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## **Food and nutritional security require adequate protein as well as energy, delivered from whole-year crop production.**

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Human food security requires the production of sufficient quantities of both high-quality protein and dietary energy. In a series of case-studies from New Zealand, we show that while production of food ingredients from crops on arable land can meet human dietary energy requirements effectively, requirements for high-quality protein are met more efficiently by animal production from such land. We present a model that can be used to assess dietary energy and quality-corrected protein production from various crop and crop/animal production systems, and demonstrate its utility. We extend our analysis with an accompanying economic analysis of commercially-available, pre-prepared or simply-cooked foods that can be produced from our case-study crop and animal products. We calculate the per-person, per-day cost of both quality-corrected protein and dietary energy as provided in the processed foods. We conclude that mixed dairy/cropping systems provide the greatest quantity of high-quality protein per unit price to the consumer, have the highest food energy production and can support the dietary requirements of the highest number of people, when assessed as all-year-round production systems. Global food and nutritional security will largely be an outcome of national or regional agro-economies addressing their own food needs. We hope that our model will be used for similar analyses of food production systems in other countries, agro-ecological zones and economies.

1       **Food and nutritional security require adequate protein as well as energy,**  
2                                   **delivered from whole-year crop production**  
3

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16

17

## 18 **Abstract**

19 Human food security requires the production of sufficient quantities of both high-quality protein  
20 and dietary energy. In a series of case-studies from New Zealand, we show that while production  
21 of food ingredients from crops on arable land can meet human dietary energy requirements  
22 effectively, requirements for high-quality protein are met more efficiently by animal production  
23 from such land. We present a model that can be used to assess dietary energy and quality-  
24 corrected protein production from various crop and crop/animal production systems, and  
25 demonstrate its utility. We extend our analysis with an accompanying economic analysis of  
26 commercially-available, pre-prepared or simply-cooked foods that can be produced from our  
27 case-study crop and animal products. We calculate the per-person, per-day cost of both quality-  
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29 mixed dairy/cropping systems provide the greatest quantity of high-quality protein per unit price  
30 to the consumer, have the highest food energy production and can support the dietary  
31 requirements of the highest number of people, when assessed as all-year-round production  
32 systems. Global food and nutritional security will largely be an outcome of national or regional  
33 agro-economies addressing their own food needs. We hope that our model will be used for  
34 similar analyses of food production systems in other countries, agro-ecological zones and  
35 economies.

36

## 37 **Introduction**

38 Since World War II, food insecurity has been an issue concerning the world's poorest, with the  
39 received wisdom being that such insecurity could be alleviated by eliminating local poverty  
40 (McLaren, 1974) and improving food distribution, since globally, food has historically been  
41 produced in excess of world population needs. However, future food and nutritional security has  
42 become a major concern for both rich and poor, given the present concurrence of rising human  
43 population, climate change and changing consumption habits (Porter et al., 2014). This new  
44 reality has been recognised (Graham *et al.*, 2007; Remans *et al.*, 2014), with attention now being  
45 paid to provision of the full range of nutrients in addition to calories, and to the development of  
46 metrics describing food system resilience on an economy-by-economy basis. Cassidy *et al.*  
47 (2013) recognised that one important key to monitoring food security is to develop a metric for

48 the number of people that can be nourished per unit area and per year by a particular crop or  
49 cropping system.

50 However, there are a number of problems in published analyses. Firstly, while the people-  
51 nourished-per-hectare metric has been applied in terms of usable calories, no similar metric has  
52 been developed for nutritious protein. Secondly, we know of no model that accounts for whole-  
53 year land utilisation, including biomass production during the period after harvest of the primary  
54 crop assessed, and before the next season's sowing. Thirdly, in such analyses, when biomass is  
55 used for production of animal foods (such as poultry meat, eggs, pork, beef or dairy products)  
56 feed conversion factors that are now achieved in best commercial practice are not used. Fourthly,  
57 the ability of blends of crop products to provide high-quality protein efficiently (Cassidy *et al.*,  
58 2013; Young and Pellett, 1994) is questionable. Finally, the cost to consumers of meeting  
59 adequate daily nutrient needs (particularly protein) in relation to agroecological productivity  
60 needs to be determined.

61 In this paper, we show that when the above issues are addressed:

- 62 • When considered from a people-fed-per-hectare perspective, food products from dairy  
63 production are commensurate with food products from plants, in terms of meeting needs  
64 for both dietary energy and for protein;
- 65 • Such foods can supply both energy and high-quality protein to the consumer cheaply  
66 compared to plant-based foods, when ready-to-eat products are properly compared;
- 67 • Use of forage biomass produced after harvesting food crops can contribute significant  
68 extra dietary energy and high-quality protein from animal foods;
- 69 • Blends of cereal and legume flours, optimised for essential amino acid content, contain  
70 significant excesses of most dispensable amino acids, implying inefficient use of plant  
71 photosynthetic productivity. Per mole of carbon, those excess amino acids deliver similar  
72 amounts of dietary energy to carbohydrate, but in terms of plant metabolic energy, are  
73 considerably more costly to synthesise.

74

## 75 **Food needs**

76 Minimum daily energy intake required for food security lies in the range 1800 – 2000

77 kcal/person/day (~7.5 – 8.4MJ/person/day) (Anon, FAO Statistics Division, 2008). This amount

78 is sufficient to meet the needs of a wealthy, sedentary, healthy adult; it is inadequate to meet  
79 those of children, growing adolescents, manual labourers or pregnant women; i.e. the majority of  
80 the human population, especially in poor countries. Adequate nutrition also requires, on average,  
81 56g/day of high-quality protein. A secure level of protein intake for adults is about 0.83g/kg  
82 body mass/day (e.g. 66g/day for an 80kg male) and needs to include adequate provision of all  
83 essential amino acids (Anon, United Nations University, 2007). The diet must also provide  
84 adequate vitamins, minerals, essential fatty acids and dietary fibre. The elements (energy,  
85 protein, minerals, micronutrients and fibre) of an adequate diet are available from both plant and  
86 animal sources, with the exception of plant dietary fibre.

