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2 **Protein futures for Western Europe: potential land use and climate impacts in**
3 **2050**

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23 **Abstract**

24 Multiple production and demand side measures are needed to improve food system
25 sustainability. This study quantified the theoretical minimum agricultural land requirements to
26 supply Western Europe with food in 2050 from its own land base, together with GHG
27 emissions arising. Assuming that crop yield gaps in agriculture are closed, livestock
28 production efficiencies increased and waste at all stages reduced, a range of food consumption
29 scenarios were modelled each based on different ‘protein futures.’ The scenarios were as
30 follows: intensive and efficient livestock production using today’s species mix; intensive
31 efficient poultry-dairy production; intensive efficient aquaculture-dairy; artificial meat and
32 dairy; livestock on ‘ecological leftovers’ (livestock reared only on land unsuited to cropping,
33 agricultural residues and food waste, with consumption capped at that level of availability);
34 and a ‘plant based eating’ scenario. For each scenario ‘projected diet’ and ‘healthy diet’
35 variants were modelled. Finally, we quantified the theoretical maximum carbon sequestration
36 potential from afforestation of spared agricultural land. Results indicate that land use could be
37 cut by 14 to 86% and GHG emissions reduced by up to approximately 90%. The yearly
38 carbon storage potential arising from spared agricultural land ranged from 90-700 Mt CO₂ in
39 2050. The artificial meat and plant based scenarios achieved the greatest land use and GHG
40 reductions and the greatest carbon sequestration potential. The ‘ecological leftover’ scenario
41 required the least cropland as compared with the other meat-containing scenarios, but all
42 available pasture was used and GHG emissions were higher if meat consumption wasn’t
43 capped at healthy levels.

44 **Keywords:** Land use, climate, food, dietary change, mitigation, protein

45 **Word count excluding references:** 6,446 + two figures (2 x 300 words) = 7,046
46 words

48 **1. Introduction**

49 The current food system is unsustainable, pushing many environmental indicators beyond safe
50 planetary boundaries (Steffen et al. 2015). To date, growing food demand has been partially
51 met by expanding the agricultural land area (Smith et al., 2010), but the conversion of natural
52 land has many adverse environmental consequences (Smith, 2013), including biodiversity and
53 carbon stock losses. With the global population set to reach 9-10 billion by 2050 (UN 2012)
54 achieving food security while staying within environmental limits poses major challenges,
55 particularly since demand for livestock products in developing countries is growing rapidly
56 (Godfray et al. 2010). In addition to their environmental impacts (Steinfeld et al. 2006), high
57 meat intakes are associated with the growing prevalence of non-communicable diseases (Pan
58 et al. 2012; Sinha et al. 2009).

59 The European context is the focus of this study. While the Western European population is
60 expected to increase very little - from 440 million in 2009, to 460 million in 2050 (UN 2012)
61 and demand for animal products unlikely to increase significantly (Alexandratos and
62 Bruinsma 2012), European diets are on average high in animal products. Annual per capita
63 meat and milk supply is approximately 80 kg and 250 kg respectively compared to the global
64 average of 42 and 90 kg (FAO 2015b). A number of strategies have been proposed to increase
65 food system sustainability, which variously considers either production- and/or consumption-
66 side changes.

67
68 As regards production, key approaches proposed in the literature include: higher crop yields
69 and increased livestock efficiencies to obtain more food per area of land or per input or per
70 environmental damage; and technical greenhouse gas (GHG) mitigation options including
71 improvements in land, nutrient and water management (Burney et al. 2010; Foley et al. 2011;
72 Mueller et al. 2012; Valin et al. 2013).

73
74 Consumption side approaches include reductions of food losses (to avoid unnecessary food
75 production) (Smith et al. 2013) and dietary changes, particularly towards reductions in meat
76 intakes (Bajželj et al. 2014; Bryngelsson et al. 2016; Smith et al. 2013; Tilman and Clark
77 2014). Numerous studies have modelled alternative dietary scenarios where the meat content
78 is varied and compensatory foods factored in, to investigate the environmental consequences,
79 and to explore the relationship between environmental and nutritional health objectives (Röös
80 et al. 2015; Saxe et al. 2013; Westhoek et al. 2014). A review by Hallström et al. (2015) finds
81 that compared with the dietary status quo, emissions are 25-55% lower in vegan diets, 20-
82 35% in vegetarian diets and 0-35% lower in diets that are less meat intensive to varying
83 degrees.

