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Swiss agriculture can become more sustainable and self-sufficient by shifting from forage to grain legume production

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Switzerland's livestock production causes high environmental costs and depends strongly on feed imports. While plant-based protein demand increases, the local grain legume production is negligible (~ 9000 hectares). Here, we investigated the potential of sustainable legume protein production based on an expert survey followed by a quantitative analysis based on yield, soil, terrain and climate data.

Pea, soybean and faba bean showed high potential for Swiss agriculture given adaptions in policy, pricing and breeding. The potential grain legume production area was 107,734 hectares on suitable arable land (Scenario I). Switzerland's self-sufficiency could be increased by cutting imports and maximizing legume production on 181,479 hectares (Scenario II) in expense of grassland and fodder maize. This would replace approximately 41% of animal protein consumption with plant-based protein, preserving 32% of milk and 24% of meat protein. In conclusion, domestic legume production could be substantially increased while improving human and environmental health.

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Global food systems require radical change to sustain human and environmental health[1]. The Swiss agricultural production is an European hotspot in terms of external costs for the environment and health, with estimated damage of over 26 billion USD per year, and third highest negative externalities per calorie supplied in the world[2]. In Switzerland, agriculture accounts for more than 14.6% of the greenhouse gas (GHG) emissions which mainly originate from livestock production (about 85% of the 6.34 Mio. t CO2eq)[3,4]. Therefore, sustainable and resource-conserving food production requires substantial decrease in livestock and thus in meat consumption[5]. Animal-based protein can be sustainably replaced by plant-based proteins from legumes[6,7]. This decreases the environmental footprint in two ways: First, the production of legume-based meat analogues releases up to five and fifty times less GHG emissions compared to egg and meat production, respectively[8,9]. Second, legumes are able to fix nitrogen from the atmosphere due to their symbiosis with bacteria[10]. As a result, they require less or no nitrogen fertilisation during cultivation and have a high value as pre-crop[11,12]. Introducing grain legumes into crop rotation was one of the most effective measures to mitigate nitrogen pollution from global cropland[13]. The amount of nitrogen fixed by legumes varies between 20-200 kg N ha^{-1}, depending on species and environmental influences[14]. Furthermore, legume cover crops can be used for carbon sequestration[6,12].

Beside environmental advantages, the nutritional composition of grain legumes - dietary fiber, essential amino acids and protein content - makes them interesting for a healthy diet. Additionally, grain legumes have a low glycemic index, are gluten-free and contain antioxidants as well as micronutrients[15]. A reduction of meat consumption by 66% is recommended by the Federal Food Safety and Veterinary Office (BLV) to prevent diseases such as cancer, diabetes and cardiovascular diseases and therefore reduce health system costs[16]. Yet, the evidence that unprocessed red meat causes these diseases is still weak[17] and legumes contain various antinutrients (Table 1). Finally, grain legumes hold economical potential, especially when they are sold as meat analogues. The sales of meat analogues from Swiss retailers almost doubled from 60 Mio CHF in 2016 to 117 Mio CHF in 2020[18].

In Switzerland, 163,844 ha were used directly for food production in 2020 accounting for 38.9% of the arable land (Supplementary Figure 1A). Grain legumes had only a minor share of 2.3% (9368 ha) of the arable land (Supplementary Figure 1B). Much larger areas were used for forage production: 111,595 ha were used for feed production (mainly maize and wheat), 125,393 ha for temporary grassland in crop rotation, while having 600,686 ha permanent grassland[19]. Additionally, almost 7000 tonnes of pea, almost 500 tonnes of faba bean and more than 330,000 t of soybean equivalents (including 250,000 tonnes of processed soybean and more than 10,000 tonnes of soybean) were imported into Switzerland in the same year[20]. Assuming a soybean yield of 3.3 t ha^{-1}, these imports require additional land of 100,000 ha abroad and were necessary to sustain livestock production.

