growth

250   assumptions versus constant crop yields). With a constant yield assumption, rainfed area would be

251   20% higher than with the SSP2 yield-growth assumption (Supplementary Figure 9a). Finally, if we

252   assume that water demand for other users would remain constant between 2000 and 2050

253   (Supplementary Figure 9b), our results indicate that irrigated area could increase by up to 15% (with a

254   low impact on rainfed crop area). We also tested the impact of decreasing groundwater storage by 50%

255   (Supplementary Figure 9c) and show that it would decrease irrigated area by about 10%. At regional

256   level, the MENA and South Asia regions, which are highly dependent on irrigation, would be affected

257   more than the rest of the world and imports would be mandatory for their populations' food

258   requirement. Finally, we assumed in all our scenarios that irrigation use efficiency will increase

259   according to the technological projections of SSP2 (2% per decade); if irrigation use efficiency

260   remained constant over the time period (Supplementary Figure 9d), irrigated area would decrease by

261   10%. Similar results can be found in Fujimori et al. (2017) showing that land use expansion for crop

262   and pasture would respectively increase by 40% and 20% from the baseline year by 2100 and that crop

263   yield rate increase would range from 0.3 to 1.2 until 2050 with highly variable change in crop yield

264   due to climate change and a doubling of crop yield due to technological improvement (Palazzo et al.

265   (2017); Supplementary Figure 6b). We hope future studies will also address the impact of extreme

266   events with this framework because global warming and climate variability are likely to increase in the

267   coming decades (Field et al. 2014). Finally, a study from Springmann et al. (2018) shows that the

268   major contribution to mitigate environmental impacts of rising food demand is technological

269   improvement (50%) followed by reducing food waste (20%), shifting diet (20%) and finally shifting to

270   SSP1 scenario (10%). Our study is a first step in conceptualizing the analytical framework and

271   solutions for the potential trade-offs between future food security and freshwater use. This framework

272   should be further expanded to test the robustness of our results, for example, through a stochastic

273 version of GLOBIOM and through an extension of the inter-comparison models done for the
274 Agriculture Model comparison: AgMip (Lampe et al. 2014).

275 In conclusion, our results show that it is possible to meet both global agricultural demand and the
276 water needs of the environment with an increase in total cropland of 20% by 2050. However, this
277 should come with substantial improvements in agriculture and water management, with an increase in
278 crop yields through technological improvements, and with the selection of less water-intensive crop
279 varieties. It would also be necessary to reallocate irrigated crop production from water-scarce regions
280 to water-abundant regions but with the considerations of externalities. Our analyses show that if trade
281 is not allowed to compensate for crop production losses, it will be more difficult to meet future crop
282 demand while sustaining environmental flows. Increase in trade and trade liberalization is often
283 mentioned as having a negative impact on the environment and on access to food by disadvantaged
284 communities, but our results show that an increase in global trade can also help meet future SDGs in
285 terms of food security and water preservation for the environment. This study also addresses the
286 adaptations required, such as crop shifting, reallocation of land use, and improvement in crop and
287 agriculture management, and the corresponding negative externalities, such as the expansion of rainfed
288 land into natural and forest areas, to meet future food demand and preserve freshwaters. Finally,
289 policies and regulations should encourage climate and socioeconomic adaptation pathways on a
290 regional level in order to anticipate global change and meet food and water requirements for humanity.

291 **Methods**

Modelling framework

293 A modelling framework was developed (Fig. 1, Supplementary Figure Fig. A1) to measure the impact
294 of meeting EFRs on global water use, future crop production strategies and land use allocation. The
295 framework links the Global Biosphere Management Model (GLOBIOM) to a water module fed by
296 runoff and EFRs calculated with the hydrological model LPJmL (more information in Supplementary
297 Figure B).

GLOBIOM model

299 GLOBIOM is an economic partial equilibrium integrated assessment model that allocates agricultural
300 crops and commodities based on an endogenous price balance between demand and supply. The
301 spatial unit used here for food supply is 2 by 2 deg. and food demand is defined for 30 world regions
302 (Supplementary Figure Table 1). GLOBIOM includes agriculture, bioenergy and forest modules to
303 optimize land-use allocation (Havlík et al. 2014, 2011). The model optimizes food and livestock
304 production at a minimum cost under socioeconomic and biophysical constraints. The baseline year is

305 2000, and the model is recursively dynamic (10 year time-step). Food demand projections follow the

