Transforming agricultural land use through marginal gains in the food system

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Abstract

There is an increasing need for transformational changes in the global food system to deliver healthy nutritional outcomes for a growing population while simultaneously ensuring environmental sustainability. However, such changes are subject to political and public constraints that usually allow only gradual, incremental changes to occur. Drawing inspiration from the British cycling team's concept of marginal gains, we show how transformation might be reconciled with incremental changes. We demonstrate that a set of marginal food system changes acting to increase production efficiency, to reduce losses or to adjust diets could collectively reduce the agricultural land required globally for food production by 21%, or over a third given higher adoption rates. The results show that while all categories of action are important, changes in consumer choices in Europe, North America and Oceania and in the supply-chain in Africa and West and Central Asia have the greatest potential to reduce the land footprint of the food system.

1   The need to transform the global food system

Agriculture uses 38% of all land (FAOSTAT, 2018a) and provides the global population with food, fuel and fibre. In the wake of rapid population growth (UN, 2017), increasing consumption per capita, and increasing demand for livestock products in countries with growing economies (Alexander et al., 2015; Delgado, 2003; Godfray et al., 2018), total food demand is projected to rise by 52 – 116% by 2100 from 2005 levels (Popp et al., 2017). This, in turn, is predicted to drive further agricultural expansion into natural ecosystems (Alexander et al., 2018; Alexandratos and Bruinsma, 2012; Bowles et al., 2019; Butler and Laurance, 2009). Agricultural expansion, combined with the intensive use of agricultural inputs, underlies increasing rates of species extinction (Alroy, 2017; Grooten and Almond, 2018), the degradation of biodiversity and ecosystem services (Haines-Young and Potschin, 2010; West et al., 2010) and agricultural greenhouse gas emissions that contribute to climate change (Smith et al., 2014). Mitigating these impacts is likely to require a substantial reduction in the land footprint of agriculture, necessitating a process of transformation in the food system (Foresight, 2011).

The concept of 'transformation' is widely discussed with respect to climate change adaptation (Kates et al., 2012; Rickards and Howden, 2012), with calls for "major, non-marginal change[s]" (Stern et al., 2006). However, the concept of transformation is increasingly criticised for its failure to direct policy change at an achievable and sustainable scale and does not take account of the complexity and inertia in human systems (Brown et al., 2019; Görg et al., 2017; Vermeulen et al., 2018; Willett et al., 2019). Instead, policy-makers tend to favour the pursuit of incremental change (Dunn et al., 2017; Mapfumo et al., 2017). Drawing inspiration from an unlikely source - the British cycling team and their search for success through the concept of marginal gains - we aim to show how the concept of transformation might be reconciled with incremental change and how this may prove a valuable tool in the transformation of the global food system.

Sir Dave Brailsford oversaw the rise of British cycling to a position of pre-eminence in international competitions: Britain has won 50% of all track and road cycling gold medals during the last two Olympic Games, and six of the last seven winners of the Tour de France were British riders competing for the Brailsford-led British team (Team Sky). Brailsford attributed this success to the concept of marginal gains (BBC News, 2015). Marginal gains describes how significant overall improvements might be achieved through the effects of making multiple small changes across the system as a whole. When each small change acts in isolation, its effect on performance are negligible. However, acting in combination, marginal gains produce a much larger improvement in performance. The competitive results of British cycling could certainly be described as transformational. So, could the marginal gains effect be beneficial elsewhere? The concept has already been applied beyond the realm of sports, for example in the transformation of

healthcare and aviation (Syed, 2015). We hypothesise that marginal gains could also be applied successfully to the global food system.

We apply the concept of multiple marginal gains to estimate achievable reductions in agricultural land areas. We believe that this is a way of sidestepping the potentially futile search for a 'silver bullet', or step-change, to transform the food system. Individual step-change transformations are unlikely as there are limited opportunities for the widespread implementation of these types of improvements. For example, factors to increase production efficiency, such as improved crop breeding and genetic techniques, are hampered by a lack of investment in research and development and face barriers to adoption from policy, intellectual property ownership, and time lags in acceptance (Brown et al., 2019). Instead, we explore a suite of achievable marginal changes in the food system that could collectively result in transformation. To explore this hypothesis, we first identify changes and then model their combined effect on the land area required for global food production.

2   Marginal food system changes

We selected 29 diverse, marginal changes (Table 1) each with the potential to reduce agricultural land area, based on existing literature (as detailed below). The changes fall into three interlinked categories—increasing production efficiency, reducing losses, and shifting diets—widely targeted for their potential to create a more sustainable food system (Foley et al., 2005; Godfray et al., 2010; Springmann et al., 2018). Rather than adhere to Brailsford's original 1% gains, we considered the plausibility of each gain in turn, and used the analysis to explore (rather than predict) the overall effect of the marginal gains approach. The rate of each change was chosen to represent the improvement that can be achieved over a short to medium time horizon (5-15 years). However, given the exploratory nature of the analysis these outcomes are not intended to be projections of a specific year, and do not account for other changes, e.g., in populations, incomes or climate. The changes outlined were considered marginal under the assumption that they act on the food system at rates selected from between 0.5 – 5%, with only the changes relating to reductions in sources of losses or waste assigned a rate of greater than 3%. The context used to select these rates is given below, and briefly summarised in Table 1. In principle, these low rates of change should be more achievable than greater changes in a smaller number of factors, i.e. the step-change approach to transformation.