Swiss meat production increased substantially until the 1980s, stabilizing at about 450,000 t per year during the last 40 years (Supplementary Fig. 1C). The per capita meat consumption ranged between 30 kg in the year 1950 and 62 kg in the year 1982, stagnating at around 50 kg on average after 1995 (Proviande.ch). Meanwhile, on much lower level, the sales of meat analogues showed a sharp increase during the last five years to about 5000 t in 2020 (Supplementary Fig. 1D). This corresponded to a per capita consumption of about 0.57 kg per year.

Similar to Switzerland, Europe is highly dependent on soybean import (Supplementary Figure 2). European protein self-sufficiency could be highly improved by expanding the share of cropland dedicated to soybean or other grain legume production[21]. Despite certain disadvantages of current varieties, the legume species characterized in Table 2 are interesting for cultivation in Europe, especially Switzerland: Pea (*Pisum sativum* L.) can be sown up to 600 m a.s.l. as a winter crop or 1200 m a.s.l. as a summer crop[22] but need a cultivation break of six to seven years. Faba bean (*Vicia faba*), also known as "broad bean" or "horse bean", can be sown up to 700 m a.s.l. but they contain antinutritive substances[23]. Soybean (*Glycine max* (L.) Merr.) was bred for the colder Swiss and Continental European climate[24] and their cultivation regions correspond to those of grain maize[25]. The maximum altitude for cultivation was recommended to be 500 m a.s.l[22]. Lupin (*Lupinus spp.*), lentil (*Lens culinaris*), and common bean (*Phaseolus vulgaris*) also show potential for cultivation; however, little knowledge about cultivation and varieties is available for Switzerland.

The objectives of this study were to assess the potential of agricultural land in Switzerland for legume cultivation and to analyze the self-sufficiency of Switzerland's protein production. First, a qualitative study was conducted among experts of the food value chain to assess the potential of different grain legume species. The aim was to evaluate the challenges and opportunities of grain legume cultivation for human consumption. Second, two scenarios were developed to assess the potential of grain legume production. Scenario I evaluates only arable land which is already under crop rotation as legume production area whereas scenario II includes also suitable permanent grassland. Higher altitudes for legume cultivation were considered using growing degree days (GDD) based on temperature data of the last 30 years. Third, the protein self-sufficiency of Swiss agriculture was analyzed under increased legume production while decreasing livestock and feed production as well as minimizing feed import.

Table 1 Overview of nutritional benefits and antinutrients in selected grain legumes based on the literature.

	Nutritional benefits	Antinutrients
Soybean	rich in all essential amino acids [57]	tripsin inhibitors[58]; purine[59]
Common pea	vitamin and mineral content[60]	tripsin inhibitors[29]
Faba bean		tannins, trypsin inhibitors[5]
Lentil	rich in iron and zinc[61]	tannins[61]
Common bean	rich in iron and zinc[62]	
Lupin	high protein content[63]	alkaloids[25]
Chickpea	high lysine, low methionine and cysteine[64]	phytic acid, tannins[65]

Results & Discussion

Feasibility of grain legume production in Switzerland: Qualitative assessment. Based on the expert interviews of the qualitative analysis, the greatest challenge for the production of grain legumes in Switzerland lies in the pricing structure (from an economical point of view) and the political framework (Fig. 1). The political framework encompasses the tariff protection and the financial discrimination of grain legumes grown for human consumption compared to those grown for feed (except for soybean). The financial discrimination was only recently removed in 2023 by new subsidy regulations[26]. The cultivation of pea and soybean in Switzerland is economically comparable to winter wheat according to a recent study[27]. The third most named challenge for wider use of grain legumes was the lack of breeding programs causing a lack of site-adapted varieties and agronomic measures. The supply chain (downstream of the production) was

Table 2 General information on the cultivation of selected grain legumes in Switzerland.