306 projections from the FAO up to 2030, but the demand is partly endogenous. Regional crop prices vary

307 with food demand, which is driven by population and per capita income. Prices are endogenous to the

308 model and depend on technology, natural resources and consumer preferences. GLOBIOM allows the

309 optimization of land use through several adaptations: reallocation of crops to more productive areas, a

310 shift to crops that are less expensive and demand less input, and a change from extensive rainfed

311 systems to intensive rainfed and irrigated systems (FAO 2016). Yields of 18 crops were simulated

312 with the Environmental Policy Integrated Climate (EPIC) model which is a connected module of the

313 GLOBIOM model (Williams et al. 1989). For further information on model parametrization and yield

314 calculation in the GLOBIOM and EPIC models, refer to the Supplementary Figure B.

Socioeconomic scenarios

316 Future socioeconomic development, including population, gross domestic product (GDP) and

317 technological change, was based on the Shared Socioeconomic Pathway 2 (SSP2) (O'Neill et al.

318 2015; Samir and Lutz 2014; Popp et al. 2017). Details on the translation of SSPs into GLOBIOM can

319 be found in Supplementary Tables 3-4. SSPs were developed by a community of scientists and

320 economists over the last 10 years to provide plausible scenarios based on past trends in economic and

321 biophysical drivers. In this study, the SSP2 scenario, known as the middle-of-the-road scenario,

322 assumes moderate adaptation and mitigation challenges, with a medium growth of the population to 9

323 billion people and a dietary requirement of 3000kcal/person/day based on Food and Agriculture

324 Organization (FAO) projections for 2030 (Samir and Lutz 2014; Kriegler et al. 2012; Fricko et al.

325 2017). The narrative of the SSP2 scenario is the following: "The world follows a path in which social,

326 economic, and technological trends do not shift markedly from historical patterns. Land use change is

327 incompletely regulated, i.e. tropical deforestation continues, although at slowly declining rates over

328 time. Rates of crop yield increase decline slowly over time, but low-income regions catch up to a

329 certain extent. Caloric consumption and animal calorie shares converge slowly towards high levels.

330 International trade remains to large extent regionalized (O'Neill et al. 2015)."

LPJmL model – hydrological model

332 Water availability was simulated with the Lund-Potsdam-Jena managed Land model (LPJml), which is

333 a dynamic global vegetation model that simulates water and carbon cycles (Sitch et al. 2003; Dieter

334 Gerten et al. 2004; Rost et al. 2008). The water module was developed with a river routine and the

335 implementation of reservoir operation (Rost et al. 2008; Biemans et al. 2011). Water availability was

336 simulated with LPJmL from 2000 to 2050 at a 0.5° by 0.5° spatial resolution. We calculated average

337 monthly water availability for every 10 year time-step from 2000 to 2050 to be used as an input for

338 GLOBIOM. The mean monthly runoff estimated by LPJmL was redistributed according to the average

339   discharge rates in each river basin to have a good spatial representation of water availability within

340   GLOBIOM (Schewe et al. 2014). Water availability was aggregated from 0.5 deg. to 2 deg. to fit the

341   Land Unit ID (LUID) of GLOBIOM, with a total of 4,845 simulation units. EFRs were calculated with

342   the Variable Monthly Flow (VMF) method (A. V. Pastor et al. 2014) .

Description of Environmental Flow Requirement (EFRs) calculations

344   Environmental Flow Requirements (EFRs) were estimated using the Pastor et al. (2014) Variable

345   Monthly Flow (VMF) method. The VMF method follows the natural variability of river discharge by

346   adjusting EFRs according to the flow season. The VMF method was designed to improve the

347   protection of freshwater ecosystems during low-flow seasons. In the VMF method, the EFRs are set to

348   60% of the mean monthly flow during the dry (low-flow) season and 30% during the wet (high-flow)

349   season. Thus, in the simulations in which the VMF method for EFRs is implemented, 40% of the river

350   water is available to other users during the dry season and 70% in the wet season. The VMF method

351   was previously validated with 11 local case studies, where EFRs were calculated based on local

352   ecological and hydrological parameters (Pastor et al. 2014). For the simulations, EFRs were calculated

353   based on the 15 previous years before the year 2000 of simulated natural runoff.

