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1 **Transforming agricultural land use through marginal gains** 2 **in the food system**

3 **Abstract**

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

14 **1 The need to transform the global food system**

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

27 The concept of ‘transformation’ is widely discussed with respect to climate change adaptation (Kates et al.,
28 2012; Rickards and Howden, 2012), with calls for “major, non-marginal change[s]” (Stern et al., 2006).
29 However, the concept of transformation is increasingly criticised for its failure to direct policy change at an
30 achievable and sustainable scale and does not take account of the complexity and inertia in human systems
31 (Brown et al., 2019; Görg et al., 2017; Vermeulen et al., 2018; Willett et al., 2019). Instead, policy-makers
32 tend to favour the pursuit of incremental change (Dunn et al., 2017; Mapfumo et al., 2017). Drawing
33 inspiration from an unlikely source - the British cycling team and their search for success through the
34 concept of marginal gains - we aim to show how the concept of transformation might be reconciled with
35 incremental change and how this may prove a valuable tool in the transformation of the global food
36 system.

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

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

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

59 **2 Marginal food system changes**

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

75 Table 1: Summary of changes to the food system considered with the potential for marginal gains in food
 76 system efficiency, and the overall rates of assumed action. Orange shading indicates consumer or retailer
 77 behavioural changes, while blue shading indicates supply changes to production or value-chains.

	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%	Reduction in pet food.
	16: Household pets	Greater use of by-products or potentially a reduction in pet numbers or size of pets.	5%	
	17: Food waste as feed	Directing food waste for uses as animal feed. Regulatory and potential health issues to consider.	2%	
	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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79 **Increasing production efficiency**

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

90 Improved crop management practices to close yield gaps have been identified as strategies that could
91 improve sustainability of the food system (Foley et al., 2011; Licker et al., 2010; Phalan et al., 2014; Van
92 Ittersum et al., 2013). Achieved yields are limited by land management choices and access to a variety of
93 inputs such as pesticides, machinery and nutrients (Godfray et al., 2010). With improved crop management
94 practices yield gaps can be reduced (Alexandratos and Bruinsma, 2012; Foley et al., 2011) and as such we
95 included increases in crop yields that could be attributed to this type of change (change 1). The 2% yield
96 increase represents the closing the yield gap from West et al. (2014) by 7%, a rate 7 times smaller than
97 assumed in that study. Progress in breeding and genetic techniques has also allowed for the development
98 of high yielding crop varieties of many staple global crops (Jaggard et al., 2010; Tester and Langridge, 2010).
99 Advances in crop breeding and genetic techniques over previous decades have therefore demonstrated the
100 potential of such approaches (Jaggard et al., 2010; Tester and Langridge, 2010), although legislative change
101 (e.g. relating to genetically modified organisms) may be required in some jurisdictions (Azadi and Ho, 2010;
102 Reuter et al., 2010). We include improved crop breeding (change 2) and crop genetic modification
103 (considered here to encompass genetic engineering and gene editing using techniques such as CRISPR-
104 Cas9, change 3) as marginal changes leading to increased crop yields. For example, a metanalysis of
105 literature from 1996 to 2016 showed that genetical engineered maize yields have increased by 10.1%
106 compared to non-engineered varieties (Pellegrino et al., 2018). While substantially newer, improving yield
107 performance is one of the main uses to which CRISPR-Cas9 gene editing has been applied (Ricroch et al.,
108 2017).

109 The production efficiency of cropland could be increased globally through reductions of fallows and a
110 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).

146 **Reducing losses**

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

156 Improving the sustainability of the food system may involve reassessing sources of feed for livestock;
157 considering both the use of food waste (change 16) and alternative sources such as insects and algae as
158 feed (change 17). In the European Union less than 3% of food waste is currently recycled as animal feed (zu
159 Ermgassen et al., 2016) for the most part due to risks of contamination and disease concerns. However
160 recycling food waste as feed is more widely practiced in Asian countries, in Japan for example 35.9% of
161 food waste is used as feed (Salemdeeb et al., 2017), and if the EU was to adopt an Asian style recycling
162 approach land use of EU pork alone could reduce by one fifth (zu Ermgassen et al., 2016)(Salemdeeb et al.,
163 2017). The use of food waste as feed has been identified as a priority research area by the animal feed
164 industry (Makkar and Ankers, 2014). It is widely recognised that feeding livestock soy or fishmeal has
165 widespread environmental consequences and globally almost a third of crops harvested are used as feed
166 (Steinfeld et al., 2006). There is also a growing interest in using insects as feed due to their nutritional
167 characteristics; as a protein source, insects have been found to contain adequate amino acid compositions
168 and antimicrobial peptides beneficial in feed (Gasco et al., 2018; Khan, 2018; Sánchez-Muros et al., 2014).
169 Additionally, the use of insects as feed is expected to have beneficial environmental consequences (van
170 Huis and Oonincx, 2017); insect production is efficient in terms of land use (Alexander et al., 2017a), insects
171 have high feed conversion efficiencies (Premalatha et al., 2011; van Broekhoven et al., 2015) and some
172 species can convert organic waste into high quality feed (Miech et al., 2016; van Broekhoven et al., 2015).
173 Reassessing livestock feed sources is clearly a substantial way to increase sustainability by reducing losses
174 and we therefore include marginal changes of this type.

175 At the consumer level considerable losses occur through discarded leftovers, inefficient food processing
176 and overconsumption (Alexander et al., 2017b). Significant food system losses are associated with
177 consumer behaviour (Alexander et al., 2017b; Gustavsson et al., 2011) and we therefore consider a
178 marginal reduction in consumer-related losses as part of this analysis (change 14). Waste reduction
179 throughout the food system could also be achieved by changing consumer attitudes, for example, we
180 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

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.