87 We focus on dietary energy (which may be derived from carbohydrate, lipid, protein or  
88 fermented fibre) and protein; the required intake of the latter takes account of its nutritional  
89 quality, in terms of its human digestibility and suitable amino acid profile. We assume a daily  
90 energy intake of 10MJ (2400 kcal), and a daily protein intake of 56g, the biological nutritional  
91 value (BV) of which is equivalent to hen egg protein, the best suited to human needs in terms of  
92 amino acid composition. Thus, the quality of other sources of protein in terms of amino acid  
93 composition is compared against that of hen egg protein. Energy and protein contents for  
94 foodstuffs were derived from relevant information at <http://nutritiondata.self.com/> which  
95 summarises USDA data. Protein BVs are taken from Akeson and Stahmann (1964).

96

### 97 **Production systems comparison**

98 We analysed the total annual production of human dietary energy (MJ) and high-quality protein,  
99 corrected for its nutritional value, from crops grown on arable land for a range of crop products  
100 (Supplementary Information. S1). We assume a southern hemisphere temperate semi-maritime  
101 climate, with sufficient rainfall and irrigation water for high levels of crop growth. We chose this  
102 cropping framework as an example because reliable productivity (dry matter yield per unit area)  
103 estimates are available, but our analysis can be applied to any set of agro-ecological conditions in  
104 which crop yields are known. Our baseline for comparisons of the calorific content and  
105 nutritional value of different food production systems is an arable cropping system that produces  
106 only high-protein milling wheat for bread production. The assumptions we make of the baseline  
107 production system are:

- 108 • Use of a wheat cultivar from which a high yield of flour suitable for manufacture of bread  
109 is possible;
- 110 • Autumn sowing to achieve maximum grain yield;
- 111 • Flour extraction rate of 80%, producing 6.4 t/ha of bakers flour and 1.6 t/ha of offal for  
112 animal feed;
- 113 • Sowing in May (southern hemisphere), allowing autumn production of 3.5t/ha of brassica  
114 dry matter, used to produce milk solids from cows. The animal production achieved is  
115 credited to the milling wheat production system.

116

117 It should be noted that while data used to erect the model are derived from the range of  
118 environments found in New Zealand, these are by no means unique to that country. Similar  
119 agroecological systems may be found in Southern Australia, Southern Africa, South America,  
120 and coastal regions of the USA, the middle-to-upper latitudes of Western Europe, areas around  
121 the Black Sea, and coastal regions of East Asia.

122

123 We compared how many adults' annual energy and quality protein needs can be met by each of  
124 the production systems (listed below, all weights as dry matter), given a calorific requirement of  
125 10MJ/day and 56g/day of high-quality protein. As stated, our baseline for the comparison of  
126 systems is the energy and protein provision of bread wheat. The other whole-year crop  
127 production systems are:

- 128 • Autumn-sown feed wheat, followed by summer-sown brassicas, producing 10t/ha of  
129 grain and 3.5t/ha of brassica
- 130 • Spring-sown oats, producing 6 tonnes of grain, 3 t/ha of straw suitable for forage and 5  
131 t/ha of brassica (Armstrong, K,(formerly NZ Institute for Plant and Food Research Ltd)  
132 pers comm);
- 133 • Spring-sown, winter-harvested milling maize, producing 10.5t/ha of grain;
- 134 • Spring-sown, winter-harvested feed maize producing 12t/ha of grain;
- 135 • Autumn-sown silage wheat, followed by summer-sown brassicas, producing a total of  
136 18.5t/ha of feed;

- 137 • Spring-sown silage maize, followed by autumn-sown Italian ryegrass, producing 29t/ha  
138 of feed dry matter.
- 139 • Spring-sown, summer-harvested vining peas, producing 9.5 tonnes/ha fresh weight of  
140 peas, 1 t/ha pea straw drymatter and 8 t/ha of drymatter from summer-sown brassicas  
141 (Snowden B, Heinz-Watties Ltd, Christchurch, pers. comm)

142 Crop yield information is courtesy of Dr John de Ruiter, New Zealand Institute for Plant and  
143 Food Research Ltd, unless otherwise stated.

144 Some authors (e.g. Cassidy *et al.*, 2013) claim that deficiencies in plant protein quality can be  
145 remedied by mixing food ingredients from different plant types, particularly combining cereals  
146 and legumes. To examine this assertion, we evaluated a system comprising spring-sown field  
147 peas (*Pisum sativum*) (5.5 t/ha) and forage oats (7 t/ha). In common with other legumes, the BV  
148 of the pea protein, estimated to lie between 50% and 55% based on amino acid composition, is  
149 confounded by the presence of varying levels of trypsin (protease) inhibitors (Mariotti *et al.*,  
150 2001); thus the reported crude BV may be too high.

151 The chosen cropping systems provide raw materials for the production of a range of foods or  
152 food ingredients (Figures 1 and 2). Protein BVs used are 0.50 (white wheat flour), 0.47 (split  
153 peas, discounted by 15% for trypsin inhibitor effect), 0.75 (poultry, pork and beef) and 0.90  
154 (milk solids) (Akeson and Stahmann, *op.cit.*) We present the data as the relative annual  
155 production per unit area (ha) of energy and protein for humans, when compared to the baseline  
156 (milling wheat alone) system (Figures 1 and 2). In essence, we are comparing the contributions  
157 of wholly plant-based cropping systems with mixed plant-animal systems to food and nutritional  
158 security in terms of the number of persons supported for their calorific and nutritional  
159 requirements per unit area.

## 160 **Conversion factors**

161 In establishing the number of people whose protein and dietary energy needs can be met from  
162 whole-year biomass production, it is important to use commercially-relevant factors for  
163 conversion of raw materials to final product; these are shown in Table 1.