84
85 Previous studies indicate that *both* production and consumption side strategies are needed to
86 deliver a sustainable food future (Foley et al. 2011; Tilman and Clark 2014). For example
87 Bajželj et al. (2014) calculate that productivity increases to close yield gaps will not halt
88 agricultural expansion, nor stabilize or decrease food-related GHG emissions (Bajželj et al.
89 2014). Instead, a combined approach of yield increases, food waste reduction and reductions

90 in animal production and consumption to meet ‘healthy diet’ recommendations could halve
91 current agricultural emissions compared with a scenario in which only yields gaps were
92 closed and waste reduced, and would lower emissions by two thirds compared with business
93 as usual (BAU) trajectories. Bajželj et al. (2014) only assumed minor increases in livestock
94 production efficiencies however; potentially more can be achieved. Other studies have
95 modelled various levels of such livestock efficiency increases (Bennetzen et al. 2016; Havlík
96 et al. 2014; Hedenus et al. 2014; Wirsenius et al. 2010) but only considered general reductions
97 in meat and dairy intakes. More specific dietary shifts have been proposed. One option is to
98 replace ruminant meat with meat from monogastric animals to decrease methane emissions
99 and increase feed conversion ratios (Hoolohan et al. 2013). Substituting meat with farmed
100 aquatic products is another. Artificial, or in-vitro meat, and the development of novel proteins
101 such as insects, algae and duckweed (Post 2012; van der Spiegel et al. 2013) are attracting
102 strong interest and represent a third possibility. Finally, plant proteins such as pulses and
103 cereals can substitute for meat and dairy in the diet. Which of these strategies that are
104 considered relevant, desirable or plausible depend on ones values and assumptions about the
105 nature of the food system problem (Garnett 2015). This said, in order to arrive at a more
106 informed understanding of future options, it is necessary to investigate what the
107 environmental implications of these possible futures might be.

108

109 Hence, the purpose of this study was calculate the land use and GHG emissions arising from a
110 set of scenarios for Western Europe in 2050 which include both production side mitigation
111 options and different ways in which the current dietary mix of animal products could be
112 varied or substituted with other protein foods of non-animal origin. The work by Bajželj et al.
113 (2014) is extended such that not only are yield gaps assumed to be closed, waste reduced and
114 diets changed, but livestock efficiencies are also increased to correspond to current levels of
115 highly intensive production in North-western Europe. Hence, this study quantifies the
116 theoretical minimum agricultural land needed and GHG emissions generated from supplying
117 the projected population of Western Europe with food produced exclusively in this region in
118 2050 under a range of different dietary changes, here called ‘protein futures’.

119

120

121 **2. Method**

122 **2.1 Overview of calculation of land use and GHG emissions**

123 A model was built in a spreadsheet to calculate the quantity of agricultural land needed and
124 GHGs generated to supply the projected 2050 Western European population with food for
125 each of the scenarios (section 2.3). We define Western Europe as stretching from and
126 including the Nordic countries in the north to Spain in the south, and from UK in the west up
127 to but excluding Poland in the east. This area corresponds to the regions Western Europe,
128 Northern Europe and Southern Europe as classified by the United Nations (UN 2015a). We
129 recognize that this region currently both imports and exports foods, including animal products
130 and animal feeds, and that future sustainable and resilient global food systems are very likely
131 to benefit from trade. However in this study we assume that all food and feed is produced and
132 consumed within the region. As such, we estimate the potential for supplying the Western
133 European population with food from its own land base. This simplifies the undertaking and
134 avoids introducing further uncertainty as regards assumptions about trade in 2050. This
135 ‘closed’ approach is also relevant in relation to the EU’s concept of ‘community preference’
136 through which member states are encouraged to give preference to consumption of food
137 produced within the region (EC 2015).

138
139 In all scenarios (except the baseline BAU scenario) it is assumed that waste is reduced by
140 50% and, in the case of crop production, the yield gap is closed. The 50% cut in food waste is
141 in line with the Sustainable Development Goal 12.3 for 2030 (UN 2015b). Such reduction
142 could potentially be achieved by regulatory and fiscal incentives and raising awareness.

143
144 Yield gaps are assumed to be relatively small for this region. They range from no gap for
145 sugar crops, to 40% for some grains and pulses (Bajželj et al. 2014). Approaches to closing
146 the yield gaps likely include faster knowledge and technology transfers, dissemination of and
147 incentives for uptake of best practices, support and investment and improved forecasting. For
148 each scenario where land is released through more efficient production and/or dietary change
149 the carbon sequestration potential was calculated (section 2.5).