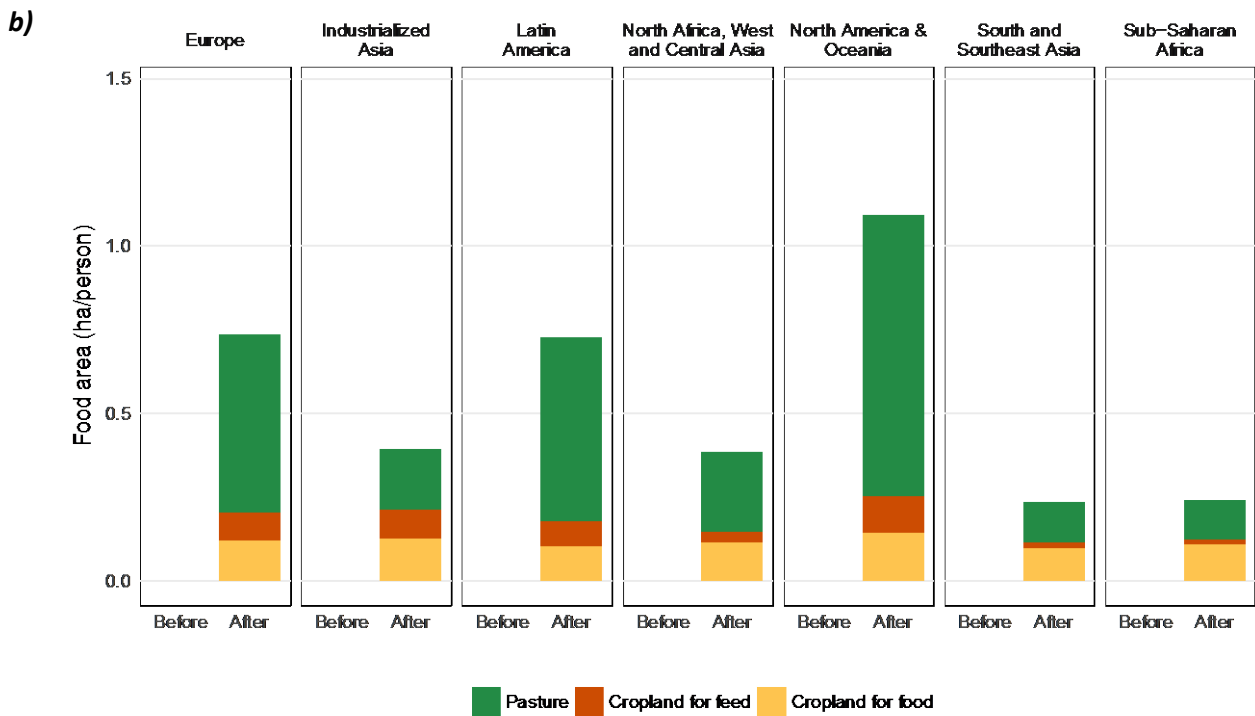
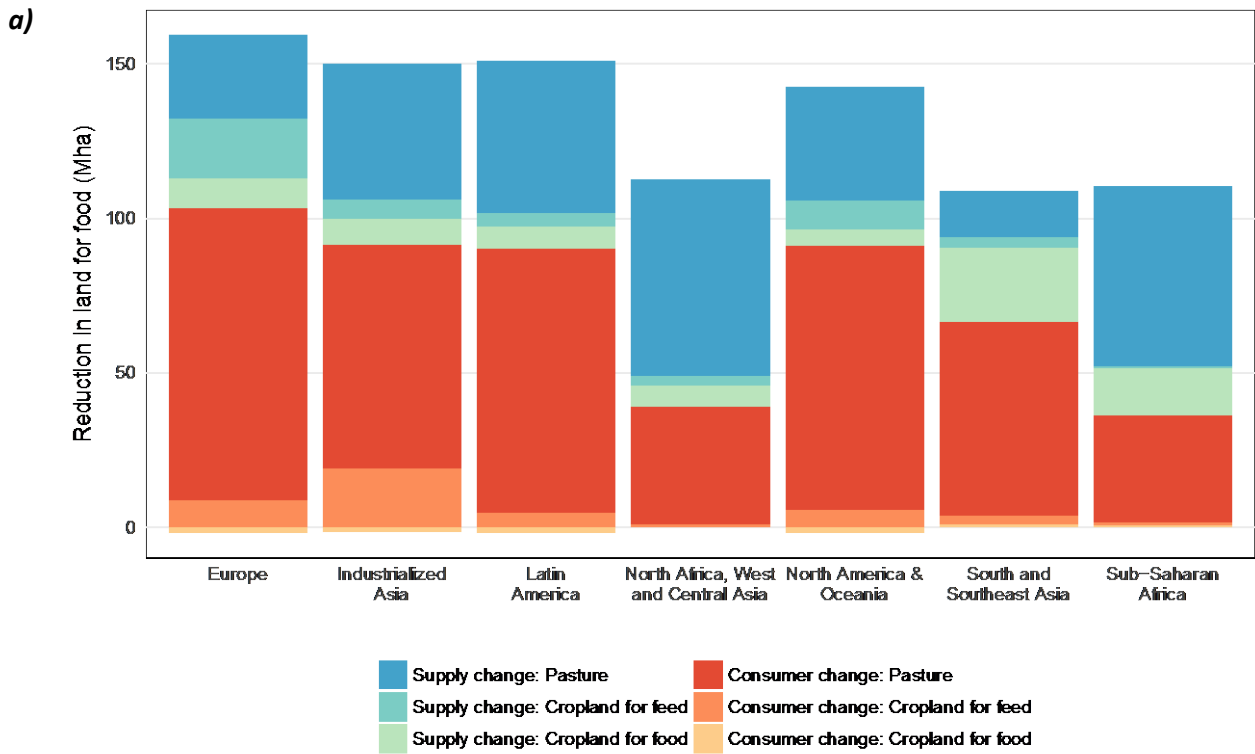
287 This representation allows the agricultural land use implications from the changes considered to be
288 calculated by adjusting different aspects of the food system. In the baseline case, summing across all
289 commodities and regions the unadjusted demand (accounting for losses) multiplied by the 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 America⁵⁸. 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.



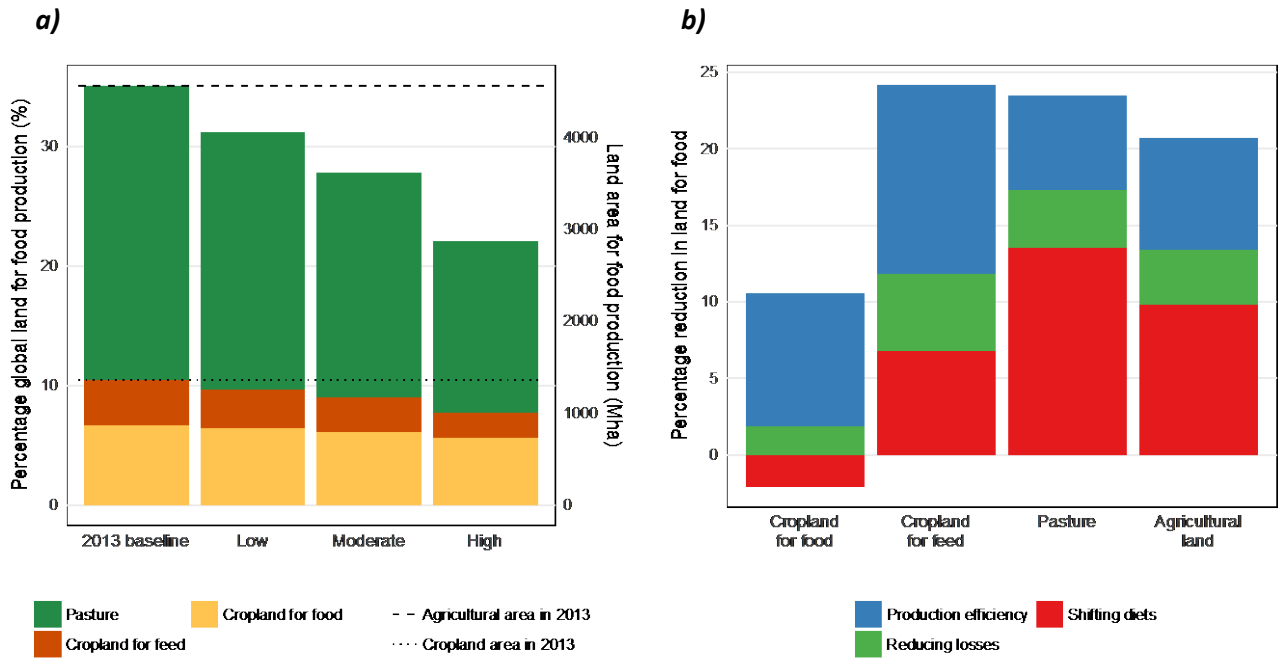
330 Figure 1. Combined effects, by region, of marginal food system gains in pasture, cropland for feed and
 331 cropland for food areas, a) reduction in area of land required for food divided into supply and consumer
 332 changes; and, b) area per person for food.