	Change	Justification summary	Rate	Action
Production efficiency	1: Crop management practices	Improvements in planting, harvesting and other actions. Better pest/disease control.	2%	Increase in crop yields.
	2: Crop breeding	Continued development of improved varieties using conventional breeding techniques.	1%	
	3: Crop genetic modification	Crop improvements through genetic modification or editing. Issues with regulatory and public acceptance.	2%	
	4: Pasture management	Better pasture management and intensification of grassland production.	2%	Increase in pasture yields.
	5: Livestock husbandry practices	Education and knowledge exchange, to disseminate best practice globally.	2%	Increase in feed conversion ratios.
	6: Livestock breeding	Continued development of improved livestock genetics and selection using conventional techniques.	1%	
	7: Livestock genetic modification	Livestock improvements through genetic modification or editing. Issues with regulatory and public acceptance.	2%	
	8: International trade	Continued food system globalisation moves crops to locations with highest production efficiency.	1%	Increase in crop yields.
	9: Vertical and urban farms	Yield increases of 350 times have been suggested as possible (White, 2017).	1%	
	10: More multi-cropping and reduced fallows	Identified as potential route of increasing production (Alexandratos and Bruinsma, 2012; Ray and Foley, 2013)	2%	
Reducing losses	11: Harvest losses	Lower on farm losses through better harvest technology and control of pests and diseases.	5%	Reduction in associated losses.
	12: Transport and storage losses	Potential for gains due to current inefficiencies, particularly in lower income countries	5%	
	13: Processing losses	Increases in efficiencies of food processing.	5%	
	14: Retailer losses	Issues of sell-by/use-by dates, and selling 'imperfect' fruit/veg, especially in higher income countries.	5%	
	15: Consumer losses	Changes including lower consumer processing losses, e.g. peelings; less over-purchasing; and using leftovers.	5%	
	16: Household pets	Greater use of by-products or potentially a reduction in pet numbers or size of pets.	5%	Reduction in pet food.
	17: Food waste as feed	Directing food waste for uses as animal feed. Regulatory and potential health issues to consider.	2%	Increased animal production efficiency.
	18: Alternative feeds	Providing animal feeds from novel sources, such as algae or insects from waste (including human waste).	1%	
	19: Offal	Eating of offal, especially in some European countries and the US, could increase towards higher historic level.	2%	
Shifting diets	20: Vegetarian diets	Growing drive towards vegetarianism in higher income countries.	2%	Substitution of meat or animal products, respectively, for plant-based foods.
	21: Vegan diets	Similar to vegetarianism, veganism has recently become a mainstream movement in many countries.	1%	
	22: Low-meat diets	Global population who eat meat adopting a meat-free day (e.g. 'meat-free Friday').	3%	
	23: Over-consumption	The world is over-eating on average, with large distributional inequalities.	5%	Reduction of over-consumption.
	24: Insects	Adoption issues due to social acceptability in Western cultures, but already widely consumed in Asia.	1%	Substitution of current animal products with the alternative being considered, to provide equal protein.
	25: Cultured meat	Technological development still required and social acceptability not yet clearly demonstrated.	0.5%	
	26: Tofu	Established alternative to meat, making substantial future expansion less likely.	1%	
	27: Imitation meat	Substitutes are increasingly acceptable to consumers on taste, but production currently limited.	2%	
	28: Aquaculture	May be more socially acceptable than other meat alternatives, e.g. tastier and healthier.	2%	

29: Monogastrics	Replacing red meat with chicken follows recent trends, with drivers including relative costs and health concerns.	3%	

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Increasing production efficiency

Agricultural intensification, i.e. managing existing land more productively often using higher rates of other inputs, is often pitted against agricultural expansion as an alternative way of satisfying food demand (Foley et al., 2011). Large-scale uptake of agricultural production changes can often be constrained by a lack of investment in the adoption of new as well as existing technologies, leading to gaps between actual and achievable yields. Uptake is dependent on education and knowledge exchange to disseminate best practices globally, and whilst education and knowledge exchange programmes exist their effectiveness is unknown (Aker, 2011). Extensive changes in individual measures to increase production efficiency may be limited; however, the potential for marginal changes regarding production efficiency and the closure of yield gaps across a suite of measures could be high. We therefore outline ten aspects where marginal changes could increase production efficiency and thereby reduce agricultural land requirements.

Improved crop management practices to close yield gaps have been identified as strategies that could improve sustainability of the food system (Foley et al., 2011; Licker et al., 2010; Phalan et al., 2014; Van Ittersum et al., 2013). Achieved yields are limited by land management choices and access to a variety of inputs such as pesticides, machinery and nutrients (Godfray et al., 2010). With improved crop management practices yield gaps can be reduced (Alexandratos and Bruinsma, 2012; Foley et al., 2011) and as such we included increases in crop yields that could be attributed to this type of change (change 1). The 2% yield increase represents the closing the yield gap from West et al. (2014) by 7%, a rate 7 times smaller than assumed in that study. Progress in breeding and genetic techniques has also allowed for the development of high yielding crop varieties of many staple global crops (Jaggard et al., 2010; Tester and Langridge, 2010). Advances in crop breeding and genetic techniques over previous decades have therefore demonstrated the potential of such approaches (Jaggard et al., 2010; Tester and Langridge, 2010), although legislative change (e.g. relating to genetically modified organisms) may be required in some jurisdictions (Azadi and Ho, 2010; Reuter et al., 2010). We include improved crop breeding (change 2) and crop genetic modification (considered here to encompass genetic engineering and gene editing using techniques such as CRISPR-Cas9, change 3) as marginal changes leading to increased crop yields. For example, a metanalysis of literature from 1996 to 2016 showed that genetical engineered maize yields have increased by 10.1% compared to non-engineered varieties (Pellegrino et al., 2018). While substantially newer, improving yield performance is one of the main uses to which CRISPR-Cas9 gene editing has been applied (Ricroch et al., 2017).

The production efficiency of cropland could be increased globally through reductions of fallows and a greater area where multi-cropping is adopted, as both increase harvest areas without additional land. This

111　is the continuation of an existing trend, where between 1961 and 2007, harvested land area grew four

112　times faster than total standing cropland area, contributing to a 9% increase in global crop production (Ray

113　and Foley, 2013). Alexandratos and Bruinsma(2012) suggest harvested areas in developing countries may

114　increase by 130 Mha, around 14%, due to increased cropping intensities, aided by an increase in the share

115　of irrigation in total arable land. Given that reduced fallows and multi-cropping could increase production

116　without increasing agricultural area we consider this to be a marginal change (change 9). With a growing

117　global urban population, urban farming has emerged as a strategy to achieve food security targets

118　(Diekmann et al., 2018). This would in effect convert land previously frequently not used for food

119　production (e.g. gardens and rooftops) into spaces that could become highly productive. Additionally, a

120　number of fruit and vegetables are much higher yielding under the indoor controlled-environment

121　technologies used in vertical farms (Despommier, 2013; Eigenbrod and Gruda, 2015), although their

122　economics remains largely unproven. Both high- and low- tech forms of urban agriculture could increase

123　production efficiency, generate land savings and reduce food miles (Eigenbrod and Gruda, 2015; Specht et

124　al., 2014). 73 urban agriculture projects were identified in 2012 (Thomaier et al., 2014) with substantial

125　continued research and public interest since (e.g., Grard et al., 2018; Othman et al., 2018; Wielemaker et

126　al., 2019). Given the potential for urban agriculture to reduce agricultural land use, it was included as a

127　marginal gain in this study (change 9). With continued globalisation of the food system, land requirements

128　could decrease as production shifts to the most suitable locations. Furthermore improvements in

129　infrastructure in developing countries, in particular rural roads, could greatly increase productivity and

130　market access (Jouanjean, 2013). As such, we consider a marginal change that reflects improving trade and

131　infrastructure resulting in greater production efficiency (change 8).