## 164 **Daily cost of nutrient provision**

165 While the productivity achieved is appropriately expressed in terms of persons nourished per  
166 hectare, where available land is the limiting factor for food production, it is useful to determine



167 the relative financial cost of meeting nutritional needs from different production systems.  
168 Conversion of raw materials to consumer-ready foods involves a variable number of unit  
169 operations of varying cost. However, these costs are summarised in the final price of the ready-  
170 to-eat product. It should be noted that the price of many such products includes an amount for the  
171 brand value associated with the producer. Therefore, the prices used in this study are derived,  
172 where possible, from products used to calculate the monthly consumer food price index  
173 generated by the New Zealand Department of Statistics (September 2015:  
174 [http://www.stats.govt.nz/browse\\_for\\_stats/economic\\_indicators/prices\\_indexes/FoodPriceIndex\\_](http://www.stats.govt.nz/browse_for_stats/economic_indicators/prices_indexes/FoodPriceIndex_HOTPSep15.aspx)  
175 [HOTPSep15.aspx](http://www.stats.govt.nz/browse_for_stats/economic_indicators/prices_indexes/FoodPriceIndex_HOTPSep15.aspx)). Other data were shelf prices for house brands in the supermarket generally  
176 regarded as the cheapest in New Zealand. Where appropriate, a \$NZ0.15/kg allowance is made  
177 for the cost of the simplest home cooking procedure required to generate a palatable, digestible  
178 product, by steaming, boiling or roasting.

179 As above, dietary energy and quality protein provision were determined from USDA data at  
180 <http://nutritiondata.self.com/>. No allowance is made for the potential impact of anti-nutritional  
181 factors, such as content of trypsin inhibitors in legumes, or indigestible peptide sequences in  
182 bread wheat.

183 Results are presented as ready-to-eat food intake (g/day) required to meet energy and quality  
184 protein needs. In some cases, the intake of protein required to meet all essential amino acid needs  
185 was less than 56 g. Consumption of that minimum intake would lead to a deficiency in  
186 dispensable amino acid intake. In those cases, the food intake necessary to consume 56 g/day of  
187 protein is used.

## 188 **Results and discussion**

189 All productivity estimates are given on a per-hectare basis, unless otherwise stated. In the milling  
190 wheat system, in which the wheat crop is followed by an autumn brassica crop to capture plant  
191 nutrients that would otherwise be lost to groundwater, flour production is sufficient to meet the  
192 energy needs of 26 people, and the protein needs of 16 people. Milk solids produced from  
193 milling offal and brassica dry matter meet the energy needs of an additional 8 people, and the  
194 protein needs of an additional 11 people. Thus, this baseline system is calculated to meet the  
195 energy needs of 34 people and protein needs of 27.

## 196 **Energy provision**

197 Figure 1 shows that milk solids production from milling offal and a post-harvest brassica crop  
198 increases dietary energy yield in the milling wheat production system by 29%, while the grain  
199 maize production system produces 43% more dietary energy than milling wheat alone.  
200 Interestingly, production of field peas plus milk solids only achieves a 4% increase in dietary  
201 energy yield relative to milling wheat alone, due to the very low contribution of energy from the  
202 field peas.

203 This analysis supports the view that, in terms of dietary energy production, animal-derived foods  
204 are generally inefficient relative to cereal crops, although it can be seen (Figure 1) that milk  
205 solids production from high-yielding silage crops is competitive with milling wheat in terms of  
206 the number of people whose dietary energy needs can be met from a hectare of prime arable  
207 land. A combination of maize silage plus short rotation ryegrass is projected to fulfil the energy  
208 requirements of about 25% more people than even the baseline system, in which milling wheat  
209 production is supplemented with a post-harvest brassica crop.

210

### 211 **Protein provision**

212 Figure 2 shows that apart from beef production, all the animal food production systems  
213 outperform the baseline milling wheat in terms of the number of people whose protein needs are  
214 met from a hectare of prime arable land. In particular, milk solids production is a highly effective  
215 use of arable land to meet the requirements of humans for high-quality dietary protein.

216

217 Cereals are the predominant sources of human foodstuffs, but are poor sources of protein: to  
218 obtain sufficient lysine from them, a considerable excess of dietary energy must be consumed. It  
219 has been suggested (Young and Pellett 1994; Ghosh, Suri, and Uauy 2012; Day 2013; Cassidy *et*  
220 *al.*, 2013) that by combining ingredients derived from a number of plant sources, deficiencies in  
221 the protein quality of particular crop products can be corrected. Under the agro-ecological  
222 conditions described, the most productive crops are cereals and field peas. Table 2 gives the  
223 optimal levels in protein of the nine amino acids essential for human nutrition (Anon, United  
224 Nations University, 2007), and the essential amino acid composition of wheat flour  
225 (<http://nutritiondata.self.com/facts/cereal-grains-and-pasta/5821/2>) and split peas (  
226 <http://nutritiondata.self.com/facts/legumes-and-legume-products/4353/2>). In cereal-based

227 diets, whether for humans or for monogastric animals, lysine is considered to be the first-limiting  
228 amino acid, and as can be seen (Table 2), legume protein appears to have this particular amino  
229 acid in excess relative to human requirement. Therefore, we estimated the optimal combination  
230 of flours from wheat and split peas needed to provide a mixture of proteins with ideal lysine  
231 content.

232 The deficit of lysine in white wheat flour can be corrected by consuming a mixture containing  
233 54.2% wheat flour and 45.8% pea flour. Consumption of *ca.* 332g of such a mixture will provide  
234 56g of protein, containing the daily requirement of lysine, but this quantity will only provide  
235 49.4% of the daily requirement of phenylalanine and tyrosine. Thus, it is necessary to consume  
236 about 670g of the wheat:pea mixture daily to ensure that needs of all essential amino acids are  
237 met, leading to the consumption of 113.4g of protein. Such an excess of protein will be  
238 converted to dietary energy in the liver, and the quantity is well-below the safe upper limit for  
239 dietary protein intake (Bilsborough and Mann, 2006))

240 Using these figures, an independent calculation of the number of people whose nutrition needs  
241 can be met from 54.2% of a hectare of milling wheat, and 45.2% of a hectare of field peas was  
242 made: the energy demands of 21 people were met (as expected) whereas the protein requirements  
243 of 22 people were met, approximately 16% more than the geometric mean of the numbers fed by  
244 the individual crops alone. Thus, while the assertion is supported that mixtures of plant products  
245 can be better protein sources than any alone, they are well below the value of the animal protein  
246 that can be produced from the same area, since that area, devoted to producing milk solids, could  
247 meet the protein needs of 62 people.