Description of crop yield calculations

355   Yields of 18 different crops are estimated using the Environmental Policy Integrated Climate (EPIC)

356   model and are adjusted according to GDP (Liu et al. 2007; Williams et al. 1989), Future crop yield

357   projections were based on SSP2 yield assumptions that consider the potential technical advancements

358   in agriculture that could occur under projected growth in GDP (Dellink et al. 2015) based on the

359   econometric relationship between historical yields and GDP growth (Dellink et al. 2015). All crop

360   yield simulations are calculated with and without climate change. The scenarios with climate change

361   assume CO_2 fertilization.

Calibration of annual irrigation demand

363   The inclusion of water use for irrigation in GLOBIOM builds on the work presented in [1] Sauer et al.

364   (2010) by defining spatially explicit irrigation demand, irrigation source and seasonality of water, as

365   well as examining the impact of climate change. GLOBIOM calibrates spatially explicit water demand

366   for irrigation, Irrigated Water Demand (*IWD)*, in the initial year 2000 using the irrigated cropland area

367   dataset available from SPAM (Liu et al. 2013) and EPIC estimates of crop irrigation water

368   requirements in order to match the FAO AQUASTAT statistics for water withdrawn for irrigation

369   (FAO 2016). For this study, simulations from the GLOBIOM model were adjusted from an annual to a

370   monthly time-step in order to account for the seasonality of water availability and demand.

Calibration of monthly irrigation demand with seasonality

The annual irrigated water demand estimated by EPIC was rescaled to a monthly time-step using a coefficient of seasonal irrigation (CSI) defined for every grid cell. CSI is based on the monthly irrigated water withdrawal from LPJmL via Equation (1).

$$CSI(c, m) = \sum_{i=1}^{m} \left(\frac{mid(c,m)}{aid(c,a)} \right) \tag{1}$$

c is the cell of the LPJmL model, m is the month, *mid* is monthly irrigation demand and *aid* is annual irrigation demand. For simulations of the impact of climate change, the annual irrigated water requirements were estimated using EPIC, which considers the potential crop yields while taking into account the local climate (Liu et al. 2007; Williams et al. 1989).

Representation of water sink in GLOBIOM

Water availability is calculated with the LPJmL model as explained in the above section and is entered as an exogenous variable in the GLOBIOM model. GLOBIOM has a fixed amount of available water within a watershed. In each simulation unit, the water can be supplied to industry, households and irrigation in the EXPLOIT scenario and reserved to freshwater ecosystems in the ENV and ENV+ scenarios, if the water is not used, it is stored. If water is not available for allocation, a change in land use will occur. Concerning the INVEST scenario, water is available at the regional scale (and economic scarcity is the main factor determining its use). In this study, we divided irrigation water demand into three categories: irrigation sourced from surface water (SWD), irrigation sourced from groundwater (GWD), and irrigation sourced from non-renewable sources (NR). We used the spatially explicit map of irrigated areas sourced from groundwater from Siebert et al. (2010) to determine the share of IWD sourced from groundwater (Equation 2). Non-renewable withdrawals were calculated as the water deficit that cannot be compensated for by surface water or groundwater in 2000. The amount of water withdrawal from groundwater and nonrenewable sources is assumed to remain constant over time.

$$IWD_{m,lu} = SWD_{m,lu} + GWD_{m,lu} + NR_{m,lu} \tag{2}$$

To determine the irrigation sourced from surface water, we determined the surface water available, under the assumption that agriculture is the residual user of water, behind industry, households, and in certain scenarios, the environment.

Biophysical and economic water scarcity

In the simulations, the biophysical scarcity at the pixel level and the economic scarcity of water from the water supply curve take into account the growing demand for surface water, as well as the effects

402 of climate, including the change in the quantity of surface water available (WA) and the change in the

403 spatially explicit water demand for irrigation (*IWD*). To calculate the scarcity cost of water,

404 GLOBIOM uses a supply function for the total volume of water withdrawn (the regional-level *IWD*)

405 and a marginal price, which increases as water becomes scarce, as well as the regional, crop, and

406 pixel-specific irrigation costs per hectare developed by Sauer et al. 2010. Future industrial and

407 domestic water consumption was based on Flörke et al. (2013) and Wada et al. (2014). In addition,

408 Environmental Flow Requirements were added to some of the scenarios for the time period and further

409 restrict the water available for agriculture.

Climate-change scenarios

411 For the climate-change scenarios, LPJmL was run with the bias-corrected output of two commonly

412 used Global Climate Models (MPI-ESM-LR & HadGEM2-A0) using the highest emission scenario

413 (Representative Concentration Pathway, RCP 8.5) (Van Vuuren et al. 2011). Climate-forcing data was

414 extracted from the ISIMIP database (Warszawski et al. 2014; Hempel et al. 2013).