132　The global consumption of livestock products is expected to increase in the coming decades; any increases

133　in production efficiency in the livestock sector could greatly contribute to creating a more sustainable food

134　system. The livestock production sector has a history of increasing efficiency since the 1960s. For example,

135　the efficiency of conversion of grain into meat in chickens and pigs has doubled (Herrero et al., 2010) and

136　carcass weights have increased by 30% for both chicken and beef cattle (Bouwman et al., 2005; Thornton,

137　2010). Such productivity increases are a result of improved animal husbandry, livestock breeding and

138　genetic techniques (Hayes et al., 2013; Thornton, 2010) and given their potential we included marginal

139　changes that capture these processes. Marginal improvements in livestock husbandry practices (change 4),

140　livestock breeding (change 5) and livestock genetic modification (change 6) all contribute to increasing

141　production efficiency through improved feed conversion efficiencies. As with crops, genetic modification

142　here considers both genetic engineering and gene editing, which either directly target improved yield traits

143　or have an indirect impact on yields through disease resistance (Van Eenennaam, 2017). For example,

144　reducing losses from African swine fever (Montoya et al., 2018) have been targeted through conveying

145　resistance by gene editing (Petersen et al., 2018).

Reducing losses

Production efficiency is reduced by losses occurring throughout the food system: from harvest to consumption between a third and a half of crops are lost (Alexander et al., 2017b; Gustavsson et al., 2011). Large changes to improve the use of 'waste' streams may be infeasible as they will require legislation regarding the handling of waste (Salemdeeb et al., 2017), and the usage of alternative feeds may be hampered by a lack of investment into technologies to increase supply chain efficiency. Changes related to consumers and retailers rely on the effectiveness of campaigns raising awareness of food waste, limited by the complex cognitive mechanisms that define our motivations and dietary behaviours. Given these constraints, we therefore consider nine marginal changes that could reduce food system losses and agricultural land requirements.

Improving the sustainability of the food system may involve reassessing sources of feed for livestock; considering both the use of food waste (change 16) and alternative sources such as insects and algae as feed (change 17). In the European Union less than 3% of food waste is currently recycled as animal feed (zu Ermgassen et al., 2016) for the most part due to risks of contamination and disease concerns. However recycling food waste as feed is more widely practiced in Asian countries, in Japan for example 35.9% of food waste is used as feed (Salemdeeb et al., 2017), and if the EU was to adopt an Asian style recycling approach land use of EU pork alone could reduce by one fifth (zu Ermgassen et al., 2016)(Salemdeeb et al., 2017). The use of food waste as feed has been identified as a priority research area by the animal feed industry (Makkar and Ankers, 2014). It is widely recognised that feeding livestock soy or fishmeal has widespread environmental consequences and globally almost a third of crops harvested are used as feed (Steinfeld et al., 2006). There is also a growing interest in using insects as feed due to their nutritional characteristics; as a protein source, insects have been found to contain adequate amino acid compositions and antimicrobial peptides beneficial in feed (Gasco et al., 2018; Khan, 2018; Sánchez-Muros et al., 2014). Additionally, the use of insects as feed is expected to have beneficial environmental consequences (van Huis and Oonincx, 2017); insect production is efficient in terms of land use (Alexander et al., 2017a), insects have high feed conversion efficiencies (Premalatha et al., 2011; van Broekhoven et al., 2015) and some species can convert organic waste into high quality feed (Miech et al., 2016; van Broekhoven et al., 2015). Reassessing livestock feed sources is clearly a substantial way to increase sustainability by reducing losses and we therefore include marginal changes of this type.

At the consumer level considerable losses occur through discarded leftovers, inefficient food processing and overconsumption (Alexander et al., 2017b). Significant food system losses are associated with consumer behaviour (Alexander et al., 2017b; Gustavsson et al., 2011) and we therefore consider a marginal reduction in consumer-related losses as part of this analysis (change 14). Waste reduction throughout the food system could also be achieved by changing consumer attitudes, for example, we consider here marginal shifts towards a greater acceptance of consuming offal products (change 18) and

181 'imperfect' food products (change 13). In the fresh fruit and vegetable sector large volumes of products are

182 unnecessarily wasted as they fail to meet quality standards, often aesthetic, set by consumers and retailers

183 despite being safe and edible sources of food (Aschemann-Witzel et al., 2015; Plazzotta et al., 2017).

184 Similarly, edible offal products are typically discarded (Henchion et al., 2016; Jayathilakan et al., 2012)

185 however, the consumption of offal products could meet increasing demand for meat products without

186 necessarily increasing livestock numbers given that up to 56% of the live weight of a beef animal can

187 contain non-meat parts (Marti et al., 2011). More recently, consumer choices concerning the provision of

188 edible food used for pet food has come under scrutiny. In China alone the land use for producing pet food

189 has been estimated as between 43.6 and 151.9 Mha with considerable associated carbon emissions (Su et

190 al., 2018). Evidently, reassessing the feeding of household pets could result in large land savings and we

191 therefore include a marginal change in pet food consumption in our analysis (change 15).

192 Increasing supply chain efficiency is a further potential mechanism to reduce food system losses. Improving

193 harvesting techniques that reduce spillage and mechanical damage and reducing pre-harvest losses such as

194 agricultural residues and unharvested crops has the potential to improve food system efficiency greatly and

195 we include this aspect as marginal change 10. In the storage and transportation sector food losses

196 frequently occur due to poor refrigeration leading to spoiling. In developing countries poor storage is

197 particularly troublesome with poor storage accounting for crop losses of up to 34% (Abass et al., 2014;

198 Kimenju and De Groote, 2010; Zorya et al., 2011). As such, we consider a marginal change in the reduction

199 of transport and storage losses (change 10). Losses during the processing of food commodities can also be

200 considerable, with studies estimating losses of up to 59% during processing (Alexander et al., 2017b;

201 Gustafsson et al., 2013); with fresh fruit and vegetable losses being particularly high in developing regions

202 (Gustafsson et al., 2013). We consider a marginal change that represents improvements in processing of

203 food commodities in this analysis (change 12). While the 5% rate for loss reductions chosen here is higher

204 than for the other changes considered (Table 1), it is nonetheless lower, and consequently more

205 achievable, than in previous studies (e.g. in Springmann et al. (2018) the 'medium' ambition for losses

206 reduction is 50% and 'high' ambition is 75%).

207 **Shifting diets**

208 Dietary choices drive land use for food production; however, diets vary in terms of their environmental

209 impacts depending primarily on the quantity of food consumed, and the proportion of animal products.

210 Western diets, typically characterised by the high consumption of livestock products, tend to have the

211 greatest environmental impacts in terms of land use requirements and greenhouse gas emissions (Buckwell

212 and Nadeu, 2018; Poore and Nemecek, 2018; Tilman and Clark, 2014). Moreover, approximately one-third

213 of global cereal crop production is used as livestock feed (Alexandratos and Bruinsma, 2012). Many argue

214 that the sustainability of the food system would greatly improve with alternative diets, particularly the

215 reduction of meat consumption (Alexander et al., 2017a; Machovina et al., 2015; Swain et al., 2018; Tilman

216 and Clark, 2014; Wellesley et al., 2015; Willett et al., 2019). However, the cultural and economic

217 importance of diets may prevent transformation in the food system though large shifts in consumption

218 choices. It is likely that any widespread policy actions to reduce meat consumption, particularly in

219 developing countries when sufficient protein is often lacking, would be met with widespread disapproval.