333

334 The total global land area required for food was found to reduce by 947 Mha (a 21% reduction) to 3629
 335 Mha (or 27.9% of the global land surface) when all marginal changes were applied at their default rates
 336 (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.

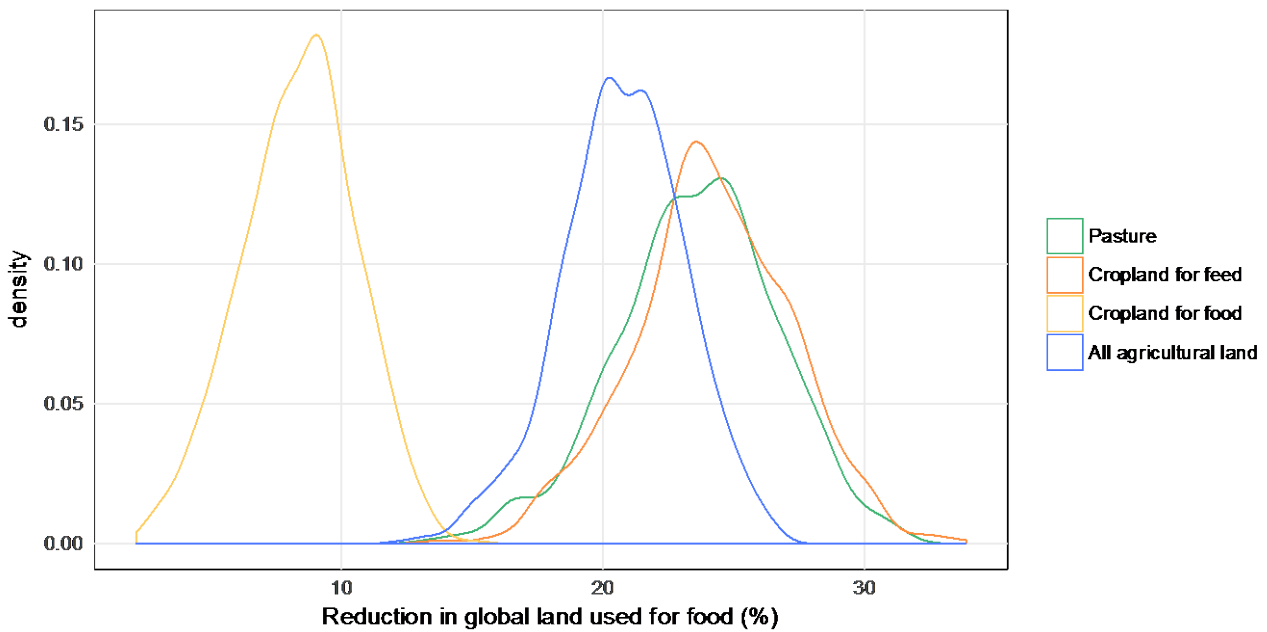
344



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



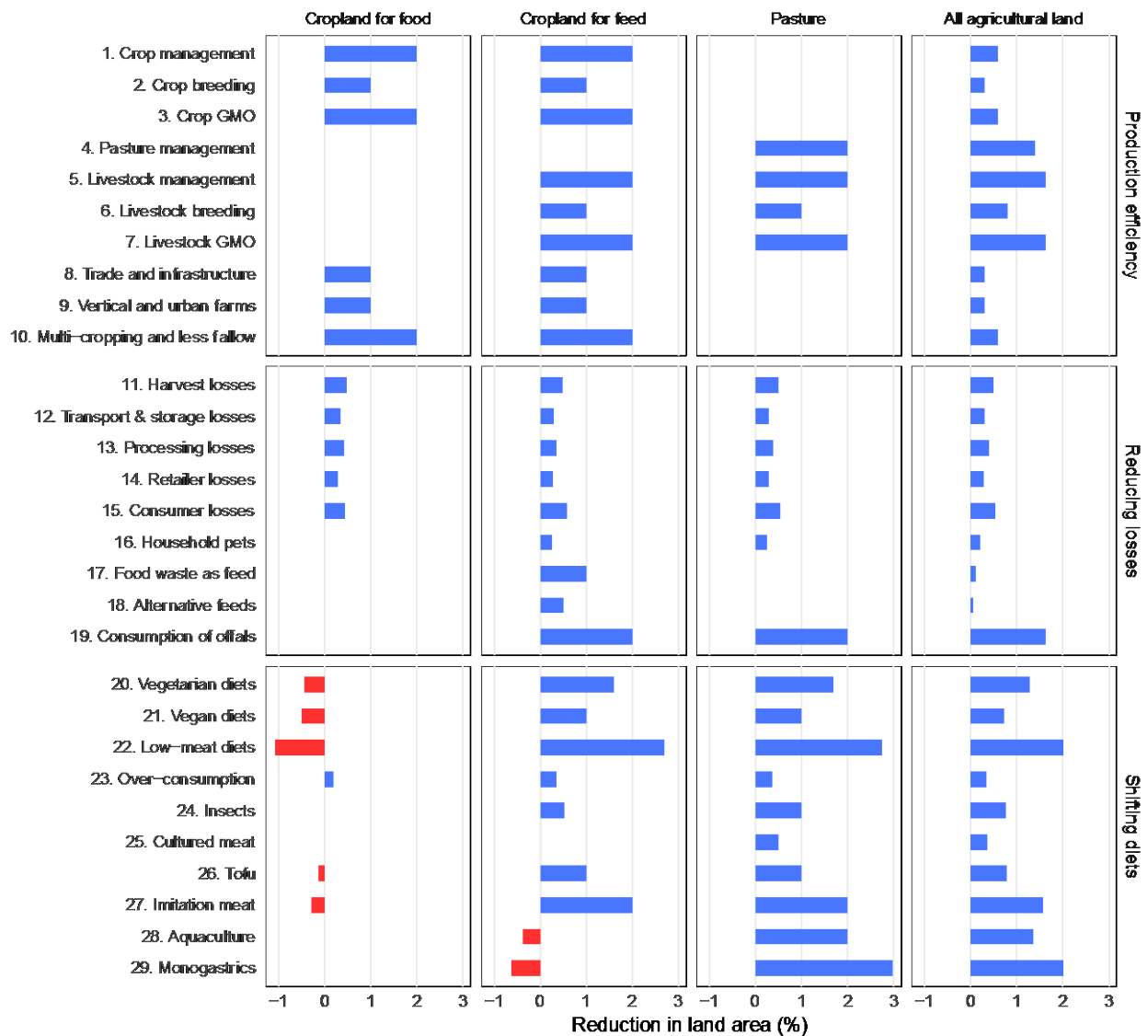
350

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

353

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

362 Individual marginal gains lead to different levels of cropland and pasture change (Figure 4). This figure
 363 shows in more detail the opposing effects of certain dietary changes on cropland and pasture. For example,
 364 substituting ruminant products with monogastric products decreases pasture area, but increases animal
 365 feed requirements from cropland. Substitution of a proportion of livestock products with greater plant-
 366 based diets (e.g. vegetarianism and veganism) decreases pasture area, but increases cropland for food.
 367 Advances in livestock production and pasture management caused the largest area reductions of all
 368 production efficiency changes. Greater consumption of offal caused the largest area reduction of all
 369 reducing loss changes, while low meat diets and monogastrics caused the largest area reduction of all
 370 shifting diet changes. However, implicit in these observed changes are the assigned rates of action (Table
 371 1).



372

373 *Figure 4. Percentage reduction in global land used by the food system from single marginal changes.*

374 **5 Discussion**

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

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; Rööös 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 (Rööös
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; Steinfeld, 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.

451 **7 References**

- 452 Abass, A.B., Ndunguru, G., Mamiro, P., Alenkhe, B., Mlingi, N., Bekunda, M., 2014. Post-harvest food losses
453 in a maize-based farming system of semi-arid savannah area of Tanzania. *Journal of Stored Products*
454 *Research* 57, 49–57. doi:<https://doi.org/10.1016/j.jspr.2013.12.004>
- 455 Aker, J.C., 2011. Dial “A” for agriculture: a review of information and communication technologies for
456 agricultural extension in developing countries. *Agricultural Economics* 42, 631–647.
457 doi:10.1111/j.1574-0862.2011.00545.x
- 458 Aleksandrowicz, L., Green, R., Joy, E.J.M., Smith, P., Haines, A., 2016. The Impacts of Dietary Change on
459 Greenhouse Gas Emissions, Land Use, Water Use, and Health: A Systematic Review. *Plos One* 11,
460 e0165797. doi:10.1371/journal.pone.0165797