	Climate / Soil	Opportunities	Stress factors	Max. altitude (m.a.s.l.)	Cultivation break (a)	Yield average[g] (t ha^{-1})	Area average[g] (ha)	Protein content (g kg^{-1} DM)
Grain legumes in total		N fixation[25]	Weeds, Lodging[25]			2.8 (± 0.46)	7102.00 (± 214.91)	
Soybean	Warm conditions[25]	Adapted to Swiss climate[24]; cold tolerance	Drought[66]	500 [22,54] - 600[f]	3	2.72 (± 0.49)	1802.8 (± 134.42)	395.782[d]
Common pea	Light fertile and well-drained soils; Tolerate low temperatures[67]	Adapted to Swiss climate	Water logging[25]	600[a], [22,54] 1200 - 1300[b,f] [22,54]	6-7	3.06 (± 0.66)	4216.8 (± 312.99)	214.455[d]
Faba bean	Soil pH best 6.5–9.0[65]		Water logging[68]; Drought[67]	600[a] [22,54] 700 - 800[b,f] [22,54]	3	2.66 (± 0.43)	929.4 (± 161.07)	295.99[d]
Lentil	Calcareous and easily warmed soils with good aeration[25]	Adapted to cold temperatures[25]	Water logging[25]	NA	NA	NA	NA	291.95[e]
Common bean	Easily warmed deep soils[25]	Drought tolerant[25]	Water logging; Cold weather (below 2°C)[25]	NA	NA	NA	NA	257[d]
Lupin	Soil pH > 6.5[c]	Attractive to insect pollinators	Anthracnose[69]	600[22,54]	3	2.74 (± 0.58)	153 (± 39.74)	348.95-367.587[d]
Chickpea	Warm and dry climate[25]	Drought tolerant[25]	Ascochyta blight[70,71]; Water logging[25]	NA	NA	NA	NA	240.55[e]

Growth conditions in terms of climate and soil, opportunities, challenging biotic and abiotic stress factors, agronomic requirements, yield and cultivation area (±standard deviation) are listed.
[a]as a winter crop
[b]as a summer crop
[c]for white lupins
[d]Swiss Feed Database, [e]USDA Food composition Database, [f]Supplementary Figure 5,6,7, [g]FAOSTAT for the years 2016 to 2020

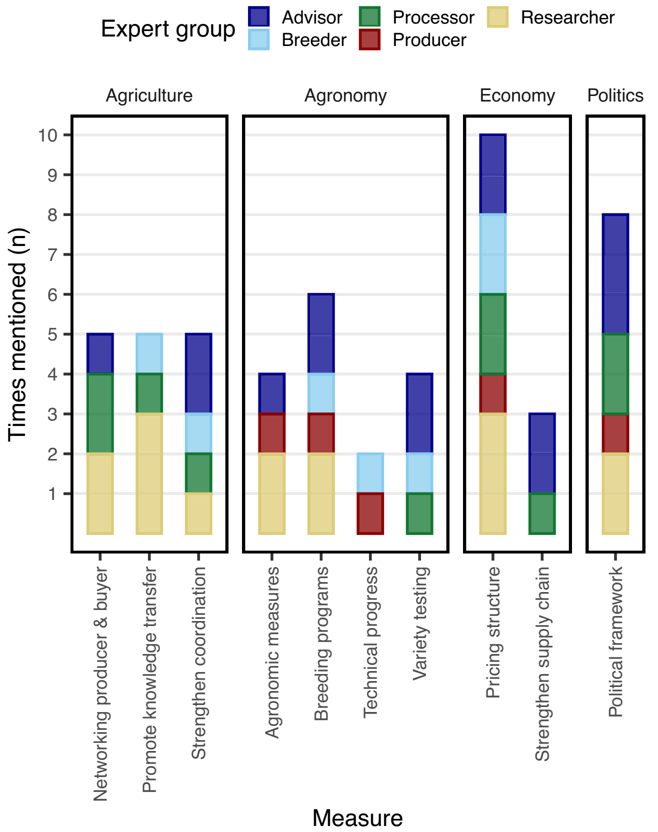

Fig. 1 Measures to increase grain legume production in Switzerland. Answers from 15 experts to the interview question "In your opinion, what measures could be taken to increase grain legume production in Switzerland?". The answers are grouped according to the different sectors addressed in the questions. Colors indicate professions of the experts.