150
151 The starting point in the modelling was the amount of different food products in the diet
152 (section 2.4). The agricultural land area needed to produce the commodities needed for the
153 diet was then calculated as follows (and detailed in Online Resource S3). First, the caloric
154 values of the 18 food groups included in the daily per capita diet (fruits, vegetables, wheat,
155 rice, beef, pork, poultry, dairy, aquatic products etc.; Table S2 and S3) were translated into
156 daily quantities (in kg) food consumed using FAO data (FAO 2011). Second, these quantities
157 were increased to take account of losses and waste along the whole supply chain using current
158 estimated waste and loss factors for Europe (FAO 2011) but here reduced by 50% to account
159 for assumed action to reduce waste. Third, the quantity of agricultural commodities needed to
160 produce these food products was calculated based on the fraction of plant crops is actually
161 consumed by humans (FAO 2011) e.g. for 1 kg of vegetable oil to be supplied, 2.9 kg of
162 rapeseed is needed. For livestock products, land use for feed production was calculated by
163 first translating the amount of an animal product (e.g. kg of milk, meat etc.) into the number

164 of animals needed to produce this amount. Forage, feed grain and protein feed requirements
165 for each animal species were then calculated based on Swedish feeding recommendations
166 (Online Resource S4); taken to represent high feed conversion efficiency systems. By-
167 products from the production of plant-based food for human consumption, mainly cereal bran
168 and oil cake, were used as feed and livestock diets adjusted accordingly. All food and feed
169 crops were assumed to be produced in Western Europe including protein feed although the
170 latter is currently imported into the region to a large extent (de Ruiter et al. 2016). Finally, the
171 land area needed to produce plant foods for human consumption and livestock feeds were
172 calculated for each crop type, assuming closure of yield gaps, from Bajželj et al. (2014).

173
174 Greenhouse gas emissions using Global Warming Potential (GWP) over 100 years were
175 calculated; characterization factors 25 for methane and 298 for nitrous oxide were used
176 (Forster et al. 2007). Emissions from fertilizers, from manure and from rice cultivation were
177 calculated following Bajželj et al. (2014); emissions in 2009 for each emission category were
178 scaled up linearly (i.e. emission factors were kept constant). That is, the nitrous oxide
179 emissions from fertilizer use were scaled based on the amount of fertilizer used, manure
180 emissions based on animal products produced and methane emissions from rice based on land
181 area used for rice cultivation (FAO 2015b). Enteric emissions needed to be calculated
182 differently to account for increased livestock efficiencies, since these increases were not
183 factored into Bajželj et al. (2014). Emission factors per animal (high/low-yielding dairy
184 109/98 kg; suckler cow 62 kg; young cattle 44 kg, pig 1.2 kg CH₄ per animal per year; Online
185 Resource S5) were multiplied by the number of animals needed in each scenario. We assumed
186 a technical potential for GHG reduction of 20% for all these emission sources (based on
187 Smith et al. (2008)). Emissions from energy use, including the production of mineral
188 fertilizers, are excluded as these are accounted for in the energy end-use sector (Smith et al.
189 2007).

190 **2.2 Strategies for future protein production**

191 How one envisions the role of livestock in future sustainable food systems depends on several
192 value-based factors e.g. assumptions about demand and the malleability of human
193 preferences; the role, potential and acceptability of technological innovations; the extent to
194 which radical transformations in the workings of the global economy can be achieved; and on
195 different underlying visions of what constitutes a sustainable and desirable food future.

196
197 Garnett (2015) describes four different 'livestock futures' based on these factors. In the first
198 future called 'Calibrated carnivory', demand for animal products is envisaged to continue
199 growing in the absence of political will. This demand is met through a universal shift to
200 highly intensive livestock systems producing meat with low GHG emissions per unit of
201 product. 'Architected flesh' similarly accepts the inevitability of growing demand, but
202 assumes rapid and dramatic technological developments in the in-vitro meat and novel
203 proteins sectors which are capable of meeting this demand. 'Livestock on leftovers' represents
204 a radical departure from BAU demand assumptions as well as from current production-side
205 approaches to addressing environmental impacts. Demand in this future is viewed as
206 malleable and there is a shift in production emphasis away from maximizing unit efficiencies.

207 Instead, livestock are produced on ‘ecological leftovers’ (Garnett 2009) – on land unsuited to
208 crop production and on food waste and agricultural residues. Finally ‘Fruits of the earth’
209 envisages global public and policy acceptance of the need to radically alter diets. Meat and
210 dairy consumption declines dramatically and diets are almost exclusively plant based.

211 **2.3 Scenarios modelled in this study**

212 This paper builds upon Garnett’s (2015) livestock future in developing six different
213 hypothetical ‘protein futures’ scenarios for Western Europe in 2050.