### 248 **Limitations on seed protein quality**

249  
250 It is worth briefly considering the reason for this. The majority of plant food sources produced  
251 from prime arable land are the seeds or storage organs of a range of crop species. The endosperm  
252 in cereal seeds and the cotyledons of legume seeds have evolved to store plant nutrients for the  
253 use of the developing seedling after germination, but before the new plant is able to  
254 photosynthesise, acquire mineral nutrients from the soil, and in the case of the legumes, to  
255 nodulate and support nitrogen fixation by symbiotic microflora.

256 Vascular plants are able to synthesise their requirements of all the amino acids found in protein  
257 from fixed carbon and nitrate nitrogen, which may be derived from the amino acids in storage  
258 protein of any composition.

259 The essential amino acids are the most chemically-active found in protein, and are often part of  
260 the active site of enzymes, or involved in forming and stabilising the three-dimensional structure  
261 of biologically-active proteins. Lysine, in particular, is able to take part in the Amadori reaction  
262 with free carbonyl groups, forming condensation products which interfere with normal  
263 cytoplasmic biochemistry, and prevent the use of the lysine in protein biosynthesis.  
264 Consequently, it is not surprising that the content of lysine in storage proteins such as glutenins  
265 and gliadins is so low (Rombouts et al., 2009). Such lysine as is found in the wheat endosperm is  
266 likely to be associated with the small number of bioactive proteins present (but inactive) in the  
267 dormant seed, ready to take part in the necessary seed respiration prior to germination.

268 Similar considerations apply to the composition of the protein of the legume cotyledon. In this  
269 case, the level of lysine is relatively high, whereas the sulphur amino acids are poorly  
270 represented (table 2). This means that unlike cereal protein, the first-limiting amino acids in  
271 legume protein are methionine and cysteine. The different ratio of lysine to sulphur amino acids  
272 between cereals and legumes is probably due to the presence of high levels of trypsin inhibitors  
273 in legume cotyledons. Legumes have evolved to produce substantial quantities of protein with  
274 trypsin-inhibiting properties (Savelkoul et al., 1992) as a defence against pests. A wide range of  
275 other anti-nutritional factors are also present in the storage organs of plants used for human and  
276 animal feeding (Mann and Coles, 1998), further limiting the biological value of most plant  
277 proteins.

278 Nevertheless, the majority of the protein in the legume cotyledon is deposited to meet the  
279 nitrogen requirements of the developing seedling, and consequently has, generally speaking, the  
280 same bias against the most chemically-active amino acids in such storage protein. It is not  
281 surprising, therefore, that all plant seed storage proteins contain an excess of dispensable amino  
282 acids relative to the monogastric requirement for amino acid balance.

283 The search for mutants in cereals with more desirable seed amino acid composition has  
284 continued since the 1960s (Munck, Karlsson, Hagberg, & Eggum, 1970; Munck & von  
285 Wettstein, 1974; Munck, 1970, 1972; Hard, 2002), but to date, there are no useful cultivars able

286 to producing significantly-enhanced levels of essential amino acids in their storage proteins.  
287 Consequently, grain-based animal diets are often supplemented with industrially-produced pure  
288 amino acids. However, such amino acids are expensive, relative to animal protein sources, and  
289 their chemical activity means that during food or feed processing they are often irreversibly  
290 bound to other materials, meaning they are not available for a role in protein nutrition. Thus, it is  
291 improbable that combinations of plant seed storage protein and synthetic amino acids will ever  
292 be able to provide for human essential amino acid needs as efficiently as animal products.

### 293 **Optimal allocation of arable land to end use**

294 As can be seen above, direct use of plant products for food is generally the best allocation of  
295 arable land if dietary energy is the metric employed. However, we show that animal products are  
296 much more effective ways of delivering high yields of usable high-quality protein. This  
297 challenges the claims of those who argue that a global diet consisting entirely of plant-derived  
298 foods is the most efficient way to meet the dietary needs of the world's population. Considerable  
299 discussion has already been devoted to the potential nutritional consequences of such a policy,  
300 and conversely, the means needed to improve livestock productivity (Anon (NAS Committee),  
301 2015; Capper and Bauman, 2013; Pinstруп-Anderson, 2012; Smil, 2014; Wirsenius et al., 2010).  
302 Clearly, then, there will be an optimal allocation of high-quality arable land to production of  
303 each nutrient. To illustrate this, we have estimated the best allocation of arable land based on two  
304 production systems: milling wheat with milk production from a post-harvest crop of brassica  
305 forage compared with production of milk solids alone from silage maize and an inter-crop of  
306 annual ryegrass. Figure 3 shows the number of people whose protein and energy needs are met  
307 from a hectare as the proportion of land allocated to each of those production systems is varied.

308

309 It is clear from this figure that the appropriate allocation to maximise the number of individuals  
310 for whom both protein and energy intake needs are met is approximately 82% to the  
311 wheat:brassica system. It should be noted that any bias should be in favour of the maize  
312 silage:annual ryegrass system, as a surplus of protein can be used to provide calories, whereas an  
313 energy surplus will not help meet a quality protein deficit. It should also be noted that the system  
314 meets the energy needs of just over 33 people from milk solids plus 5.25 tonnes of flour, or

315 435g/person/day. That level of white flour consumption would provide just under 50% of the  
316 recommended daily intake of dietary fibre.

### 317 **Economic considerations**

318 Supplementary Information S2 complements the above analysis of the production of calories and  
319 proteins of high quality and analyses the daily cost of meeting energy and quality protein needs  
320 from a range of foods. These are divided into four categories (Table 3): meats, legumes, cereals  
321 and potatoes, and dairy (including eggs). Products were selected for inclusion provided there was  
322 both price and suitable nutrition information available.

323 As expected, meats and dairy products (with the exception of butter: \$2.09/day, data not shown)  
324 were an expensive source of dietary energy, as were legumes, while starchy products (cereals  
325 and potatoes) were considerably cheaper. Table 4 provides means and variation for the cost of  
326 both daily energy and daily quality protein from each category. The cost of meeting daily protein  
327 requirement from a single foodstuff was calculated in two ways. Firstly, we determined the cost  
328 of providing the equivalent of 56g of quality protein, by correcting for BV. This figure was not  
329 corrected for the impact of anti-nutritional factors often found in plant-derived foodstuffs such as  
330 legumes, as the cooking process reduces the impact of these. However, baking does not deal with  
331 the digestive inaccessibility of particular peptide motifs in wheat flour (Larsen NG, *pers.comm.*),  
332 so the cost of properly meeting protein needs from these foods is understated by an unknown  
333 amount.