mentioned as another challenge, meaning that there are not sufficient collection points for producers. The producers also lack knowledge about the quality demands of the food industry. Similarly, Watson et al.[28] stressed the importance of inclusion of the whole supply chain to stimulate grain legume production. The risk of a poor harvest or even total failure, meaning low yield stability, can be seen as one of the biggest agronomic challenges (Fig. 1). In agreement, it was reported that low profitability, yield fluctuations and sensitivity to biotic stress as main constraints to global legume production[7]. The relatively small amount of research into cultivation techniques - when compared to other crops - and the lack of experience among farmers play a subordinate role. With the exception of soybean, adapted varieties and specific recommendations for farmers are currently missing in Switzerland (but are progressing, especially for pea, according to the results of the survey).

Depending on the grain legume species, the qualitative survey revealed large differences in the estimated cultivation potential. (Supplementary Figure 3). In particular, common pea and soybean showed great potential for being cultivated in Switzerland. Pea has been established in Switzerland as a forage crop for many years and are better adapted to Swiss climate than other grain legumes such as chickpea. Additionally, peas are characterised by an appealing nutritional composition[29]. The progress in soybean breeding made by the Swiss national breeding program of Agroscope over the last 40 years has set an example for adapting grain legumes to the national conditions; both with respect to the relatively cold, moist climate and with respect to market demand[24,30,31].

Potential for grain legume production: quantitative assessment. For the quantitative assessment, the potential production of grain legumes was estimated and compared with the agricultural production in recent years as baseline. In 2020, Swiss farmers cultivated 397,896 ha arable land and 600,686 ha permanent grassland. Temporary grassland and fodder maize accounted for 125,393 and 46,847 ha[19]. The cultivated area for soybean, faba bean and dry pea was 2042, 957 and 3573 ha, respectively. Between 2016 and 2022, the protein yield for soybean, faba bean and pea ranged from 0.82 to 1.32 t, 0.60 to 0.93 t and from 0.42 to 0.77 t, respectively (Table 3). The domestic ruminant and monogastric protein production was 128,478 t and 63,836 t, respectively (equation (1) and (2)). This production consisted of 7497 t egg, 103,999 t milk and 80,818 t meat protein. Together with 11,870 t of net imported animal protein, the total consumption of animal protein in Switzerland amounted to 204,184 t according to equation (3). The total used animal fodder in Switzerland is summarized for concentrated feed in Table 4 and for roughage in Table 5. In 2020, the fodder use was 7,752,000 t dry matter (DM) of which about 5,876,765 t were roughage and 1,523,395 t concentrated feed according to the statistical service of the Swiss Farmers' Union (AGRISTAT)[32]. Between 2016 and 2022, the roughage production ranged from 5,849,755 t to 5,937,313 t DM (Table 4). About 54% of the concentrated feed was imported in the year 2020, including 369,067 t of side products and 388,755 t of cereals[20]. The gross and net self-sufficiency of Switzerland's agriculture was 55.6 and 49.3%.