- 461 Alexander, P., Brown, C., Arneth, A., Dias, C., Finnigan, J., Moran, D., Rounsevell, M., 2017a. Could
462 consumption of insects, cultured meat or imitation meat reduce global agricultural land use? *Global*
463 *Food Security* 15, 22–32. doi:10.1016/j.gfs.2017.04.001
- 464 Alexander, P., Brown, C., Arneth, A., Finnigan, J., Moran, D., Rounsevell, M.D.A., 2017b. Losses,
465 inefficiencies and waste in the global food system. *Agricultural Systems* 153, 190–200.
- 466 Alexander, P., Brown, C., Rounsevell, M., Finnigan, J., Arneth, A., 2016. Human appropriation of land for
467 food: The role of diet. *Global Environmental Change* 41, 88–98.
- 468 Alexander, P., Rabin, S., Anthoni, P., Henry, R., Pugh, T.A.M., Rounsevell, M.D.A., Arneth, A., 2018.
469 Adaptation of global land use and management intensity to changes in climate and atmospheric
470 carbon dioxide. *Global Change Biology* 24, 2791–2809. doi:10.1111/gcb.14110
- 471 Alexander, P., Rounsevell, M.D.A., Dislich, C., Dodson, J.R., Engström, K., Moran, D., 2015. Drivers for global
472 agricultural land use change: The nexus of diet, population, yield and bioenergy. *Global Environmental*
473 *Change* 35, 138–147. doi:10.1016/j.gloenvcha.2015.08.011
- 474 Alexandratos, N., Bruinsma, J., 2012. World agriculture towards 2030/2050: the 2012 revision 160.
- 475 Alroy, J., 2017. Effects of habitat disturbance on tropical forest biodiversity. *Proceedings of the National*
476 *Academy of Sciences* 114, 6056–6061. doi:10.1073/pnas.1611855114
- 477 Amado, N.B., Sauer, I.L., 2012. An ecological economic interpretation of the Jevons effect. *Ecological*
478 *Complexity* 9, 2–9. doi:10.1016/j.ecocom.2011.10.003
- 479 Aschemann-Witzel, J., de Hooge, I., Amani, P., Bech-Larsen, T., Oostindjer, M., 2015. Consumer-Related
480 Food Waste: Causes and Potential for Action. *Sustainability* 7, 6457–6477. doi:10.3390/su7066457
- 481 Azadi, H., Ho, P., 2010. Genetically modified and organic crops in developing countries: A review of options
482 for food security. *Biotechnology Advances* 28, 160–168.
483 doi:<https://doi.org/10.1016/j.biotechadv.2009.11.003>
- 484 Bajželj, B., Richards, K.S., Allwood, J.M., Smith, P., Dennis, J.S., Curmi, E., Gilligan, C. a., 2014. Importance of
485 food-demand management for climate mitigation. *Nature Climate Change* 4, 924–929.
486 doi:10.1038/nclimate2353
- 487 Balmford, A., Green, R.E., Scharlemann, J.P.W., 2005. Sparing land for nature: exploring the potential
488 impact of changes in agricultural yield on the area needed for crop production. *Global Change Biology*
489 11, 1594–1605. doi:10.1111/j.1365-2486.2005.001035.x
- 490 BBC News, 2015. Should we all be looking for marginal gains? [WWW Document]. URL