334 The second method of estimating the cost of providing for daily protein needs was based firstly  
335 on calculating the minimum quantity of the food required to supply the daily needs of essential  
336 amino acids, then, if this quantity did not provide the equivalent of 56g of egg protein, increasing  
337 the quantity of food until this threshold was met. This approach thus ensures that the minimum  
338 cost either to supply all essential amino acids **or** the necessary total amount of protein is  
339 calculated for the analysis.

340 Employing either approach, we find that legumes are expensive sources of protein, with meat  
341 also costly. Among the meats, chicken is markedly cheaper than other sources, while lentils and  
342 frozen peas are cheaper protein sources than other legumes. The mean cost of protein from the  
343 cereals and potatoes group is higher than from meat, but rolled oats are a significant exception in  
344 this group, meeting daily protein needs for 40% lower cost than white bread, the next cheapest



345 alternative. However, the cheapest way to meet protein needs is consumption of dairy foods. It is  
346 noticeable that the cost of protein from whole milk powder is only half that from fresh milk,  
347 presumably due to eliminating the need for continuous chilling of the product. Cheese also  
348 provides quality protein at the same low cost as whole milk powder. Since, as shown above, this  
349 class of foods is several-fold the most productive use of arable land, these results argue strongly  
350 for at least a proportion of total arable land to be used to produce dairy foods.

351 While generally speaking, the contrasting approaches to calculating daily protein intake cost give  
352 similar results for the plant-based foodstuffs, the meat and dairy product daily costs are markedly  
353 higher when the calculations based on 1<sup>st</sup>-limiting amino acid content are compared to BV-based  
354 values. This is because these products have protein essential amino acid relative contents in  
355 excess of those required for ideal protein nutrition, and, accordingly, dispensable amino acid  
356 contents that are lower than can be sustained. Clearly, if low-cost protein sources were available  
357 that could complement the protein composition of these dairy and meat products, more cost-  
358 effective protein nutrition might be possible. Similarly, least-cost daily diets could be developed  
359 from a combination of these foods.

### 360 **Further considerations**

361 The study reported here considers the optimum allocation of prime arable land (in this case, in a  
362 temperate, semi-maritime agroecological framework) – land with the greatest flexibility of use  
363 for food production. It should be noted that much of the world's agriculturally-productive land  
364 falls outside this category, due to terrain that restricts mechanisation, or other agroecological  
365 considerations. Logically, agricultural productivity from such land, which is likely to be biased  
366 towards animal products, should be integrated with that from the prime arable land we consider.  
367 This may involve, for instance, beef and lamb finishing on arable land after the majority of  
368 growth has been achieved from forage on steep terrain. A significant use for such land in New  
369 Zealand is for the production of dairy heifer replacements.

370 A second consideration, not discussed above, is the land required for production overheads, such  
371 as seed for sowing, or feed for layer replacement breeders, broiler breeders or breeding sows. In  
372 a wheat production system, around 2.5% of the total land area will be used for seed production,  
373 with similar requirements for oats, brassicas, ryegrass and maize. Less than 1% of total feed use  
374 in poultry production is required for breeding stock, and at the end of their breeding life, the

375 birds provide a further return of useful food. Breeding sows use about 3% of total feed put into a  
376 pork production system. Hence, there is little difference between production of plant-based and  
377 animal-derived foods with respect to production overhead land use.

378 We have not discussed root crops here. In the agroecological system described, root crops of  
379 importance in human nutrition include potato (*Solanum tuberosum*) and, to a lesser extent,  
380 Swede turnip (*Brassica napus*). Sugar beet (*Beta vulgaris*) is an important source of energy for  
381 human use, and protein and fibre for ruminant nutrition, but is not grown in New Zealand:  
382 cultivars developed specifically for animal use (as fodder beet) have a long history in this  
383 country, but pose many management problems, so are used sparingly. As a consequence, no data  
384 are available with which to make useful comparisons.

385 Potatoes are an important crop for the production of both table ware and raw materials for the  
386 production of processed foods. However, establishing the contribution they can make to food  
387 security in competition with other uses of arable land is very complex: there is a very wide range  
388 of management systems, and the practice of “ground-keeping” potatoes as a storage mechanism  
389 makes the question of whole-year land utilisation difficult to address. Furthermore, they must be  
390 managed in long-term rotations: at least ten years is recommended between crops in the same  
391 soil.

392 Nevertheless, according to the form of analysis used above, a single hectare of a main crop of  
393 potatoes producing 80 tonnes of table ware could, potentially, meet the energy needs of 70  
394 people and the protein needs of 74 people annually. The individuals nourished this way would,  
395 however, have to consume more than 1.5kg of potatoes/day – an intake only managed by rural  
396 Irish before the Great Famine of the mid-nineteenth century.

## 397 **Conclusions**

398 The analysis described in this review clearly shows that prime arable land is capable of providing  
399 the most enhanced global food security from a carefully-selected mixture of uses aimed at  
400 production of both plant-based and animal-based foods. This complementation of food  
401 production systems is most important when focusing on meeting global need for high-quality  
402 protein, even if a crop such as potato is considered. The analysis shows that animal-based food  
403 production, particularly dairy production, can also make a critical contribution to food energy



404 needs. This particularly so when utilisation of biomass produced after a main crop is harvested,  
405 and before the next summer's cropping programme begins, is considered. The cost-benefit  
406 analysis included supports this conclusion.

407 Clearly, the findings reported here cannot be generalised globally without further effort in data  
408 acquisition and deepened analysis. However, it is equally clear that the means to achieve global  
409 food security are more broad-based than earlier thought, and that mankind may enjoy a more  
410 varied diet in the future than has been feared.