214

215 In the first of these protein futures, called the Intensive Livestock scenario and corresponding
216 to Garnett’s (2015) ‘Calibrated carnivory’ future, demand trajectories for all types of animal
217 products continue in line with FAO projections (Alexandratos and Bruinsma 2012). Reduced
218 GHG impacts per kg of meat, egg and milk produced are achieved through breeding, feeding
219 and housing developments. All animals are reared in confined systems and fed on arable feed-
220 crops.

221

222 The Dairy and Poultry scenario is a variant on the first. BAU demand trajectories are taken as
223 the norm but there is an increasing global preference for poultry meat given their high feed
224 conversion efficiency, a perception that poultry meat is healthy and its versatility – a quality
225 that lends itself well to convenience foods. Therefore, by 2050 most meat consumed is poultry
226 based. Ruminants (intensively reared) are still used to supply dairy products and culled cows
227 and calves enter the meat chain, meaning that a limited quantity of ruminant meat continues to
228 be consumed. In Intensive Livestock and in Dairy and Poultry, animal production efficiencies
229 are assumed to increase to a level corresponding to the highly intensive systems of North-
230 western Europe, modelled here as current best practice systems in Sweden (see Online
231 Resource S4).

232

233 The Dairy and Aquaculture scenario is another variant on Intensive Livestock scenario. It too
234 assumes that demand for animal protein continues apace but increasing health consciousness,
235 combined with the high feed conversion efficiencies achieved by intensive aquaculture
236 systems mean that by 2050 almost all animal flesh consumed comes from aquatic products.
237 As in Dairy and Poultry, intensive dairying still continues. It is assumed that 80% of
238 aquaculture products are low trophic-level finfish produced in high yielding closed
239 recirculating systems (calculations are based on Nile tilapia) (Little et al. 2008). 20% is
240 supplied by mussels, oysters and other filter feeding, extractive bivalve species which do not
241 require feed inputs.

242

243 A fourth scenario, Artificial Meat and Dairy corresponds to Garnett’s (2015) ‘Architected
244 flesh.’ The assumption here is that technological breakthroughs in production have been
245 matched by consumer acceptance of in vitro meat. Both meat and dairy now can be produced
246 by this means. Other novel proteins produced from algae and insects (reared on food waste
247 and agricultural by-products) add to the mix. Protein production in this scenario is essentially
248 landless.

249

250 The Plant Based Eating scenario, corresponding with Garnett's (2015) 'Fruits of the earth', is
251 animal free (except a small amount of seafood from wild stocks). Concerted policy actions to
252 discourage animal product consumption, combined with growing public concerns for the
253 environment, and with technological developments in the production of plant based novel
254 proteins, have created a situation where diets are now universally mostly vegan. Grazing land
255 is released for other purposes and cropland is used to produce foods for direct human
256 consumption.

257
258 The final, sixth scenario is based on the 'Livestock on Leftovers' future in Garnett (2009) and
259 is here called Ecological Leftovers. Here, a radical shift in policy focus and public attitudes to
260 meat is assumed. The sustainability focus now is on achieving resource 'effectiveness' rather
261 than efficiency (Garnett et al. 2015); an approach that aligns with current agro-ecological
262 thinking (Francis et al. 2003). Rather than seeking to maximize livestock unit efficiencies by
263 feeding animals crops grown on arable land, the role of farm animals in utilizing pasture land
264 unsuited to crop production and in consuming agri-food by-products inedible to humans is
265 emphasized. Hence in this scenario, livestock production is limited to levels achievable from
266 using available biomass from pastures, food waste and crop and food by-products (Online
267 Resource S6).

268
269 These six protein futures scenarios are compared against two counter scenarios. First is a
270 BAU baseline scenario in which consumption trends follow FAO projections (Alexandratos
271 and Bruinsma 2012); calorie intakes increase as does livestock's share of overall
272 consumption. Yield improvements continue in line with current trends and waste is generated
273 at current levels. Second is an 'improved baseline' scenario, here called Yields and Waste, in
274 which the crop yield gaps are closed and waste reduced by 50%, but livestock production
275 efficiencies are as in BAU unlike in the six protein futures discussed above. Data for the BAU
276 and Yields and Waste scenarios were taken from Bajželj et al. (2014). All scenarios are
277 summarized in Table S1.