- 491 <https://www.bbc.co.uk/news/magazine-34247629> (accessed 10.1.18).
- 492 Bhat, Z.F., Kumar, S., Bhat, H.F., 2017. In vitro meat: A future animal-free harvest. *Critical Reviews in Food*
493 *Science and Nutrition* 57, 782–789. doi:10.1080/10408398.2014.924899
- 494 Bouwman, A.F., Van der Hoek, K.W., Eickhout, B., Soenario, I., 2005. Exploring changes in world ruminant
495 production systems. *Agricultural Systems* 84, 121–153. doi:10.1016/j.agsy.2004.05.006
- 496 Bowles, N., Alexander, S., Hadjikakou, M., 2019. The livestock sector and planetary boundaries : A ‘ limits to
497 growth ’ perspective with dietary implications. *Ecological Economics* 160, 128–136.
498 doi:10.1016/j.ecolecon.2019.01.033
- 499 Brown, C., Alexander, P., Arneith, A., Holman, I., Rounsevell, M., 2019. Achievement of Paris climate goals
500 unlikely due to time lags in the land system. *Nature Climate Change* 9, 203–208. doi:10.1038/s41558-
501 019-0400-5
- 502 Buckwell, A., Nadeu, E., 2018. What is the Safe Operating Space for EU livestock? RISE Foundation, Brussels.
- 503 Butler, R.A., Laurance, W.F., 2009. Is Oil Palm the Next Emerging Threat to the Amazon? *Tropical*
504 *Conservation Science* 2, 1–10. doi:10.1177/194008290900200102
- 505 Chan, N.W., Gillingham, K., 2015. The Microeconomic Theory of the Rebound Effect and its Welfare
506 Implications. *Journal of the Association of Environmental & Resource Economists Abstract* 2, 133–159.
507 doi:10.1071/AR9620031
- 508 Delgado, C.L., 2003. Rising consumption of meat and milk in developing countries has created a new food
509 revolution. *The Journal of Nutrition* 133, 3907S-3910S.
- 510 Despommier, D., 2013. Farming up the city: the rise of urban vertical farms. *Trends in biotechnology* 31,
511 388–389.
- 512 Diekmann, L.O., Gray, L.C., Baker, G.A., 2018. Growing ‘good food’ : urban gardens , culturally acceptable
513 produce and food security.
- 514 Dinerstein, E., Olson, D., Joshi, A., Vynne, C., Burgess, N.D., Wikramanayake, E., Hahn, N., Palminteri, S.,
515 Hedao, P., Noss, R., Hansen, M., Locke, H., Ellis, E.C., Jones, B., Barber, C.V., Hayes, R., Kormos, C.,
516 Martin, V., Crist, E., Sechrest, W., Price, L., Baillie, J.E.M., Weeden, D., Suckling, K., Davis, C., Sizer, N.,
517 Moore, R., Thau, D., Birch, T., Potapov, P., Turubanova, S., Tyukavina, A., De Souza, N., Pintea, L., Brito,
518 J.C., Llewellyn, O.A., Miller, A.G., Patzelt, A., Ghazanfar, S.A., Timberlake, J., Klöser, H., Shennan-
519 Farpón, Y., Kindt, R., Lillesø, J.P.B., Van Breugel, P., Gaudal, L., Vogé, M., Al-Shammari, K.F., Saleem,
520 M., 2017. An Ecoregion-Based Approach to Protecting Half the Terrestrial Realm. *BioScience* 67, 534–
521 545. doi:10.1093/biosci/bix014
- 522 Dunn, M., Rounsevell, M.D., Carlsen, H., Dzebo, A., Lourenço, T.C., Hagg, J., 2017. To what extent are land
523 resource managers preparing for high-end climate change in Scotland? *Climatic Change* 141, 181–195.
524 doi:10.1007/s10584-016-1881-0
- 525 Eigenbrod, C., Gruda, N., 2015. Urban vegetable for food security in cities. A review. *Agronomy for*
526 *Sustainable Development* 35, 483–498. doi:10.1007/s13593-014-0273-y
- 527 Eisler, M.C., Lee, M.R.F., Tarlton, J.F., Martin, G.B., Beddington, J., Dungait, J.A.J., Greathead, H., Liu, J.,
528 Mathew, S., Miller, H., Misselbrook, T., Murray, P., Vinod, V.K., Van Saun, R., Winter, M., 2014.
529 *Agriculture: Steps to sustainable livestock*. *Nature* 507, 32–34.
- 530 FAO, 2013. Save and grow - a policymaker’s guide to the sustainable intensification of smallholder crop
531 production. Food and Agriculture Organization of the United Nations, Rome, Italy.

- 532 FAOSTAT, 2018a. Resources/Land (2018-09-24). Food and Agriculture Organization of the United Nations,
533 Rome, Italy.
- 534 FAOSTAT, 2018b. Food Supply - Livestock and Fish Primary Equivalent (2018-09-24). Food and Agriculture
535 Organization of the United Nations, Rome, Italy.
- 536 FAOSTAT, 2018c. Production/Livestock Primary (2018-09-24). Food and Agriculture Organization of the
537 United Nations, Rome, Italy.
- 538 FAOSTAT, 2018d. Commodity Balances/Livestock and Fish Primary Equivalent (2018-09-24). Food and
539 Agriculture Organization of the United Nations, Rome, Italy.
- 540 FAOSTAT, 2018e. Production/Crops (2018-09-24). Food and Agriculture Organization of the United Nations,
541 Rome, Italy.
- 542 FAOSTAT, 2018f. Commodity Balances/Crops Primary Equivalent (2018-09-24). Food and Agriculture
543 Organization of the United Nations, Rome, Italy.
- 544 FAOSTAT, 2018g. Food Supply - Crops Primary Equivalent (2018-09-24). Food and Agriculture Organization
545 of the United Nations, Rome, Italy.
- 546 Foley, J. a, Defries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C.,
547 Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E. a, Kucharik, C.J., Monfreda, C., Patz, J. a,
548 Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. *Science* (New
549 York, NY) 309, 570–4. doi:10.1126/science.1111772
- 550 Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D.,
551 O’Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C.,
552 Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a
553 cultivated planet. *Nature* 478, 337–42. doi:10.1038/nature10452
- 554 Foresight, 2011. The Future of Food and Farming, Final Project Report. The Government Office for Science,
555 London.
- 556 Fuchs, R., Alexander, P., Brown, C., Cossar, F., Henry, R., Rounsevell, M., 2019. US–China trade war imperils
557 Amazon rainforest. *Nature* 567, 451–454.
- 558 Gasco, L., Finke, M., Van Huis, A., 2018. Can diets containing insects promote animal health?
- 559 Gerber, P.J.P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013.
560 Tackling climate change through livestock – A global assessment of emissions and mitigation
561 opportunities. Food and Agriculture Organization of the United Nations (FAO), Food and Agriculture
562 Organization of the United Nations (FAO), Rom.
- 563 Godfray, H.C.J., Aveyard, P., Garnett, T., Hall, J.W., Key, T.J., Lorimer, J., Pierrehumbert, R.T., Scarborough,
564 P., Springmann, M., Jebb, S.A., 2018. Meat consumption, health, and the environment. *Science* 361,
565 eaam5324. doi:10.1126/science.aam5324
- 566 Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S.,
567 Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. *Science*
568 (New York, NY) 327, 812–8. doi:10.1126/science.1185383
- 569 Görg, C., Brand, U., Haberl, H., Hummel, D., Jahn, T., Liehr, S., 2017. Challenges for Social-Ecological
570 Transformations : Contributions from Social and Political Ecology 1–21. doi:10.3390/su9071045
- 571 Grard, B.J., Chenu, C., Manouchehri, N., Houot, S., Frascaria-lacoste, N., Aubry, C., 2018. Rooftop farming
572 on urban waste provides many ecosystem services.