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484

<b>Raw material conversion</b>	<b>Live weight Production (FCR: kg feed:kg liveweight)</b>	<b>Useable food ingredient (yield per kilogram live weight)</b>	<b>Notes</b>
Wheat to poultry meat	1.5	0.6	In commercial practice in New Zealand, whole-of-life feed conversion ratios routinely fall below 1.5 kg/kg (Foulds <i>pers. comm</i> ). It should be noted that commercial feed formulations usually contain only 85% wheat or maize, with the balance made up of meat meals or, less often, plant protein sources such as soya bean meal. Small quantities of synthetic amino acids are often used.
Maize to poultry meat	1.5	0.6	
Wheat to pork	2.1	0.6	See above. In this case, FCR values are unpublished data of the senior author.
Maize to pork	2.1	0.6	
Wheat to beef	7.0	0.6	Note that the FCR used applies to the effect of using an arable crop product as a substantial supplement, not whole-of-life total diet. On the other hand, the recovery figure does not take into account the use of meatmeals for further animal production.
Maize to beef	7.0	0.6	
<b>Wheat or maize to milk solids</b>		<b>Yield/kg feed</b>	
Grain @ 12.5Mj/kg		181g	Budget figure for nett conversion of forage dietary energy to milk solids is 69MJ/kg solids. New Zealand farmers are paid on the basis of the amount of protein and fat they deliver. Our calculations include a further 50% to allow for milk lactose production.
Milling offal @ 10.0Mj/kg		144g	
Forage @ 10.0Mj/kg		144g	

485

486 Table 1. Conversion factors used to translate crop biomass production to useful food ingredients.  
487

Essential Amino Acid	Ideal Content (mg/g protein)	Daily requirement (80kg adult (mg))	Wheat (10.3%) (mg/g flour)	Peas (24.6%) (mg/g flour)
Tryptophan	6	336	12.33	11.18
Threonine	23	1288	27.28	35.45
Isoleucine	30	1680	34.66	41.22
Leucine	59	3304	68.93	71.54
Lysine	45	2520	22.14	72.03
Methionine + cysteine	22	1232	39.03	25.37
Phenylalanine + tyrosine	38	2128	80.78	74.92
Valine	39	2184	40.29	47.11
Histidine	15	840	22.33	24.27

488

489 Table 2. Essential amino acid composition of ideal protein and wheat and pea seed proteins.

490

<u>Foodstuff (Ready-to-eat)</u>	price/kg, \$NZ	Energy (Kcal)	Gross (G/kg)	Protein		To meet daily requirement (g of product as-is)		Cost/day to meet requirement (\$NZ)		
				Amino acid value	Nett (g/Kg)	Energy	Protein	Energy	Protein	From 1 <sup>st</sup> - limiting AA
<b>Meats</b>										
Chicken, breast fillets	\$11.79	1650	310	1.33	412	1455	136	\$17.15	\$1.60	\$2.13
Ground beef	\$13.43	2460	240	0.67	161	976	348	\$13.10	\$4.68	\$4.03
Corned Silverside	\$10.99	2510	180	0.94	169	956	331	\$10.51	\$3.64	\$3.42
Pork pieces	\$18.99	3760	140	1.50	210	638	267	\$12.12	\$5.06	\$7.60
Whole Chicken	\$13.61	1078	111	1.32	147	2227	382	\$30.31	\$5.20	\$6.87
Smoked frankfurters	\$9.99	3050	120	1.33	160	787	351	\$7.86	\$3.51	\$4.66
Plain frankfurters	\$8.99	3050	120	1.33	160	787	351	\$7.07	\$3.15	\$4.20
Smoked whole chicken	\$9.99	1650	180	1.33	239	1455	234	\$14.53	\$2.34	\$3.11
<b>Legumes as canned</b>										
Chilli beans	\$7.00	1120	60	1.09	65	2143	856	\$15.00	\$5.99	\$6.53
Baked beans	\$5.80	940	60	0.71	43	2553	1315	\$14.81	\$7.62	\$8.51
Butter beans	\$3.80	1430	90	0.96	86	1678	648	\$6.38	\$2.46	\$2.36
Lentils	\$4.00	1160	90	0.86	77	2069	724	\$8.28	\$2.89	\$2.53
Frozen peas	\$2.25	780	50	0.84	42	3077	1333	\$6.92	\$3.00	\$2.57
chickpeas	\$5.50	1190	50	1.07	54	2017	1047	\$11.09	\$5.76	\$6.16
<b>Cereal and potato</b>										
White bread	\$1.82	2660	80	0.52	42	902	1346	\$1.64	\$2.45	\$2.26
Breakfast Biscuits	\$5.45	3730	110	0.52	57	643	979	\$3.51	\$5.34	\$4.10
Rolled Oats	\$3.27	3790	130	0.95	124	633	453	\$2.07	\$1.48	\$1.41
Dry Pasta	\$5.65	3710	130	0.45	59	647	957	\$3.65	\$5.41	\$4.78
White rice	\$2.44	1300	30	0.71	21	1846	2629	\$4.50	\$6.40	\$6.34
Potatoes	\$1.80	1980	40	1.09	44	1212	1284	\$2.18	\$2.31	\$3.96

of product as-is)

<b>Foodstuff (Ready-to-eat)</b>	<i>price/kg,</i>	<i>Energy (Kcal)</i>	<i>Gross (G/kg)</i>	<i>Amino acid value</i>	<i>Nett (g/Kg)</i>	<i>Energy</i>	<i>Protein</i>	<i>Energy</i>	<i>Protein</i>	<i>From 1<sup>st</sup>-limiting AA</i>
<b>Dairy</b>										
Whole milk (fresh chilled)	\$1.67	640	30	1.37	41	3750	1363	\$6.25	\$2.27	\$3.12
Whole milk powder	\$8.19	4960	260	1.37	356	484	157	\$3.96	\$1.29	\$1.76
Cheddar cheese	\$8.05	4030	250	1.25	313	596	179	\$4.79	\$1.44	\$1.80
Eggs	\$6.27	1420	130	1.37	178	1690	314	\$10.59	\$1.97	\$2.70

491

492 Table 3: Calculation of daily cost of meeting dietary energy and protein needs. Price data from New Zealand metropolitan