278 **2.4 Projected and healthy diets**

279 The caloric intake from animal products in the Intensive Livestock scenario, which includes
280 all types of livestock products, was used as a baseline and all other scenarios were set to
281 supply equivalent calories from animal products (poultry and dairy in Dairy and Poultry,
282 aquatic products and dairy in Dairy and Aquaculture, Artificial meat and dairy in Artificial
283 Meat and Dairy); from plant-based protein (pulses and cereals in Plant Based Eating); or from
284 a combination of animal and plant protein (Ecological Leftovers limits livestock production to
285 what can be produced from pastures, by-products and food waste and therefore pulses and
286 cereals are added to the diet to reach the same caloric values and approximately the same
287 content and mix of essential amino acids). In all scenarios 11 grams per person per day of
288 wild seafood was included based on the current yearly catch in European waters of five
289 million tonnes (NEF 2012). The complete diets are presented in Tables S2 and S3.

290
291 Each scenario, apart from BAU, is modelled with two dietary variants; a 'Projected Diet' and
292 a 'Healthy diet'. In the Projected Diet variant, dietary patterns are assumed to follow current

293 trends (Alexandratos and Bruinsma 2012). That is, vegetable oil and sugar intakes are in
294 excess of healthy eating recommendations (Bajželj et al. 2014) as are animal protein intakes.
295 For the Dairy and Aquaculture, Artificial Meat and Dairy and Plant Based Eating scenario
296 protein intakes increase to align with terrestrial meat based equivalents. The Projected Diet of
297 the Ecological Leftover scenario is however different as in this case the amount of animal
298 products in the diet is determined by the amount of animal products that can be produced on
299 pastures and from agri-food by-products and food waste, divided upon the total population.

300

301 The ‘Healthy Diet’ assumes a transition to diets lower in overall calories, vegetable oils, sugar
302 and animal products, and higher in cereals, fruit and vegetables, in line with healthy eating
303 recommendations (Bajželj et al. 2014). The Online Resource S2 provides further details.

304 **2.5 Use of land spared – carbon sequestration**

305 The land spared in the different scenarios could be used for several purposes. It could be used
306 to sequester carbon through forest plantation or by producing biofuels to displace fossil fuels
307 (Albanito et al. 2015). Alternatively it could be used to produce more food (or biomass for
308 non-food purposes) for export, potentially sparing agricultural land or reducing deforestation
309 pressures overseas. It could also be used to allow for preservation of extensive agricultural
310 production systems with high biodiversity benefits (section 3.4). In this study, the first of
311 these options only was quantified.

312

313 The carbon sequestration potential was calculated by first overlaying cropland and pasture
314 data (Ramankutty et al. 2008) with data on Global Ecological Zones (FAO 2015a) to estimate
315 the amount of pasture and cropland in different climate zones. Data from the IPCC guidelines
316 (IPCC 2006) were used to calculate how much carbon that would be captured in above-and
317 below-ground biomass by reforestation. The cumulative emissions up until 2050 from a linear
318 reforestation of spared land between 2015 and 2050 was annualized over the same period and
319 compared with the direct emissions from agriculture in the year 2050. It was assumed that the
320 pasture and cropland used for agriculture were in carbon balance i.e. neither losing nor
321 sequestering carbon. Although some studies suggest perpetual C sequestration by grasslands
322 (Soussana et al. 2007) repeat sampling surveys and long term experiments show no change in
323 soil C over decadal time scales (see Smith 2014 for a full discussion); it was therefore judged
324 premature to assume carbon sequestration in mature grasslands in this study.

325

326 **3. Results and discussion**

327

328 **3.1 Land use**

329 When livestock production is intensified large amounts of land are released. In the Intensive
330 Livestock scenario (crop yield gaps closed, waste reduced and livestock efficiencies
331 increased), land requirements are only half that of the Yield and Waste scenario (crop yield
332 gaps closed and waste reduced but livestock efficiencies only slightly improved) (Fig. 1).
333 Most of spared land is pasture; biodiversity impact of such abandonment is discussed in
334 section 3.4.

335

336 Land use for Dairy and Poultry and Dairy and Aquaculture is approximately 15% lower than
337 in the Intensive Livestock scenario. This is because beef from suckler systems is replaced
338 with poultry meat or aquaculture products, which have lower land use requirements. Overall
339 land requirements in scenarios without any livestock production (Artificial Meat and Dairy
340 and Plant Based Eating) are significantly less than for the other scenarios, including when
341 compared with 'land efficient' scenarios where monogastric meat and fish (Dairy and Poultry
342 and Dairy and Aquaculture) replace most ruminant meat.

343

344 In all scenarios that include animal products, Healthy Diets require less land than the
345 Projected Diet variant since animal product intakes decline in line with healthy eating
346 recommendations, and cereals, fruit and vegetables, consumed as substitutes, are less land
347 intensive. However in the Artificial Meat and Dairy and Plant Based Eating scenarios,
348 Healthy Diets are more land demanding than Projected Diets. This is because fruits,
349 vegetables and cereals whose consumption increases in Healthy Diet, require more land than
350 the sugar and vegetable oils they replace (Table S2).