220 Similarly, technological development and social acceptance hamper large increases in the consumption of

221 cultured meat, insects and imitation meat (Bhat et al., 2017; Moritz et al., 2015; van Huis, 2013) . We

222 therefore consider a range of individual marginal dietary changes that combined may be a more feasible

223 pathway to transform the food system.

224 In high-income countries, the movement towards vegan and vegetarian diets is growing as consumers

225 become increasingly aware of the negative environmental and health consequences related to the

226 consumption of animal products. In the UK alone, the market for meat-free foods increased by 6% between

227 2015 and 2017 (MINTEL, 2017). Furthermore, while consumers may not opt to switch entirely to vegetarian

228 or vegan diets and increasing numbers in developed countries are adopting reduced-meat or 'flexitarian'

229 diets that include for example 'meat free Mondays'. Recent studies quantifying the benefits of reduced

230 meat consumption have reported potential greenhouse gas emission and agricultural land use reductions

231 of up to 70% (Aleksandrowicz et al., 2016; Tilman and Clark, 2014), with vegan diets providing the greatest

232 reductions. The production of ruminants is particularly detrimental to the environment, with beef and

233 cattle milk production respectively contributing 41% and 20% of the livestock sector emissions (Gerber et

234 al., 2013). With this in mind, replacing ruminant meat with other types such a pork and poultry could

235 deliver environmental benefits. Wirsenius, Azar, & Berndes (2010) found land savings of up to 24% in a

236 ruminant meat substitution scenario, albeit land savings were still lower than a vegetarian scenario, and

237 diets high in eggs and poultry meat have higher land use efficiency (Alexander et al., 2017a). Widespread

238 global changes in animal product consumption to bring environmental benefits is unlikely, but small

239 changes are still effective and we consider marginal increases in vegetarianism (change 20), veganism

240 (change 21), low meat diets (change 22) and the replacement of red meat with poultry (change 29).

241 The market for other meat substitutes such as imitation meat, tofu and aquaculture has grown in recent

242 years (MINTEL, 2014) however substitutes such as insects and cultured meat are less socially accepted.

243 However, uptake of alternative protein sources could reduce agricultural land areas. Indeed significant land

244 saving potential were shown by replacing 50% of animal products with other protein sources (Alexander et

245 al., 2017a); with imitation meat and insect consumption demonstrating the greatest land use efficiency.

246 Owing to the potential of such alternatives, despite their non-mainstream reputation, we include marginal

247 changes that reflect small increases in the uptake of insect consumption (change 24), cultured meat

248 consumption (change 25), tofu consumption (change 26), imitation meat consumption (change 27) and

249 aquaculture consumption (change 28).

250 The type of food consumed is often the focus of studies exploring the environmental impact of dietary

251 choices however; overconsumption, particularly in the developed world, is also an important factor. Indeed

252 overconsumption has been found to be at least as large a contributor to losses as other types of consumer

253 waste(Gustavsson et al., 2011) and 'healthy diet' scenarios that effectively reduce over consumption have

254 demonstrated significant land use and greenhouse gas emission savings could be made if over consumption

255 is addressed (Bajželj et al., 2014; Green et al., 2015). To account for the importance of changing the

256 quantity of food consumed we include a marginal change that reduces overconsumption (change 23).

257 **3   Methods**

258 The identified marginal changes (Table 1) act to increase yields, reduce losses, decrease consumption per

259 capita, or adjust the commodities consumed. Average production efficiencies (areas required per unit mass

260 of food) and diets in 7 world regions were considered in terms of cropland for food, cropland for feed and

261 pasture for 90 commodities. Constant population was assumed, with diets and yields adjusted only to

262 reflect the marginal changes considered. The magnitude of each change is based on what may be

263 achievable in the short to medium term and represents a cumulative change rate in each case, i.e., they are

264 not annual rates. The objective is to explore the magnitude of net transformation from the identified

265 marginal changes, rather than to be predictive for a particularly year.

266 A 2013 baseline was used, the most recent year for which the required data were available (FAOSTAT,

267 2018b, 2018c, 2018a, 2018d, 2018e, 2018f, 2018g). Crop areas were allocated to the use of each crop (e.g.

268 food or feed) from FAOSTAT (2018f, 2018d) commodity balance sheet data. To account for quantities of

269 crops processed (e.g. soyabeans), areas used to produce those quantities were allocated by economic value

270 between the resulting commodities (e.g. soyabean oil and meal). Monogastric species were allocated their

271 feed requirement from the total FAO feed quantities. These feed requirements were calculated by

272 multiplying the quantity of animal product produced by their feed conversion ratio (Alexander et al., 2016).

273 Ruminant-derived products were then allocated the remaining feed pro rata by feed requirement, with

274 remaining nutrition assumed to be derived from pasture. Pasture areas were allocated between ruminant

275 products by feed requirements using the same feed requirement ratios.

276 The resultant country level data were aggregated into the 7 world regions used by Gustavsson et al. (2011),

277 weighted by current production quantity, and used to calculate a mean production efficiency for each

278 commodity and region. For animal products these efficiencies expressed the area requirements for feed

279 and pasture per unit of mass. Similarly, baseline regional diets were determined from weighted commodity

280 balance data (2018f, 2018d). Loss rates and methodology from Gustavsson et al. (2011) were used to

281 estimate regional losses per food system stage (i.e. commodity for agricultural product, handling and

282 storage, processing, distribution, and consumer waste). Losses due to over-consumption were also

10

283 estimated by comparing human nutritional requirements with the quantities consumed after accounting

284 for previous stage losses, following Alexander et al. (2017b). Regional food supply requirements were

285 converted to areas using global production efficiency, thereby accounting for imports and exports and

286 providing a more comparable dietary footprint between regions.

287 This representation allows the agricultural land use implications from the changes considered to be

288 calculated by adjusting different aspects of the food system. In the baseline case, summing across all

289 commodities and regions the unadjusted demand (accounting for losses) multiplied by the unadjusted

290 production efficiencies reproduces the global FAO global pasture areas and crop areas used for food and

291 feed. Changes that improve crop production yields (changes 1-3, 8 and 9) were represented by the same

292 change in production efficiencies, i.e. reducing the required area per unit of food or feed. Similarly, for

293 pasture yield improvements (change 4) reduces the area required for ruminant products for pasture.