Water management policy scenarios

416 To measure the impact of EFRs restrictions on future land and water use, agricultural production and

417 trade, four water management policy scenarios were developed, with three levels of restrictions in

418 water use compared to an unlimited water supply scenario:

419 - The Water Investment Scenario (INVEST or INV) assumes large-scale development of

420 irrigation infrastructure and water reallocation. This scenario assumes that all freshwater

421 within a region can be used and reallocated to optimize irrigation on the basis of economic

422 constraints such as crop demand and does not consider EFRs. In this scenario, water demand

423 and supply is calculated on an annual time-step and water allocation is constrained on a

424 regional scale.

425 - The Maximum Exploitation Scenario (EXPLOIT or EXP) assumes that all freshwater from

426 rivers and groundwater aquifers can be used up to full depletion in each land unit (2 by 2

427 deg.). Water use for agriculture is constrained by local water availability and by local water

428 demand from other sectors (industrial and domestic) at a monthly time step. EFRs are not

429 considered. This scenario is referred to as the business-as-usual scenario.

430 - The Environmental Flow Requirement scenario (ENVIRONMENT or ENV) assumes that

431 water needs to be allocated to the environment first. Water use for irrigation is restricted by

432 water demand from other sectors (industrial and domestic) at the land unit level. EFRs are

433 estimated using the Pastor et al. (2014) VMF method (A. V. Pastor et al. 2014).

434 - The High Environmental Flow Requirement scenario (ENVIRONMENT+ or ENV+) is the

435 same as ENV, but with 50% greater EFR demand. This scenario tests the sensitivity of the

14

436   system to higher EFRs and sets a high priority on attaining good ecological status of the
437   rivers.

438 All water use restriction scenarios were analyzed with climate change (CC) and without climate
439 change (noCC) (Supplementary Figure Fig. A1).

Description of trade scenarios

441 We designed trade scenarios to evaluate how markets (through bilateral trade) compensate for water
442 scarcity at local levels caused by biophysical limitations, climate change, and reduced water
443 availability due to EFRs.

444 • Constrained Trade (Con_T): regional bilateral trade flows are set according to the reference scenario
445 (EXPLOIT without climate change) with SSP2 yield projections and no increases in irrigation use
446 efficiency.

447 • Unconstrained Trade (Unc_T): regional bilateral trade flows follow the default setup, in which trade
448 is optimized according to bilateral trade policies and assumptions about trade costs.

455 **Author contributions**

456 Data input preparation, analysis and writing were done by A.V.P., concepts and ideas were developed
457 by all authors, model conceptualization, writing and simulations were performed by A.M.P and A.V.P.

458 **Competing interests**

459 The authors declare no competing interests.

460 **Data availability**

461 The data that support the findings of this study are available from the corresponding author upon
462 request. Correspondence and requests for source data and materials should be addressed to lead author
463 A.V.P. and access to code should be addressed to A.V.P and A.M.P. following institutional rules.

464

465 **Table 1. Water withdrawal for agriculture (irrigation) under different climate change**
466 **and water management scenarios.**

Scenarios	noCC[a]*	CC [a]*
Baseline 2000	2516	2516
INV 2050	2983	2911
(% change from baseline 2000)	19	16
EXP 2050	2461	2261
(% change from baseline 2000)	-2	-10
ENV 2050	1774	1561
(% change from baseline 2000)	-30	-38
ENV+ 2050	1440	1219
(% change from baseline 2000)	-43	-52

467

468 [a] noCC stands for no climate change, CC stands for climate change

469 [b] INV stands for INVEST scenario (No water constrain), EXP stands for EXPLOITATION
470 scenario (water limited locally), ENV(+) for ENVIRONMENT(+) scenarios (water constrained
471 locally and by environmental flows)

472 * The units are $km^3 \ yr^{-1}$.