351

352 Out of the scenarios which include livestock production, the Ecological Leftovers scenario
353 uses the least cropland because ruminant production is mostly pasture-based and since overall
354 meat supply is limited to what can be obtained by feeding food waste and biomass from
355 pastures. This raises the question whether it is most valuable to spare cropland or pasture land.
356 The amount of meat supplied is 45 kg carcass weight meat per person and year for the
357 Projected Diet i.e. approximately half of current consumption in the region and very close to
358 the global average of 46 kg (FAO 2015b). In the Healthy Diet the amount of meat is capped at
359 'healthy levels' (14 kg carcass weight per capita and year; section 2.4).

360 **3.2 Greenhouse gas emissions caused by agriculture**

361 Closing yield gaps and reducing waste only (Yields and Waste - Projected Diet) achieves very
362 minor GHG reductions compared to the BAU scenario since yields are already high in this
363 region and the increased nitrous oxide emissions arising from increased fertiliser applications
364 cancel the climate benefit of a higher yield (Fig. 2).

365
366 Compared with the Projected Diet scenario variant, Healthy Diets reduce GHG emissions
367 drastically for the Yields and Waste, Intensive Livestock and Ecological Leftovers scenarios
368 because less beef meat is consumed and produced. For Dairy and Poultry and Dairy and
369 Aquaculture, emissions from Healthy Diet variants are 20-30% lower than Projected Diets
370 because of reduced overall animal protein intakes.

371
372 In contrast, emissions increase for Artificial Meat and Dairy and Plant Based Eating in the
373 Healthy Diet variant since more land and fertiliser is used to produce fruits and vegetables,
374 leading to additional nitrous oxide emissions. However, the increase is from very low levels
375 compared with other scenarios.

376
377 The EU has a target to reduce its GHG emissions by 80% by 2050 compared to 1990 levels
378 (EC 2011). If this target is applied equally to all sectors, GHG emissions from agriculture
379 should not exceed 86 Mt CO_{2e} per year in Western Europe by 2050. The scenarios that fall
380 within this limit are Artificial Meat and Dairy and Plant Based Eating for both Projected Diets
381 and Healthy Diets, and Dairy and Poultry and Dairy and Aquaculture for Healthy Diets (Fig.
382 2).

383
384 It could be argued that given the technical difficulties of mitigating nitrous oxide and methane
385 emissions, and the fact that food is a ‘special case’ sector, a less ambitious target may be
386 appropriate – although this would require targets for energy and transport to go beyond 80%.
387 Thus the European Commission’s low carbon economy Roadmap aims for agricultural
388 emission reductions of a modest 42-49% (EC 2011). A reduction target for agriculture of 45%
389 for this Western Europe region would give a limit of 238 Mt CO_{2e} per year. All the Healthy
390 Diets and all Projected Diets except for the Yields and Waste and Ecological Leftovers
391 scenarios stay within this limit. However, the Projected Diet for the Intensive Livestock
392 scenarios is very close to the boundary and since uncertainties for these calculations are in the
393 range of ±50% or more (Röös and Nylinder 2013), it cannot be considered a ‘safe’ option.
394 Hence, decreased beef meat consumption seems to be essential in order to reach the EU GHG
395 reduction target of 45% for agriculture by 2050 even in a situation where yield gaps are
396 closed, waste reduced and livestock efficiencies increased.

397
398 This study did not include emissions from energy use in agriculture or for post-farm activities
399 such as processing, packaging, storage and transports. These emissions currently contribute to
400 about half of food consumption GHGs in high income countries (Garnett 2011). Emission
401 trajectories from the energy and transport sectors to 2050 are highly uncertain. If the reduction
402 targets in the EU Roadmap are achieved for the transport and power sectors, this would mean
403 GHG reductions of between 54-67% and 93-99% for these sectors respectively (EC 2011). In

404 that case, energy and transport within the food system would add little to the total climate
405 impact of the food system. On the other hand, if these targets are not met emissions associated
406 with post-harvest stages in the food chain will continue to have major impacts.