- 573 Green, R., Milner, J., Dangour, A.D., Haines, A., Chalabi, Z., Markandya, A., Spadaro, J., Wilkinson, P., 2015.
574 The potential to reduce greenhouse gas emissions in the UK through healthy and realistic dietary
575 change. *Climatic Change* 129, 253–265. doi:10.1007/s10584-015-1329-y
- 576 Grooten, M., Almond, R.E.A. (Eds., 2018. *Living Planet Report - 2018: Aiming Higher*. WWF, Gland,
577 Switzerland.
- 578 Gustafsson, J., Cederberg, C., Sonesson, U., Emanuelsson, A., 2013. The methodology of the FAO study:
579 Global Food Losses and Food Waste—extent, causes and prevention”-FAO, 2011. SIK Institutet för
580 livsmedel och bioteknik.
- 581 Gustavsson, J., Cederberg, C., Sonesson, U., Otterdijk, R. van, Meybeck, A., 2011. Global food losses and
582 food waste— Extent, causes and prevention. Food and Agriculture Organization of the United Nations
583 (FAO), Rome, Italy.
- 584 Haines-Young, R., Potschin, M., 2010. The links between biodiversity, ecosystem services and human well-
585 being. *Ecosystem Ecology: a new synthesis* 1, 110–139.
- 586 Hayes, B.J., Lewin, H.A., Goddard, M.E., 2013. The future of livestock breeding: genomic selection for
587 efficiency, reduced emissions intensity, and adaptation. *Trends in Genetics* 29, 206–214.
588 doi:https://doi.org/10.1016/j.tig.2012.11.009
- 589 Henchion, M., McCarthy, M., O’Callaghan, J., 2016. Transforming Beef By-products into Valuable
590 ingredients: Which spell/recipe to Use? *Frontiers in nutrition* 3, 53.
- 591 Herrero, M., Thornton, P.K., Notenbaert, A.M., Wood, S., Msangi, S., Freeman, H.A., Bossio, D., Dixon, J.,
592 Peters, M., van de Steeg, J., Lynam, J., Rao, P.P., Macmillan, S., Gerard, B., McDermott, J., Seré, C.,
593 Rosegrant, M., 2010. Smart Investments in Sustainable Food Production: Revisiting Mixed Crop-
594 Livestock Systems. *Science* 327, 822 LP – 825.
- 595 Jaggard, K.W.W., Qi, A., Ober, E.S.S., 2010. Possible changes to arable crop yields by 2050. *Philosophical*
596 *Transactions of the Royal Society B: Biological Sciences* 365, 2835–2851. doi:10.1098/rstb.2010.0153
- 597 Jayathilakan, K., Sultana, K., Radhakrishna, K., Bawa, A.S., 2012. Utilization of byproducts and waste
598 materials from meat, poultry and fish processing industries: A review. *Journal of Food Science and*
599 *Technology* 49, 278–293. doi:10.1007/s13197-011-0290-7
- 600 Jouanjean, M., 2013. *Foster Agricultural Trade and Market Integration in Developing Countries: an*
601 *Analytical Review*. London: Overseas Development Institute pp1-26.
- 602 Kates, R.W., Travis, W.R., Wilbanks, T.J., 2012. Transformational adaptation when incremental adaptations
603 to climate change are insufficient. *Proceedings of the National Academy of Sciences* 109, 7156–7161.
604 doi:10.1073/pnas.1115521109
- 605 Khan, S.H., 2018. Recent advances in role of insects as alternative protein source in poultry nutrition.
606 *Journal of Applied Animal Research* 46, 1144–1157. doi:10.1080/09712119.2018.1474743
- 607 Kimenju, S.C., De Groote, H., 2010. Economic analysis of alternative maize storage technologies in Kenya,
608 in: *Joint 3rd African Association of Agricultural Economists (AAAE) and 48th Agricultural Economists*
609 *Association of South Africa (AEASA) Conference*, Cape Town, South Africa, September. pp. 19–23.
- 610 Lambin, E.F., Meyfroidt, P., 2011. Global land use change , economic globalization , and the looming land
611 scarcity. *Proceedings of the National Academy of Sciences of the United States of America* 108, 3465–
612 3472. doi:10.1073/pnas.1100480108
- 613 Licker, R., Johnston, M., Foley, J.A., Barford, C., Kucharik, C.J., Monfreda, C., Ramankutty, N., 2010. *Mind*

- 614 the gap: how do climate and agricultural management explain the ‘yield gap’ of croplands around the
615 world? *Global ecology and biogeography* 19, 769–782.
- 616 Machovina, B., Feeley, K.J., Ripple, W.J., 2015. Biodiversity conservation: The key is reducing meat
617 consumption. *Science of the Total Environment* 536, 419–431. doi:10.1016/j.scitotenv.2015.07.022
- 618 Makkar, H.P.S., Ankers, P., 2014. Towards sustainable animal diets: a survey-based study. *Animal Feed
619 Science and Technology* 198, 309–322.
- 620 Mapfumo, P., Onyango, M., Honkponou, S.K., Mzouri, E.H. El, Githeko, A., Rabeharisoa, L., Obando, J.,
621 Omolo, N., Majule, A., Denton, F., Ayers, J., Agrawal, A., 2017. Pathways to transformational change in
622 the face of climate impacts: an analytical framework. *Climate and Development* 9, 439–451.
623 doi:10.1080/17565529.2015.1040365
- 624 Marti, D., Johnson, R.J., Mathews, K.H., 2011. Where’s the (not) Meat?: Byproducts from Beef and Pork
625 Production. US Department of Agriculture.
- 626 Miech, P., Berggren, Å., Lindberg, J.E., Chhay, T., Khieu, B., Jansson, A., 2016. Growth and survival of reared
627 Cambodian field crickets (*Teleogryllus testaceus*) fed weeds, agricultural and food industry by-
628 products. *Journal of Insects as Food and Feed* 2, 285–292.
- 629 MINTEL, 2017. Meat-free Foods - UK - May 2017.
- 630 MINTEL, 2014. Meat-Free and Free-From Foods-UK. London.
- 631 Montoya, M., Reis, A.L., Dixon, L.K., 2018. African swine fever : A re-emerging viral disease threatening the
632 global pig industry. *The Veterinary Journal* 233, 41–48. doi:10.1016/j.tvjl.2017.12.025
- 633 Moritz, M.S.M., Verbruggen, S.E.L., Post, M.J., 2015. Alternatives for large-scale production of cultured
634 beef: A review. *Journal of Integrative Agriculture* 14, 208–216. doi:10.1016/S2095-3119(14)60889-3
- 635 Othman, N., Mohamad, M., Latip, R.A., Ariffin, M.H., 2018. Urban farming activity towards sustainable
636 wellbeing of urban dwellers. *Earth and Environmental Science* 117. doi:10.1088/1755-
637 1315/117/1/012007
- 638 Pellegrino, E., Bedini, S., Nuti, M., Ercoli, L., 2018. Impact of genetically engineered maize on agronomic,
639 environmental and toxicological traits: A meta-analysis of 21 years of field data. *Scientific Reports* 8,
640 1–12. doi:10.1038/s41598-018-21284-2
- 641 Petersen, B., Niemann, H., Thomas, C., Fuchs, W., 2018. Efficient inhibition of African swine fever virus
642 replication by CRISPR / Cas9 targeting of the viral p30 gene (CP204L) 1–7. doi:10.1038/s41598-018-
643 19626-1
- 644 Phalan, B., Green, R., Balmford, A., 2014. Closing yield gaps: perils and possibilities for biodiversity
645 conservation. *Phil Trans R Soc B* 369, 20120285.
- 646 Phalan, B., Green, R.E., Dicks, L. V., Dotta, G., Feniuk, C., Lamb, A., Strassburg, B.B.N., Williams, D.R.,
647 Ermgassen, E.K.H.J. zu, Balmford, A., 2016. How can higher-yield farming help to spare nature?
648 *Science* 351, 450–451. doi:10.1126/science.aad0055
- 649 Phalan, B., Onial, M., Balmford, A., Green, R.E., 2011. Reconciling Food Production and Biodiversity
650 Conservation: Land Sharing and Land Sparing Compared. *Science* 333, 1289–1291.
651 doi:10.1126/science.1208742
- 652 Plazzotta, S., Manzocco, L., Nicoli, M.C., 2017. Fruit and vegetable waste management and the challenge of
653 fresh-cut salad. *Trends in Food Science & Technology* 63, 51–59.
654 doi:https://doi.org/10.1016/j.tifs.2017.02.013