473

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718

Climate change

RCP8.5

2 Global Circulation Models

Socio-economic change

SSP2 Middle of the Road scenario

Consumer preferences   GDP

Population

Water availability computed by LPJmL
with runoff following discharge repartition per river basin
(Schewe et al. 2014)

Environmental flow requirements calculated
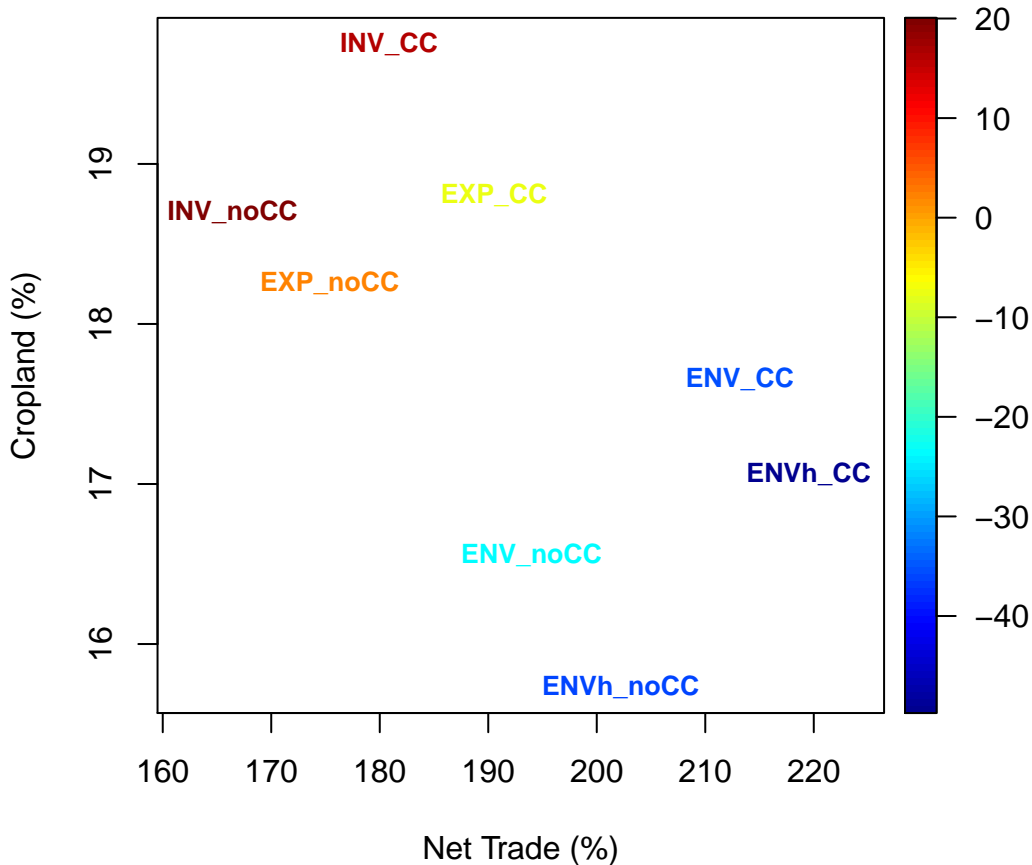with natural runoff simulated with LPJmL
with the VMF method

Exogenous water demand for industry and housefolds
(Florke et al. 2013, Wada et al. 2014)

Water management scenarios:

- INVEST has water restrictions on an annual scale and at regional spatial scale

- EXPLOIT has water restrictions on a monthly scale and at the grid cell level (2 by 2°)

- ENVIRONMENT has water restrictions on a monthly scale and at the grid cell level (2 by 2°)
including environmental flows

- ENVIRONMENT+ has water restrictions on a monthly scale and at the grid cell level (2 by 2°)
including stricter environmental flows thresholds (50% more than ENVIRONMENT)

GLOBIOM - Global Biosphere Management Model
includes a
new water module with:
- Water storage/availability per grid cell
- Water supply optimization to the most productive land and crop
with an endogenous land allocation module

Crop yield simulated by EPIC model (EPIC is integrated into GLOBIOM)

Water demand for irrigation calculated from EPIC

Exogenous groundwater availability calculated from Siebert et al. (2010)