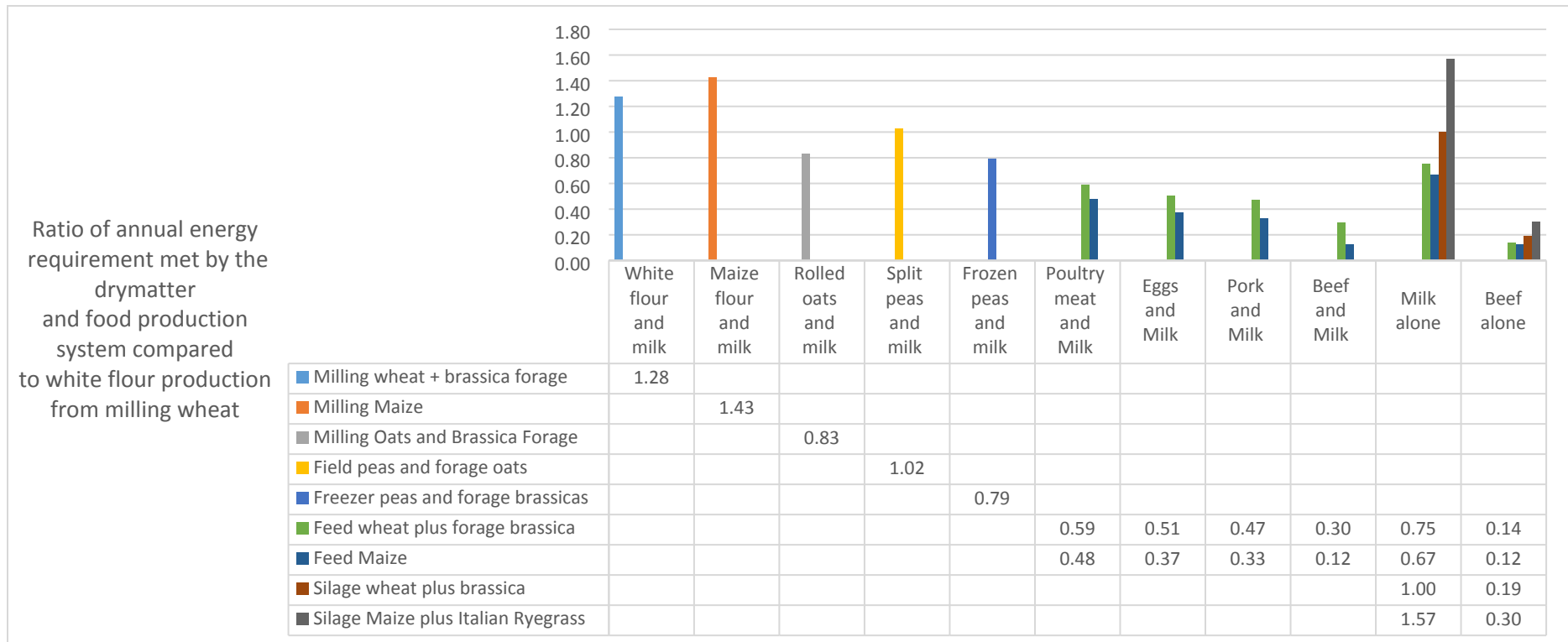
493 supermarkets. Amino acid value of egg protein = 1.00; prices are \$NZ.

494

	<b>Energy</b>		<b>Protein</b>			
	Mean	S.D.	<i>From BV estimate</i>		<i>From 1<sup>st</sup>-limiting amino acid content</i>	
			Mean	S.D.	Mean	S.D.
Meats	\$14.08	\$7.35	\$3.65	\$1.29	\$4.50	\$1.86
Legumes	\$10.41	\$3.84	\$4.62	\$2.12	\$4.78	\$2.63
Cereal and Potatoes	\$2.92	\$1.12	\$3.90	\$2.05	\$3.81	\$1.77
Dairy	\$6.40	\$2.95	\$1.74	\$0.46	\$2.35	\$0.67

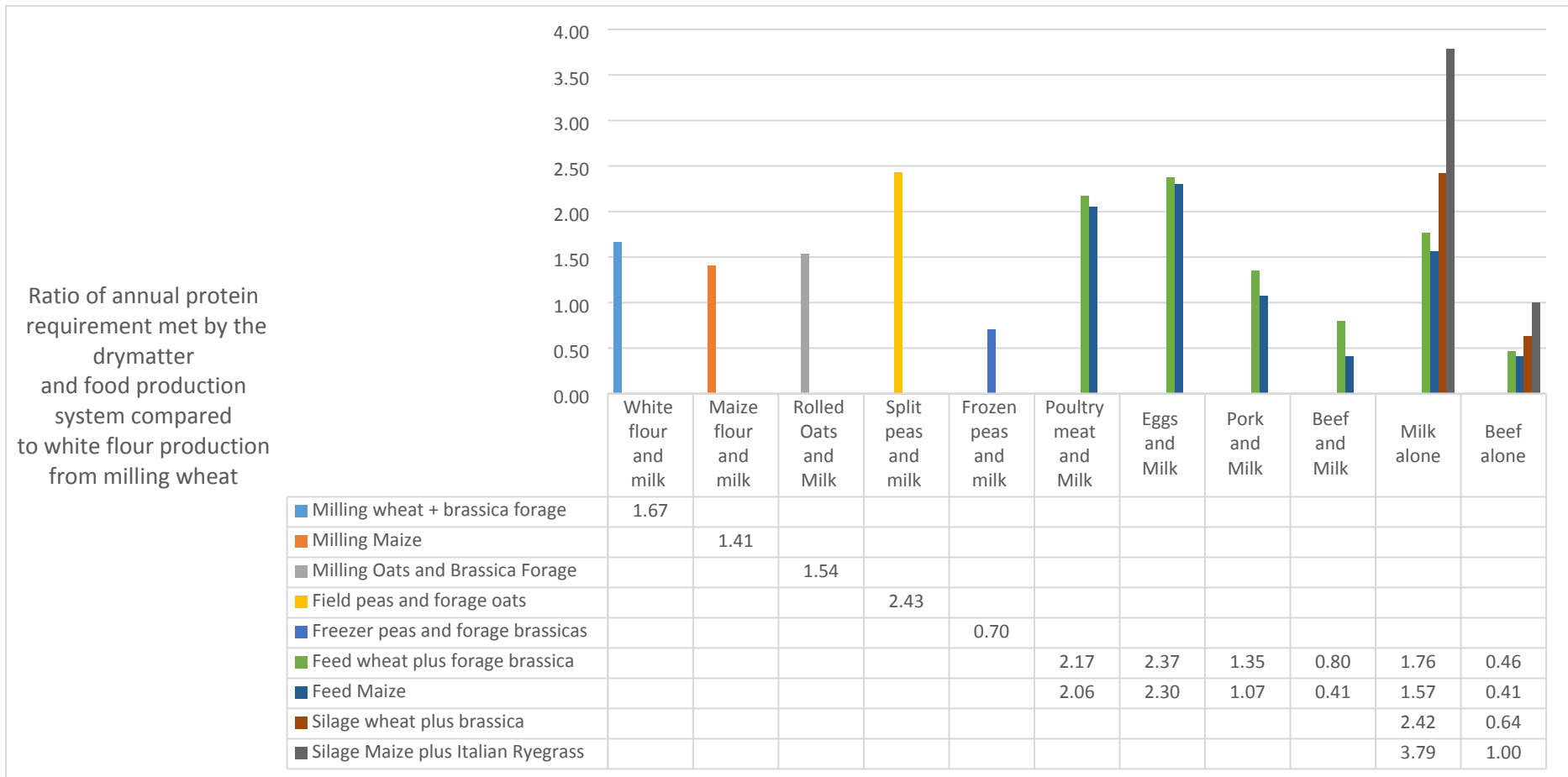
495 Table 4: Mean cost of providing daily energy and protein from each food category. Prices are \$NZ.