- 655 Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers.
656 *Science* 360, 987–992.
- 657 Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., Bodirsky, B.L., Dietrich, J.P.,
658 Doelmann, J.C., Gusti, M., Hasegawa, T., Kyle, P., Obersteiner, M., Tabeau, A., Takahashi, K., Valin, H.,
659 Waldhoff, S., Weindl, I., Wise, M., Kriegler, E., Lotze-Campen, H., Fricko, O., Riahi, K., van Vuuren, D.P.,
660 2017. Land-use futures in the shared socio-economic pathways. *Global Environmental Change* 42,
661 331–345. doi:<http://dx.doi.org/10.1016/j.gloenvcha.2016.10.002>
- 662 Premalatha, M., Abbasi, Tasneem, Abbasi, Tabassum, Abbasi, S.A., 2011. Energy-efficient food production
663 to reduce global warming and ecodegradation: The use of edible insects. *Renewable and Sustainable*
664 *Energy Reviews* 15, 4357–4360. doi:10.1016/j.rser.2011.07.115
- 665 Ramankutty, N., Foley, J.A., 1999. Estimating historical changes in global land cover : Croplands historical
666 have converted areas. *Global Biogeochemical Cycles* 13, 997–1027. doi:10.1029/1999GB900046
- 667 Ray, D.K., Foley, J.A., 2013. Increasing global crop harvest frequency: recent trends and future directions.
668 *Environmental Research Letters* 8, 044041. doi:10.1088/1748-9326/8/4/044041
- 669 Reuter, H., Middelhoff, U., Graef, F., Verhoeven, R., Batz, T., Weis, M., Schmidt, G., Schröder, W., Breckling,
670 B., 2010. Information system for monitoring environmental impacts of genetically modified
671 organisms. *Environmental Science and Pollution Research* 17, 1479–1490. doi:10.1007/s11356-010-
672 0334-y
- 673 Rickards, L., Howden, S.M., 2012. Transformational adaptation: agriculture and climate change. *Crop and*
674 *Pasture Science* 63, 240. doi:10.1071/CP11172
- 675 Ricroch, A., Clairand, P., Harwood, W., 2017. Use of CRISPR systems in plant genome editing: toward new
676 opportunities in agriculture. *Emerging Topics in Life Sciences* 1, 169–182. doi:10.1042/etls20170085
- 677 Rööös, E., Bajželj, B., Smith, P., Patel, M., Little, D., Garnett, T., 2017. Greedy or needy? Land use and climate
678 impacts of food in 2050 under different livestock futures. *Global Environmental Change* 47, 1–12.
679 doi:10.1016/j.gloenvcha.2017.09.001
- 680 Rööös, E., Patel, M., Spångberg, J., Carlsson, G., Rydhmer, L., 2016. Limiting livestock production to pasture
681 and by-products in a search for sustainable diets. *Food Policy* 58, 1–13.
682 doi:10.1016/j.foodpol.2015.10.008
- 683 Salemdeeb, R., zu Ermgassen, E.K.H.J., Kim, M.H., Balmford, A., Al-Tabbaa, A., 2017. Environmental and
684 health impacts of using food waste as animal feed: a comparative analysis of food waste management
685 options. *Journal of Cleaner Production* 140, 871–880.
686 doi:<https://doi.org/10.1016/j.jclepro.2016.05.049>
- 687 Sánchez-Muros, M.-J., Barroso, F.G., Manzano-Agugliaro, F., 2014. Insect meal as renewable source of food
688 for animal feeding: a review. *Journal of Cleaner Production* 65, 16–27.
689 doi:<https://doi.org/10.1016/j.jclepro.2013.11.068>
- 690 Schmidhuber, J., Tubiello, F.N., 2007. Global food security under climate change. *Proceedings of the*
691 *National Academy of Sciences* 104, 19703–19708. doi:10.1073/pnas.0701976104
- 692 Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E., Tubiello, F., Smith P.M.
693 Bustamante, H. Ahammad, H. Clark, H. Dong, E.A. Elsiddig, H. Haberl, R. Harper, J. House, M. Jafari,
694 O.M., C. Mbow, N.H. Ravindranath, C.W. Rice, C. Robledo Abad, A. Romanovskaya, F. Sperling, and
695 F.T., 2014. Agriculture, Forestry and Other Land Use (AFOLU), in: [Edenhofer, O., R., Pichs-Madruga, Y.
696 Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann,
697 J., Savolainen, S. Schlömer, C. von Stechow, T.Z. and J.C.M. (Eds.), *Climate Change 2014: Mitigation of*