407 **3.3 Carbon sequestration on spared land**

408 As regards forest plantations on spare land, Fig. 2 shows the potential annual average carbon
409 sequestration achievable if all land were to be afforested. It is neither realistic nor desirable
410 that all spared land is afforested; both for environmental and socioeconomic reasons (section
411 3.4). However, the maximum potential is shown here to avoid introducing assumptions about
412 plausible afforestation potentials and to be consistent with the purpose of the study i.e. to
413 show maximum potentials. Since the potential scales linearly with area, the potential can be
414 scaled by the area considered likely to be put aside for afforestation; so for example if only
415 10% of the area were converted to forest, the mitigation potential would be 10% of the
416 maximum value presented. The values for carbon dioxide captured represents the mean of all
417 carbon sequestration between now and 2050 and it would be larger at a time closer to now and
418 gradually lower beyond 2050 since uptake slows as trees mature. Naturally, scenarios that free
419 more land have greater sequestration potential.

420

421 Although the carbon sequestration potential from forest plantation is large it is critical to note
422 that carbon sequestration in biomass is reversible i.e. if forests are later cut down or destroyed
423 by fire, sequestered carbon will return to the atmosphere. Thus the climate benefits obtain
424 only as long as the forest is left standing. In this case however, the one-off sequestration of
425 carbon could compensate for some level of continuous emissions of methane and nitrous
426 oxide which are not as long-lived as carbon dioxide. To establish how much would require
427 more detailed climate modelling than the GWP we used here. While forest planting on low-
428 quality agricultural land could be an important short term mitigation strategy its merits need
429 to be weighed against other land use options (Albanito et al. 2015), which are not considered
430 here.

431 **3.4 Other related health and sustainability implications**

432 This study considered only land use and GHG emissions. Food systems generate a multitude
433 of environmental and health impacts which need to be addressed. These include, on the
434 environmental side, factors such as water stress and local availability of irrigation water, as
435 well as pesticide use. The need for both may increase if diets higher in fruit and vegetables, as
436 the Healthy Diet modelled here, supplied throughout the year are achieved (Eurostat 2007;
437 Hess et al. 2015).

438

439 Turning to biodiversity, many threatened species in the EU depend on habitats created and
440 maintained by low-intensity farming (Kleijn et al. 2009). In the EU27, 32% of farmland is
441 classified as High Nature Value (HNV) (Paracchini et al. 2008) meaning it contains high
442 species and habitat diversity (Andersen 2003). Typical HNV areas include grasslands such as
443 alpine meadows, the eastern and southern European steppes and the Spanish and Portuguese
444 montados (Paracchini et al. 2008) whose conservation value is usually maintained by
445 ruminant grazing. All the scenarios modelled here, except for Ecological Leftovers, move

446 food/feed production off pasture land – when in fact the consequences as regards biodiversity
447 would probably be negative. From this perspective, the Ecological Leftovers scenario for a
448 healthy diet may present a middle way; reducing land use and GHG emissions considerably
449 compared to the BAU scenario, yet still entailing 30 million grazing animals that could be
450 used to preserve HNV farmland. Of course a subset of the Ecological Leftovers scenario in
451 which ruminant grazing is confined only to critical HNV areas could be envisaged. The
452 impacts of different scenarios on landscape aesthetics will also vary and need to be
453 considered, bearing in mind that preferences evolve over time.

454
455 As regards animal welfare, impacts will vary according to production system, quality of
456 management and the extent to which health and welfare traits are included in breeding goals
457 (Nielsen et al. 2011). Current intensive systems can cause problems such as metabolic
458 diseases and leg disorders associated with selection for high production traits. Furthermore
459 intensive production systems can limit the animals' ability to perform key behaviours that are
460 important to their wellbeing, so creating stress and reducing their ability to cope (Hötzel
461 2014). On the other hand, more free range systems (as modelled in Ecological Leftovers)
462 potentially give rise to a different set of problems including poor nutrition or exposure to
463 temperature extremes. Other concerns include the spread of zoonotic diseases and livestock's
464 role in contributing to antimicrobial resistance; the outcomes here will depend on the quality
465 of management.

466
467 As regards human nutrition, it is important to note that animal products supply not just protein
468 but diverse essential micronutrients including B vitamins, iron, calcium, zinc and vitamin A.
469 A more detailed scenarios analysis would need to include requirements for these nutrients too
470 in constructing the healthy diet variants (Millward and Garnett 2010) although it is unlikely
471 that the broad brush findings outline here will change dramatically. A fuller analysis would
472 also need to consider the impact of different dietary scenarios on the socio-economic
473 determinants of good health – including the affordability of diets. Impacts of different
474 scenarios on employment in the food sector, and on food prices would therefore need to be
475 assessed.