294 Changes impacting animal feed conversion ratios (changes 5-7 and 17-19) were applied as a reduction in

295 feed and pasture area requirements for animal products. Rates of losses changes (11-16 and 23) act on the

296 rates of losses calculated above, adjusted by the rate of marginal gain action. Dietary changes (20-22 and

297 24-29) adjust the regional demand with resultant diets applied to regional populations to calculate required

298 food supplies. Changes involving substitution between foods were applied so as to maintain a constant

299 protein quantity in the diet (Alexander et al., 2016). In the case of new foods or production systems (e.g.

300 insects, cultured meat and aquaculture) feed requirements are derived from feed conversion ratios

301 (Alexander et al., 2017a). Therefore, these commodities are all assumed to be produced from feed grown

302 for the purpose with the associated land requirements not from waste streams. Changes are applied as

303 multiplicative factors to the relevant quantities and, therefore, multiple changes affecting the same

304 quantity have a compounded impact.

305 To explore sensitivities to variation in the adoption rates considered, the rates of change were adjusted by

306 a factor of 0.5 and 2, respectively, to give 'low' and 'high' change conditions. Additionally, a Monte Carlo

307 approach, with 1000 samples, was used with factors from 0 to 2 drawn from a uniform distribution applied

308 independently to each marginal change rate.

309 **4   Results**

310 In 2013, 93.7% (4576 Mha) of the 4884 Mha of agricultural areas were appropriated by the food system.

311 The remaining agricultural areas were associated with the production of crops for fibre and bioenergy.

312 Therefore, 35.2% of the 13 billion ha global land surface is used for food production. This corresponds to a

313 global average of 0.63 ha per person.

314   How might this land area change under the concept of marginal gains? Country level changes were

315   aggregated to seven global regions; high and medium income countries to Europe; North America &

316   Oceania and Industrialized Asia regions and the lower income countries to sub-Saharan Africa; North Africa,

317   Western & Central Asia; South & Southeast Asia and Latin America[58]. The combined effect of the 29

318   marginal changes considered here reduced the land requirement for food production in each of these

319   regions, from 109 Mha in sub-Saharan Africa to 157 Mha in Europe (Figure 1a). Considerable differences in

320   the proportions of reductions from supply and consumer changes were evident between regions. The

321   majority of European, North America and Oceania land use reductions were related to consumer choices

322   (63% and 64%, respectively). Conversely, sub-Saharan Africa and North Africa, West and Central Asia had

323   lower proportion of gains from consumer choices (33% and 35% respectively), with the majority of land

324   area reductions arising from production and supply chain improvements. The area required per person for

325   food also showed considerable variation between regions (Figure 1b). North America and Oceania had the

326   highest current per capita areas of (1.46 ha/person), which drops by 25% to 1.09 ha/person under the

327   marginal gains. South and South East Asia has the lowest areas for food per capita (initially 0.28 ha/person),

328   which declines by the lowest of any region in absolute and percentage terms, to 0.24 ha/person; a 16%

329   reduction.
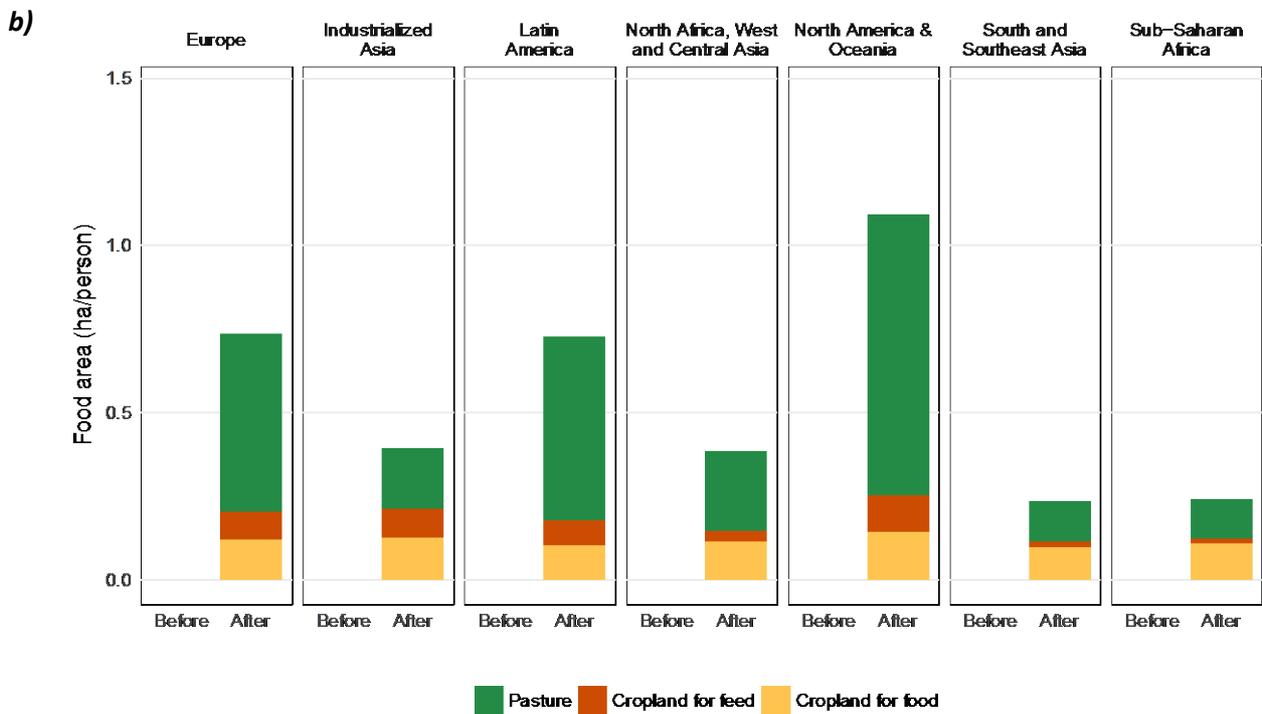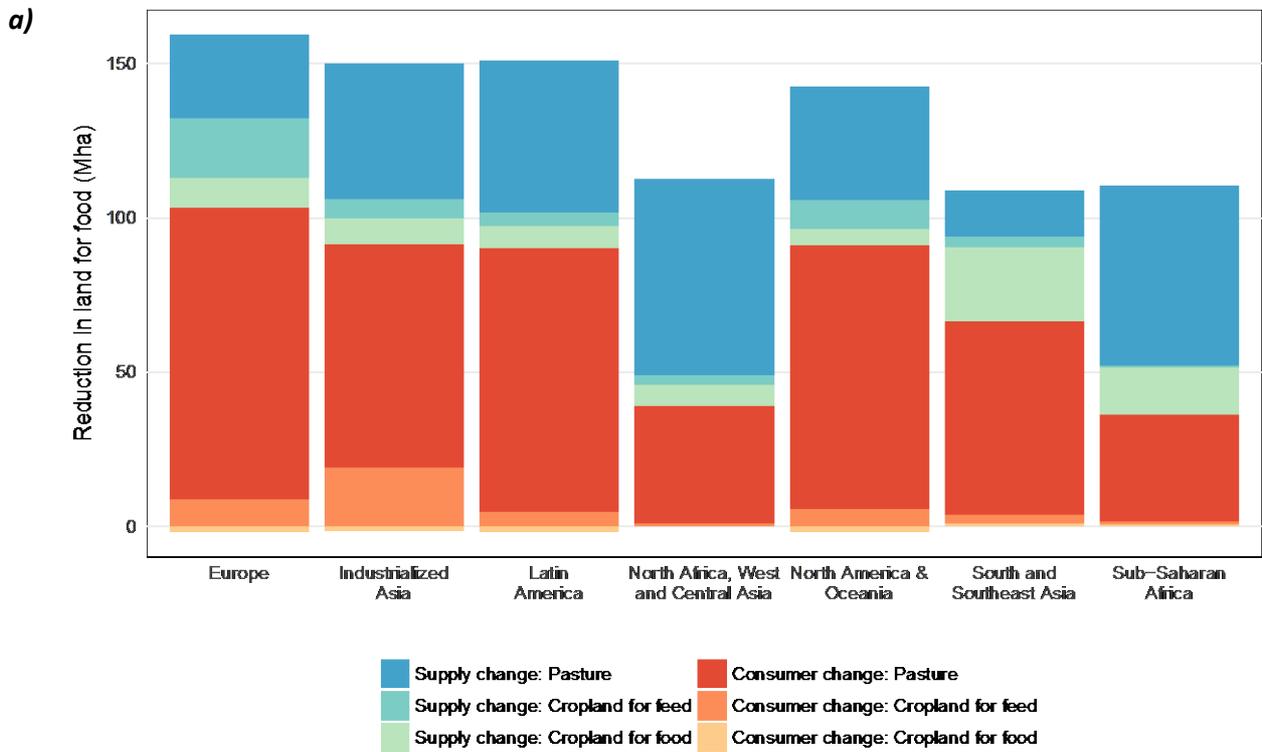
Figure 1. *Combined effects, by region, of marginal food system gains in pasture, cropland for feed and cropland for food areas, a) reduction in area of land required for food divided into supply and consumer changes; and, b) area per person for food.*