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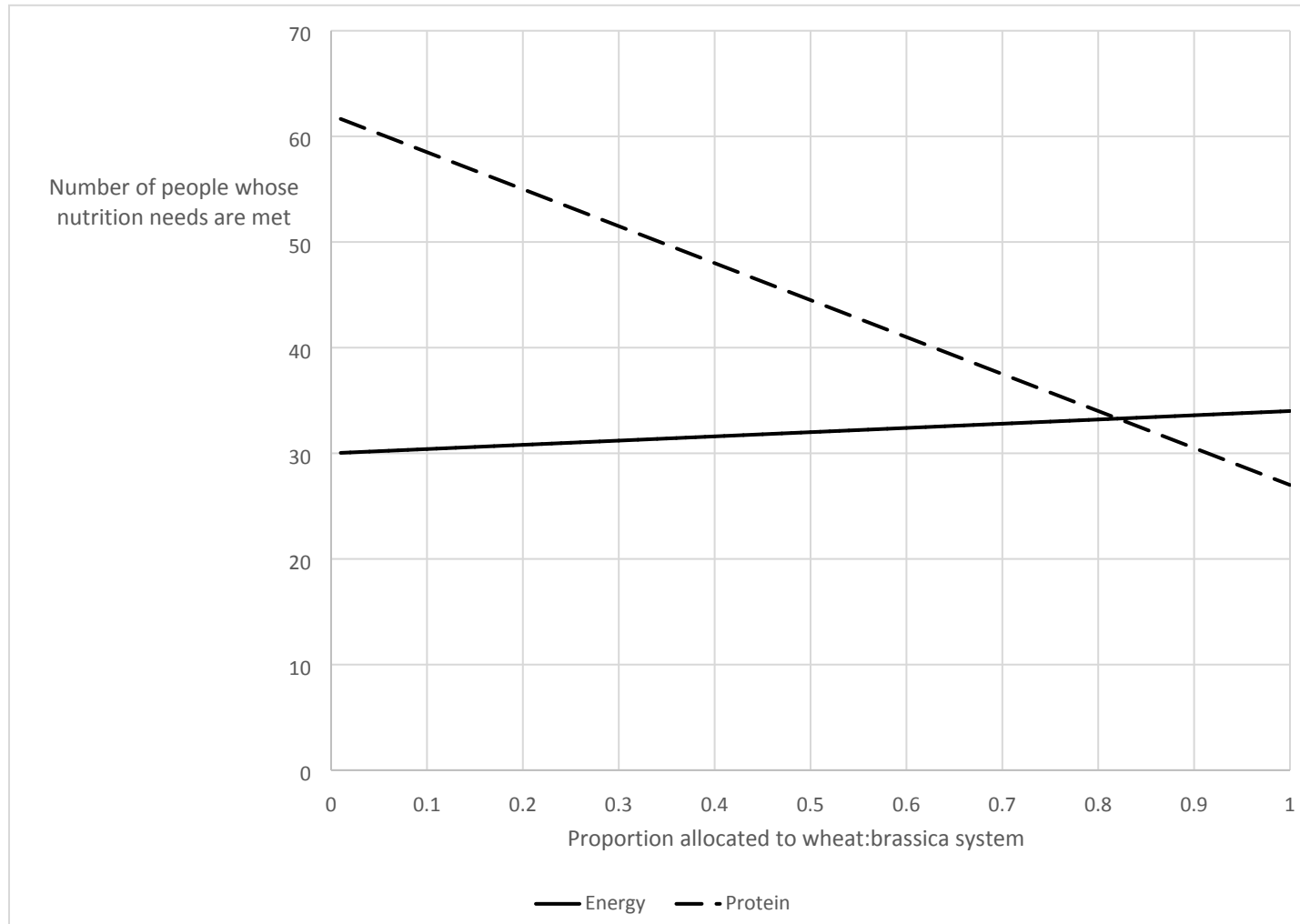
498 Figure 1. Bars represent the ratio between the numbers of people whose annual energy needs are met by the system described, and by  
499 production of milling wheat for bread (26). Gaps in the table are because not all food ingredients can be produced from any given  
500 arable production system.



502

503 Figure 2. Bars represent the ratio between the numbers of people whose annual protein needs are met by the system described, and by  
 504 production of milling wheat for bread (16). Gaps in the table are because not all food ingredients can be produced from any given  
 505 arable production system.

507

508  
509

510 Figure 3. Estimation of optimal allocation of prime arable land to maximise the number of people fed (per hectare basis, meeting both  
511 energy and protein needs).