- 698 Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the
699 Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and NY,
700 USA, pp. 811–922.
- 701 Specht, K., Siebert, R., Hartmann, I., Freisinger, U.B., Sawicka, M., Werner, A., Thomaier, S., Henckel, D.,
702 Walk, H., Dierich, A., 2014. Urban agriculture of the future: an overview of sustainability aspects of
703 food production in and on buildings. *Agriculture and Human Values* 31, 33–51. doi:10.1007/s10460-
704 013-9448-4
- 705 Springmann, M., Clark, M., Mason-D’Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., De Vries, W.,
706 Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R.,
707 Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockström, J., Willett, W.,
708 2018. Options for keeping the food system within environmental limits. *Nature*. doi:10.1038/s41586-
709 018-0594-0
- 710 Steinfeld, H., Gerber, P., Wassenaar, T.D., Castel, V., Rosales, M., Rosales, M., de Haan, C., 2006. Livestock’s
711 long shadow: environmental issues and options. Food & Agriculture Org.
- 712 Steinfeld, H., 2006. Livestock’s Long Shadow.
- 713 Stern, N., Peters, S., Bakhshi, V., Bowen, A., Cameron, C., Catovsky, S., Crane, D., Cruickshank, S., Dietz, S.,
714 Edmonson, N., 2006. Stern Review: The economics of climate change. HM treasury London.
- 715 Stoate, C., Báldi, A., Beja, P., Boatman, N.D., Herzon, I., van Doorn, A., de Snoo, G.R., Rakosy, L., Ramwell,
716 C., 2009. Ecological impacts of early 21st century agricultural change in Europe – A review. *Journal of*
717 *Environmental Management* 91, 22–46. doi:10.1016/j.jenvman.2009.07.005
- 718 Su, B., Martens, P., Enders-Slegers, M.-J., 2018. A neglected predictor of environmental damage: The
719 ecological paw print and carbon emissions of food consumption by companion dogs and cats in China.
720 *Journal of Cleaner Production* 194, 1–11. doi:https://doi.org/10.1016/j.jclepro.2018.05.113
- 721 Swain, M., Blomqvist, L., McNamara, J., Ripple, W.J., 2018. Reducing the environmental impact of global
722 diets. *Science of the Total Environment* 610, 1207–1209.
- 723 Syed, M., 2015. *Black Box Thinking: The Surprising Truth About Success*. John Murray.
- 724 Tester, M., Langridge, P., 2010. Breeding technologies to increase crop production in a changing world.
725 *Science* 327, 818–822.
- 726 Thomaier, S., Specht, K., Henckel, D., Dierich, A., Siebert, R., Freisinger, U.B., Sawicka, M., 2014. Farming in
727 and on urban buildings : Present practice and specific novelties of Zero-Acreage Farming (ZFarming)
728 30. doi:10.1017/S1742170514000143
- 729 Thornton, P.K., 2010. Livestock production: recent trends, future prospects. *Philosophical transactions of*
730 *the Royal Society of London Series B, Biological sciences* 365, 2853–2867. doi:10.1098/rstb.2010.0134
- 731 Tilman, D., Clark, M., 2014. Global diets link environmental sustainability and human health. *Nature* 515,
732 518–522. doi:10.1038/nature13959
- 733 UN, 2017. *World Population Prospects: The 2017 Revision, Key Findings and Advance Tables (No. Working*
734 *Paper No. ESA/P/WP/248)*. United Nations, Department of Economic and Social Affairs, Population
735 Division.
- 736 van Broekhoven, S., Oonincx, D.G. a. B., van Huis, A., van Loon, J.J. a., 2015. Growth performance and feed
737 conversion efficiency of three edible mealworm species (Coleoptera: Tenebrionidae) on diets
738 composed of organic by-products. *Journal of Insect Physiology* 73, 1–10.

- 739 doi:10.1016/j.jinsphys.2014.12.005
- 740 Van Eenennaam, A.L., 2017. Genetic modification of food animals. *Current Opinion in Biotechnology* 44,
741 27–34. doi:10.1016/j.copbio.2016.10.007
- 742 van Huis, A., 2013. Potential of Insects as Food and Feed in Assuring Food Security. *Annual Review of*
743 *Entomology* 58, 563–83. doi:10.1146/annurev-ento-120811-153704
- 744 van Huis, A., Oonincx, D.G.A.B., 2017. The environmental sustainability of insects as food and feed. A
745 review. *Agronomy for Sustainable Development* 37, 43. doi:10.1007/s13593-017-0452-8
- 746 Van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis
747 with local to global relevance-A review. *Field Crops Research* 143, 4–17. doi:10.1016/j.fcr.2012.09.009
- 748 Vermeulen, S.J., Dinesh, D., Howden, S.M., Cramer, L., Thornton, P.K., 2018. Transformation in Practice: A
749 Review of Empirical Cases of Transformational Adaptation in Agriculture Under Climate Change.
750 *Frontiers in Sustainable Food Systems* 2. doi:10.3389/fsufs.2018.00065
- 751 Wellesley, L., Happer, C., Froggatt, A., 2015. Changing climate, changing diets: pathways to lower meat
752 consumption. Royal Institute of International Affairs, Chatham House.
- 753 West, P.C., Gerber, J.S., Engstrom, P.M., Mueller, N.D., Brauman, K. a., Carlson, K.M., Cassidy, E.S.,
754 Johnston, M., MacDonald, G.K., Ray, D.K., Siebert, S., 2014. Leverage points for improving global food
755 security and the environment. *Science* 345, 325–328. doi:10.1126/science.1246067
- 756 West, P.C., Gibbs, H.K., Monfreda, C., Wagner, J., Barford, C.C., Carpenter, S.R., Foley, J.A., 2010. Trading
757 carbon for food: Global comparison of carbon stocks vs. crop yields on agricultural land. *Proceedings*
758 *of the National Academy of Sciences* 107, 19645–19648. doi:10.1073/pnas.1011078107
- 759 White, M., 2017. Vast vertical farms growing much, much more with less [WWW Document]. *AgInnovators*.
760 URL <https://www.aginnovators.org.au/news/vast-vertical-farms-growing-far-far-more-less> (accessed
761 9.17.18).
- 762 Wielemaker, R., Oenema, O., Zeeman, G., Weijma, J., 2019. Science of the Total Environment Fertile cities :
763 Nutrient management practices in urban agriculture. *Science of the Total Environment* 668, 1277–
764 1288. doi:10.1016/j.scitotenv.2019.02.424
- 765 Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D.,
766 Declerck, F., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Reddy, K.S.,
767 Narain, S., Nishtar, S., Murray, C.J.L., 2019. The Lancet Commissions Food in the Anthropocene : the
768 EAT – Lancet Commission on healthy diets from sustainable food systems. *Lancet*. doi:10.1016/S0140-
769 6736(18)31788-4
- 770 Wirsenius, S., Azar, C., Berndes, G., 2010. How much land is needed for global food production under
771 scenarios of dietary changes and livestock productivity increases in 2030? *Agricultural Systems* 103,
772 621–638. doi:10.1016/j.agsy.2010.07.005
- 773 Zorya, S., Morgan, N., Diaz Rios, L., Hodges, R., Bennett, B., Stathers, T., Mwebaze, P., Lamb, J., 2011.
774 Missing food: the case of postharvest grain losses in sub-Saharan Africa.
- 775 zu Ermgassen, E.K.H.J., Phalan, B., Green, R.E., Balmford, A., 2016. Reducing the land use of EU pork
776 production: where there's swill, there's a way. *Food Policy* 58, 35–48.
777 doi:<https://doi.org/10.1016/j.foodpol.2015.11.001>

778