The total global land area required for food was found to reduce by 947 Mha (a 21% reduction) to 3629 Mha (or 27.9% of the global land surface) when all marginal changes were applied at their default rates (Figure 2a). This total reduction comprised a 24% (118 Mha) reduction in cropland for feed, a 23%

337 reduction in pasture (755 Mha), but only an 8% (74 Mha) reduction in cropland for food. Reducing the

338 change rates by half ('low' case, Figure 2a) gave a total reduction of 502 Mha (11%), while doubling the

339 rates ('high' case, Figure 2a) gave a reduction of 1691 Mha (37%) to 2885 Mha, an agricultural area not

340 seen since before the 1800s (Ramankutty and Foley, 1999). Such changes would reduce average land for

341 food production per person to 0.40 – 0.56 ha. Stochastic sampling of the marginal change rates (from

342 values between 0 and 2%) gave probability distributions of land area reductions within a similar range, as

343 shown in Figure 3.
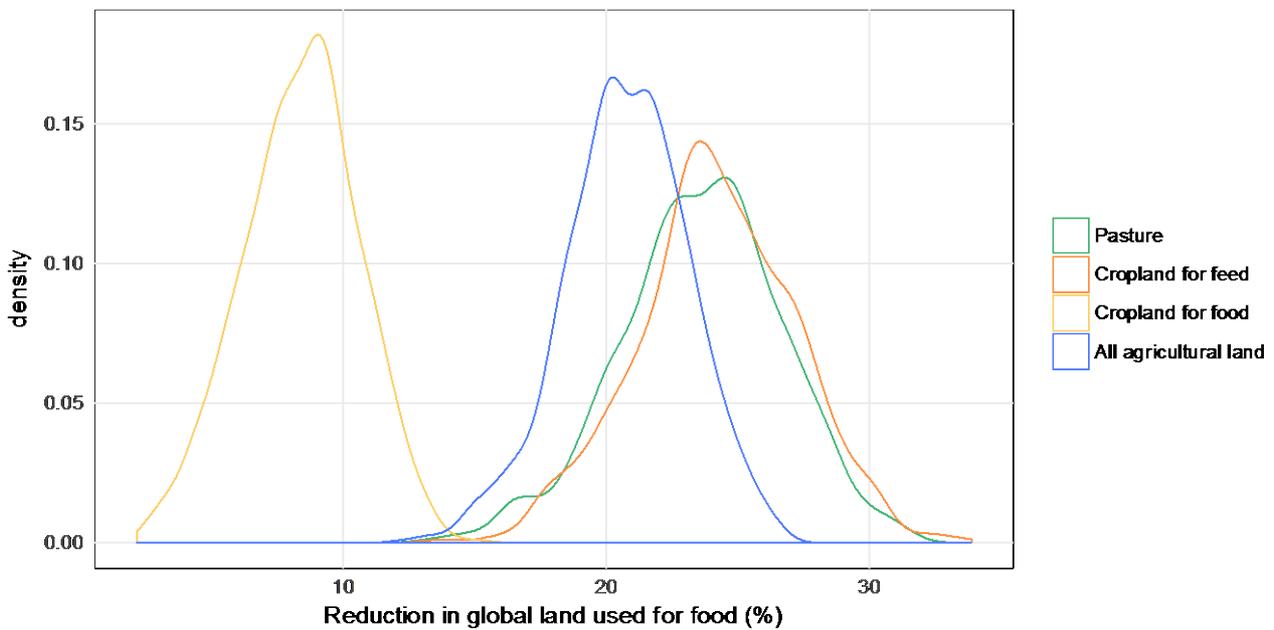
344 *a)*   *b)*
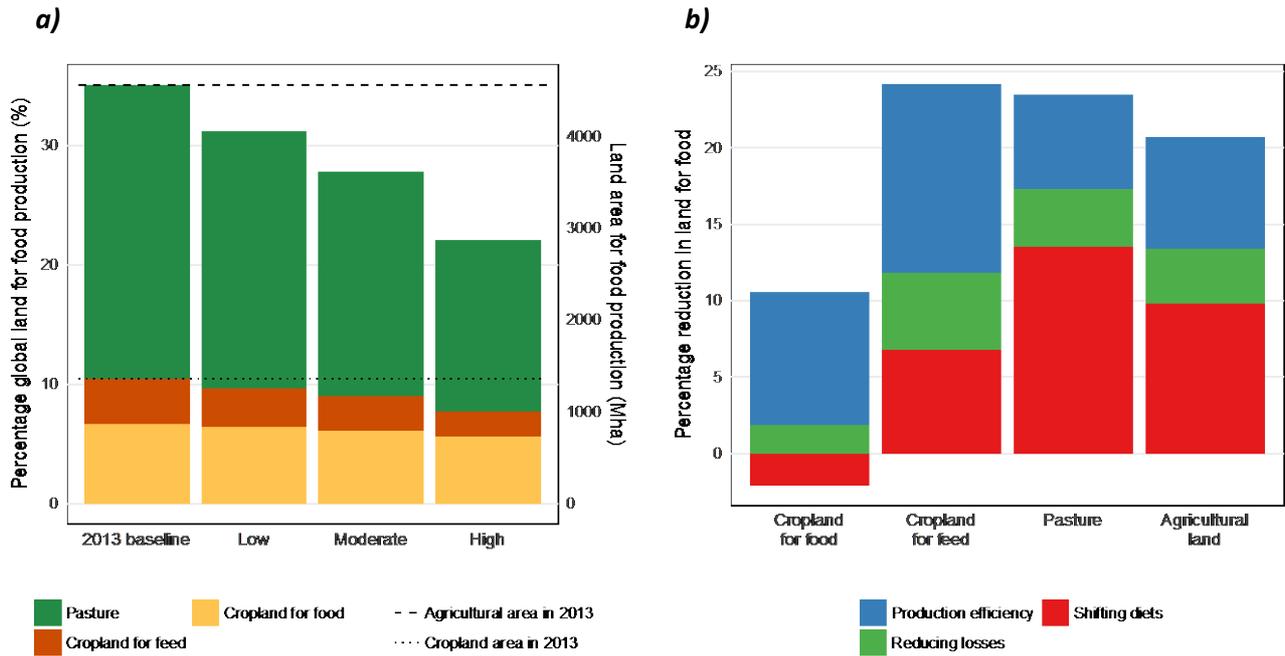
345