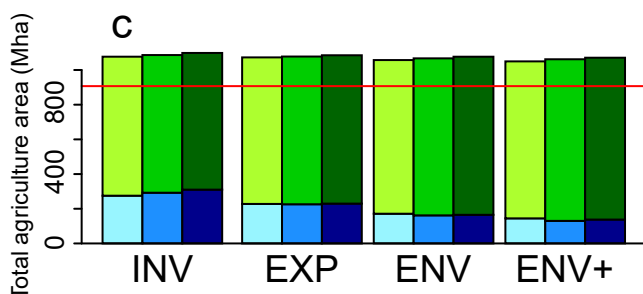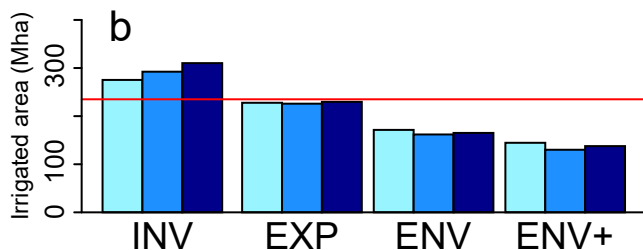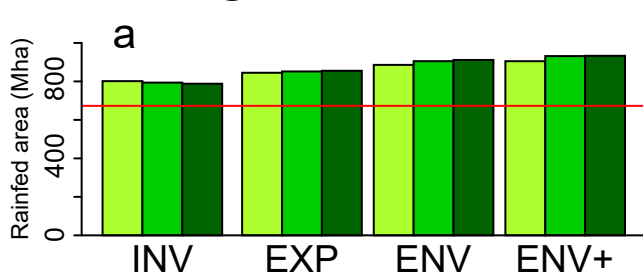Land use allocation of forest, agricultural and bioenergy crops

Relative resource change between 2000 and 2050

Agriculture Area

a — Rainfed area (Mha): INV, EXP, ENV, ENV+

b — Irrigated area (Mha): INV, EXP, ENV, ENV+

c — Total agriculture area (Mha): INV, EXP, ENV, ENV+

Agriculture Production

d — Rainfed production (10³T): INV, EXP, ENV, ENV+

e — Irrigated production (10³T): INV, EXP, ENV, ENV+

f — Total agriculture production (10³T): INV, EXP, ENV, ENV+
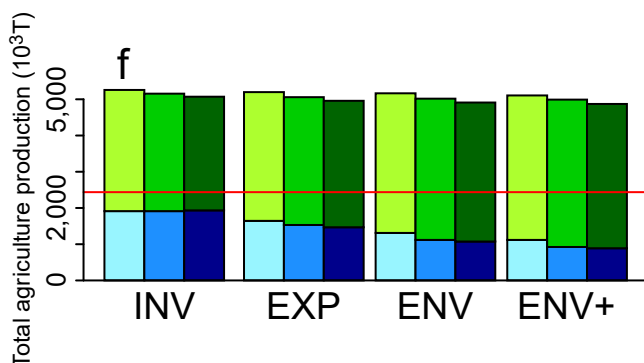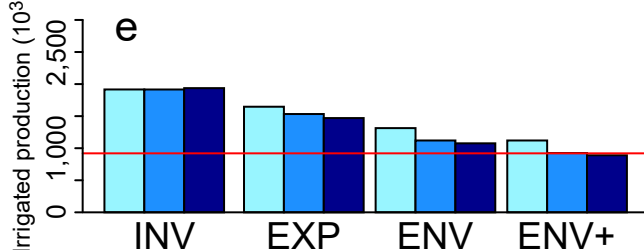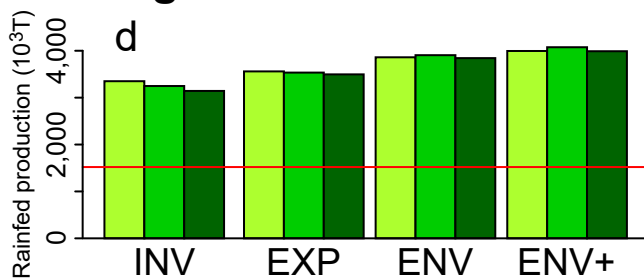
Legend: No climate change — GCM1 — GCM2 — Baseline 2000

a EXP 2050

d EXP 2050

Irrigated areas (x 10³ Ha)

0   0.1   1   10   100   500   3,900

Rainfed ares (x 10³ Ha)

0   5   10   100   500   3,600

b EXP CC - EXP noCC

e EXP CC - EXP noCC

c ENV CC - EXP noCC

f ENV CC - EXP noCC

Absolute differences in irrigated areas
in 2050 (x 10³ Ha)

−2,100 −300 −5 −1 1 5 300 2,100

Absolute differences in rainfed areas
in 2050 (x 10³ Ha)

−2,100 −300 −5 −1 1 5 300 2,100

Former Soviet Union

Europe

Mid. East Nrth Afr.

East Asia (inc. China)

North America

300

200 0

South Asia (inc. India)

South−East Asia

Sub−Saharan Africa

Latin America

300

Baseline 2000
INV CC
EXP noCC
EXP CC
ENV noCC
ENV CC
ENV+ CC

Oceania

300

0