476 **3.5 Comparison with other studies and reflections**

477 To our knowledge, no other study has modelled land use and GHG emissions for Western
478 European food production in 2050 under assumptions of both production and demand side
479 mitigation options. Our results can, however, be compared to global studies and studies of
480 other regions in relative terms. Westhoek et al. (2014) modelled the impacts from halving the
481 2007 consumption of meat, dairy products and eggs in the EU27 and found that GHG
482 emissions were reduced by 25–40% and per capita use of cropland for food production by
483 23%. This is in line with our findings for the transition from Projected Diets to Healthy Diets
484 for Intensive Livestock and Ecological Leftovers in which consumption of meat and milk are
485 reduced by 60-70% and 23% respectively (egg consumption constant); land use decreases 12-
486 32% and GHG emissions by 50-60% mostly because of reduced ruminant production.

487
488 Hedenus et al. (2014) modelled global GHG emissions in 2050 and 2070 from a set of
489 scenarios in which livestock efficiencies were increased (+20% for beef, +50% for dairy and

490 +25% for other meat), dedicated technical measures implemented and diets changed (75% of
491 red meat replaced by white meat or plant based protein). Emissions were related to the
492 emission pathways consistent with the 2 °C target. The study concludes that the technical and
493 production side mitigation strategies alone would not suffice to reach this target and that
494 dietary change would also be needed.

495

496 Our study extends and complements the study by Hedenus et al. (2014) by modelling
497 scenarios which offer extremes of potential; yield gaps closed, waste reduced and livestock
498 intensities increased to current highest levels in all areas in the region. It shows that even
499 under these extreme assumptions some form of dietary change will be necessary to reach EU
500 climate change targets. On the other hand, land availability is less critical; this said either
501 reduction in waste and/or livestock efficiency or yield increases and/or dietary change will be
502 needed for the Western European land base to support the projected population. As regards
503 consumption, an entirely plant-based future or a future with only artificial meat and dairy are
504 extreme scenarios. These scenarios show enormous potential for reducing land use and GHG
505 emissions but are of course highly open to question on grounds of public acceptability, health
506 and other sustainability implications as discussed in section 3.4.

507

508 Clearly, a composite of the scenarios modelled here and other as yet un-investigated and
509 unforeseen scenarios, optimised to consider a range of trade-offs (section 3.4.) is likely to be
510 the preferable way forward considering the multiple sustainability challenges that need to be
511 addressed. Considering the uncertain future, the need for resilience in the food system and
512 varying consumer preferences a multitude of different protein production systems will also be
513 needed. Nevertheless, this study clearly illustrates the need for both production and demand
514 side strategies to reach climate change targets if Western Europe is to supply its projected
515 population with food in 2050. Which measures to prioritise and which protein future to
516 promote as the main vision depends on societal values and beliefs as regards technological
517 innovations, the feasibility of achieving changes both in agricultural practices and in diet
518 patterns and ultimately on how society chooses to conceptualise and define a sustainable food
519 system.

520

521 **4. Conclusion**

522 This study investigated a range of protein futures scenarios assuming in all cases that the full
523 range of technically possible mitigation options were undertaken: closure of crop yield gaps,
524 50% reductions in food waste and livestock intensification to increase land and GHG
525 efficiency. It found that, compared with the BAU projections for 2050, land use and GHG
526 emissions in Western Europe could in principle be halved even if current dietary patterns
527 were not altered. However, this is still not sufficient to reach EU climate change targets.

528
529 A shift towards healthier diets, in which fruit and vegetable intakes increased and animal
530 products and vegetable oil intakes reduced in line with healthy eating recommendations could
531 cut land use further still and reduce emissions to about a quarter of BAU projections.

532
533 Replacing red meat with poultry or aquaculture products reduced land use by a further 15%
534 while GHG emissions were cut by approximately 50%. The healthy diet variants of diets with
535 poultry or aquaculture products instead of red meat achieved further small reductions in
536 GHGs and land use requirements.

537
538 Both projected diets and healthy diets without farmed meat and dairy cut land use
539 requirements by half again compared with the mean of diets containing meat, while GHG
540 emissions were less than a third. Strikingly, GHG emissions from these scenarios were less
541 than a tenth of BAU emissions while land use requirements were reduced by 80%. Within
542 these scenarios there was little variation in GHGs or land use between the projected and
543 healthy diet variants.

544
545 An 'ecological leftovers' approach, in which livestock production is limited to use of biomass
546 resources not used as human food, required the least cropland compared to other diets with
547 meat, but used all available pasture. GHG emissions were 35-160% higher (depending on
548 projected or healthy diet) than in the mean of livestock-containing scenarios based on
549 intensive feed crop production.

550
551 The carbon sequestration potential through afforestation on land spared from agricultural
552 production ranged between 90-700 Mt CO₂ per year in 2050 although there was no
553 sequestration in the BAU scenario.

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