346 *Figure 2. Global areas of pasture, cropland for feed and cropland for food a) from the combined effects of all*

347 *29 marginal gains considered, by rate (i.e. low, moderate and high), and b) percentage reductions with*

348 *moderate rates by type of marginal change.*

349

Figure 3: Sampled reduction in land used for food production, from 1000 randomly selected marginal change rates from a multiple of 0 to 2 times that of the assumed rate (Table 1).

The 3 categories of change (increasing production efficiency, reducing losses and shifting diets) produce different proportional effects on land use types (Figure 2b). Pasture area reductions are mainly (58%) attributable to dietary shifts, with a further 16% from reducing losses and 26% from production efficiencies. Conversely, dietary shifts were associated with an increase in cropland food, as animal products are substituted for diets with a greater fraction of plant-based foods. Area reductions of cropland for animal feed were approximately half (51%) due to production efficiencies, with 21% from reducing losses and 28% from dietary shifts. The net effect for total agricultural land area was more balanced, with 48% of the reduction caused by shifting diets, 35% by production efficiencies and 17% from reducing losses.

Individual marginal gains lead to different levels of cropland and pasture change (Figure 4). This figure shows in more detail the opposing effects of certain dietary changes on cropland and pasture. For example, substituting ruminant products with monogastric products decreases pasture area, but increases animal feed requirements from cropland. Substitution of a proportion of livestock products with greater plant-based diets (e.g. vegetarianism and veganism) decreases pasture area, but increases cropland for food. Advances in livestock production and pasture management caused the largest area reductions of all production efficiency changes. Greater consumption of offal caused the largest area reduction of all reducing loss changes, while low meat diets and monogastrics caused the largest area reduction of all shifting diet changes. However, implicit in these observed changes are the assigned rates of action (Table 1).
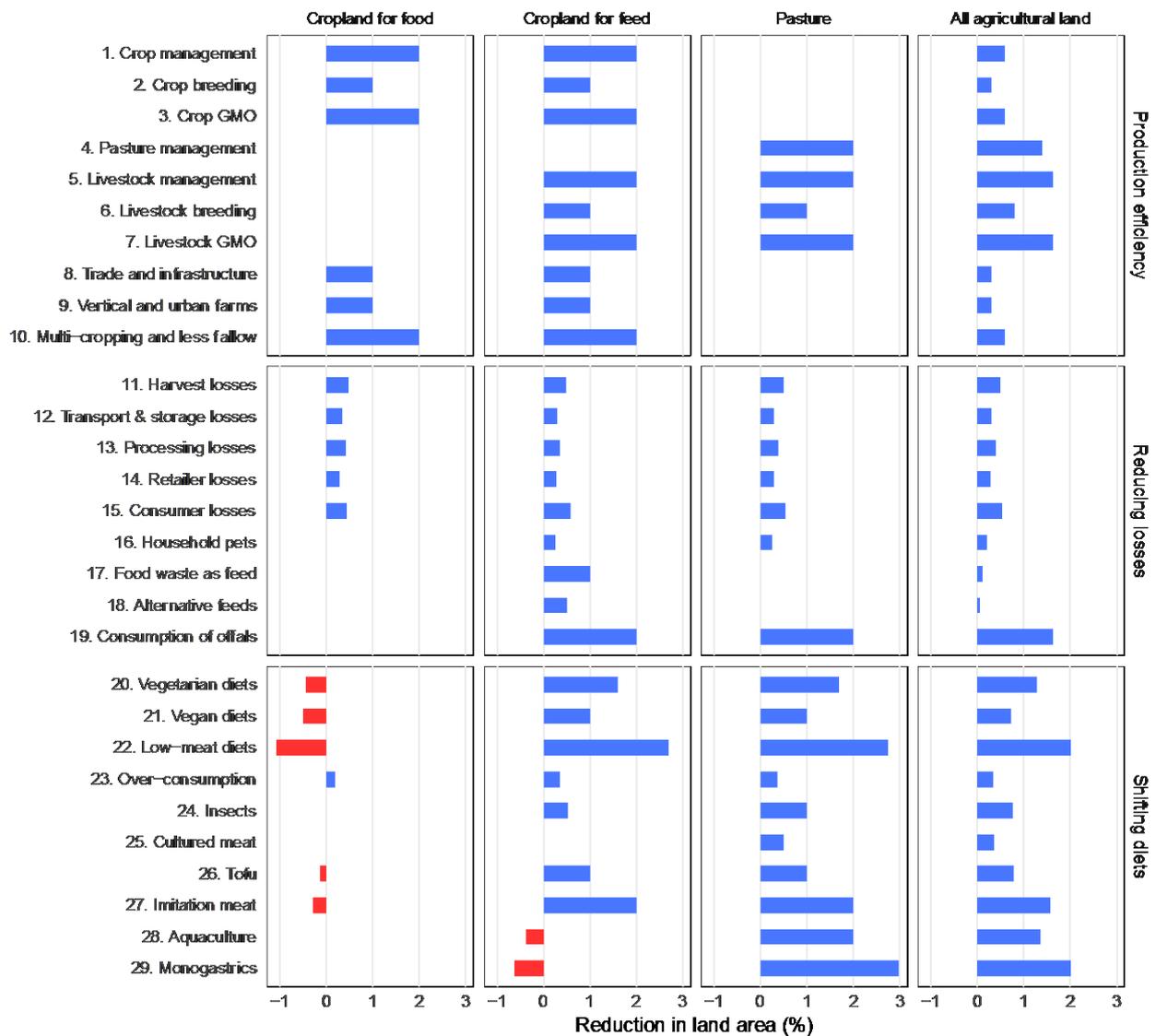
Figure 4. Percentage reduction in global land used by the food system from single marginal changes.

5 Discussion

There is a pressing need to understand how humanity could transform the global food system in ways that would minimise environmental degradation, whilst satisfying the nutritional requirements of the global population. The concept of marginal gains suggests that transformation need not necessarily result from sudden or large changes in existing systems. Application of the marginal gains concept to the global food system shows that the land area used for food production could be reduced considerably (by up to 37% of the current agricultural area) through changes that are plausibly achievable now. The 29 marginal gains selected here encompass some of the most discussed potential changes to the food system, such as increases in yields due to biotechnology, as well as some less recognised possibilities, such as decreasing the quantity of livestock products that are fed to pets. The magnitude of this effect is comparable to those

16

384   identified by previous studies focusing on a few major, non-marginal and, as a result, less plausible changes

385   to the food system (Alexander et al., 2017a, 2016; Röös et al., 2017; Willett et al., 2019).

386   Particularly notable is the scope for meat consumption allowed by the marginal gains approach, despite the

387   large land footprint of livestock production. This result aligns with the suggestion that some pastures are, in

388   terms of agricultural production, unsuitable for anything other than the rearing of ruminant livestock (Röös

389   et al., 2016), but contrasts with suggestions that substantial reductions in consumption of animal source

390   foods are necessary to achieve environmental sustainability (Willett et al., 2019). Pasture is also important

391   for biodiversity and for the livelihoods of minority groups such as nomadic pastoralists who rely on

392   livestock for most of their nutrient intake (Eisler et al., 2014). However, the approach presented here did

393   not account for the impact of greenhouse gas emissions from livestock production on climate change,

394   which will impact on future agricultural productivity (Schmidhuber and Tubiello, 2007; Steinfield, 2006).

395   Neither did it consider animal welfare across the marginal gains related to increased livestock production

396   efficiencies or the replacement of ruminant livestock with monogastrics or aquaculture. Thus, evaluating

397   changes in livestock production requires a rigorous and widespread analysis of the environmental and

398   ethical impacts of production.

399   Historically, changes to the food system that have increased production have not necessarily resulted in

400   reductions in land area. This is due to the 'rebound effect', where increasing efficiency increases

401   affordability of certain agricultural products leading to greater demand, sometimes termed a Jevons effect

402   (Amado and Sauer, 2012; Chan and Gillingham, 2015). The profits from fulfilling this increased demand

403   drive agricultural expansion, rather than reduction. Such rebound effects have occurred with the

404   production of soybean in Brazil, and oil palm in Indonesia and Malaysia (Lambin and Meyfroidt, 2011).

405   Another concern is the abandonment of agricultural land without restoration, which can increase the risk of

406   erosion, wildfire, and general landscape degradation. In Europe, for example, abandonment of agricultural

407   land now threatens between 5-65% of important bird habitats (Stoate et al., 2009).

408   Nevertheless, when land gains are realised, they can significantly improve the prospects for biodiversity

409   conservation, and the supply of ecosystem services. The need for the preservation of large swathes of

410   intact natural landscapes for species conservation is becoming increasingly apparent, especially for

411   endangered species with small ranges (Balmford et al., 2005; Phalan et al., 2016, 2011). The land areas that

412   might be spared due to marginal gains are large enough to generate very substantial benefits for

413   biodiversity (Dinerstein et al., 2017). However, further work is required to reconcile the spatial generality of

414   the calculated effects of global marginal changes with the need for large, region-specific reductions in

415   agricultural land to prevent the degradation of the most valuable ecosystems such as tropical rainforest.

416   This will depend on ensuring that various political and cultural institutions have measures in place to

417   balance the trade-offs arising from changes within the food system, and to support the maintenance of the

418   land spared for nature. Political interventions may also have unintended environmental outcomes, for
419   example recent US-China trade conflicts have shifted international trade in soy, potentially leading to
420   agricultural expansion and large-scale deforestation in the tropics (Fuchs et al., 2019).

421   Reductions in land used for food differ widely between regions, especially between low and high-income
422   regions. The benefits of marginal gains in high-income countries were mostly through the consumption
423   changes, highlighting the need for alterations in consumption patterns within these regions. In particular,
424   Europe, North America and Oceania could play an important leadership role in improving consumer
425   choices, especially concerning overconsumption, the dietary mix and other wastes and losses in the system.
426   The benefits of marginal gains in low-income countries were stronger on the production-side of the food
427   system. This implies a need to support food producers in changing the efficiency of food production and
428   distribution, e.g. through improved infrastructure, access to capital, or farmer advisory services (FAO,
429   2013).

430   The marginal gains approach has considerable utility for decision-making and policy implementation, since
431   marginal gains reflect policy preferences for incremental change (Dunn et al., 2017; Mapfumo et al., 2017).
432   However, it is critical to understand that the benefits offered by marginal gains cannot be achieved without
433   considerable and concerted action across multiple policy sectors. Implementing marginal gains is not the
434   easy option, to which we are sure Dave Brailsford would attest: it marks, however, a feasible and tractable
435   pathway to transformation. It is not a license for inaction, but a call to arms for what might be achieved
436   with appropriate policy intervention and societal change.

437   **6   Conclusions**

438   Land is central to the food system, and its profligate appropriation has caused significant environmental
439   damage, largely due to mismanagement of agricultural and natural ecosystems and wasteful human
440   behaviour. Because of this, there have been multiple calls for transformation in the global food system, but
441   with no clear roadmaps for achieving this aspiration. Large-scale changes in the food system are obstructed
442   by political and public inertia and a tendency towards incremental change. For example, public
443   acceptability of the EAT–Lancet reference diet remains questionable. However, we show here that
444   transformation can also occur through simultaneous action on the multiple factors that underpin food
445   systems. The relatively smaller shift in each factor reduces potential barriers to adoption, in comparison to
446   the larger-scale change more typically proposed. It is important to recognise that even achieving marginal
447   gains requires considerable and coordinated efforts across policy sectors. Nonetheless, acting collectively
448   plausible marginal changes can reduce global land areas used for food production substantially, up to 37%
449   under the assumptions used here, suggesting that such an approach may lead to an achievable food system
450   transformation.

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