The potential area for grain legume cultivation in Switzerland was estimated based on agronomic soil properties, altitude and climate expressed as GDD using equation (4). The daily temperature average during the growing season for soybean, faba bean and pea increased by about 2°C in the last 30 years, i.e., the required GDD for cultivation were reached at higher altitudes (Supplementary Figure 5, 6, 7). Therefore, the maximum altitudes for cultivation of the three legumes were elevated by 100 m compared to the literature[22]. The potential area for soybean, faba bean and dry pea cultivation was assessed based on arable land (Scenario I, moderate) and including suitable permanent grassland (Scenario II, maximal) (Fig. 2A). Relatively large areas, especially above 800 m.a.s.l., were additionally identified in scenario II compared to the moderate scenario I (Fig. 2B). The areas of Scenario I and II are often contiguous, making cultivation feasible (Fig. 2C, Supplementary Figure 4). On the identified areas, the protein production in crop rotation was estimated for both scenarios in two ways: when only a single legume would be cultivated and when the three legumes species would be grown combined at the same time.

In scenario I, the potential area for the single cultivation of soybean, faba bean and pea on Swiss arable land was 206,422, 282,625 and 294,875 ha, respectively (Table 3). This corresponded to a production area of 51,605, 70,656 and 42,125 ha with three, three and six years cultivation break in the crop rotation, respectively. These numbers represent a more than 15, 60 and 11-fold increase in production area compared to the area in 2020 for soybean, faba bean and pea, respectively (Table 2, Supplementary Figure 1A). With such an increase, soybean, faba bean and pea could produce 55,230 (± 8607), 54,099 (± 8021), and 25,109 (± 4877) t of protein equivalent to 57 (± 9), 34 (± 5) and 21 (± 4)% of meat protein consumed in Switzerland, respectively (Table 3). Next to single cultivation, the legume species could be combined vertically on different altitudes according to their niches and horizontally having two grain legumes in the crop rotation at the same time. This would cover maximally 37.5% of the agricultural land and result in the following combined production: below 600 m a.s.l., soybean (51,605 ha) and faba bean

Table 3 Potential area and production for selected grain legumes in Switzerland.

Scenario	Crop	Cultivation break	Protein yield	Potential area	Production area single	Protein production single	Replacing meat protein single	Potential area combined	Production area combined legume 1	Production area combined legume 2	Production area combined	Protein production combined	Replacing meat protein
		(a)	(t ha^{-1})	(ha)	(ha)	(t)	(%)	(ha)	(ha)	(ha)	(ha)	(t)	(%)
I	Soybean	3	1.07 (±0.17)	206,422	51,605	55,230 (±8607)	57 (±9)	206,422	51,605	0	51,605	55,230 (±8607)	57 (±9)
I	Faba bean	3	0.77 (±0.11)	282,625	70,656	54,099 (±8021)	34 (±5)	76,203	19,051	25,803	44,854	34,343 (±5092)	21 (±3)
I	Pea	6	0.6 (±0.12)	294,875	42,125	25,109 (±4877)	21 (±4)	12,250	1750	9525	11,275	6721 (±1305)	6 (±1)
I	Total							294,875	72,406	35,328	107,734	96,293 (±15,004)	84 (±13)
II	Soybean	3	1.07 (±0.17)	319,359	79,840	85,447 (±13,316)	89 (±14)	319,359	79,840	1531	81,371	87,086 (±13,572)	90 (±14)
II	Faba bean	3	0.77 (±0.11)	460,826	115,206	88,209 (±13,078)	55 (±8)	141,467	35,367	39,920	75,287	57,644 (±8,546)	36 (±5)
II	Pea	6	0.6 (±0.12)	510,795	72,971	43,495 (±8448)	36 (±7)	49,970	7139	17,683	24,822	14,795 (±2874)	12 (±2)
II	Total							510,795	122,345	59,134	181,479	159,525 (±24,992)	139 (±22)

The potential area and production in scenario I and II for one single legume or with other legumes combined in crop rotation. The potential area is the available land per legume species. The production area single and protein production single takes the cultivation break into account for each legume species separately, i.e., only one single legume is cultivated at the same time. The potential area combined is the available land for soybean, faba bean and pea when growing these legumes at the same time in low, middle and high altitudes, respectively. The production area combined accounts for the cultivation of one legume (max. 25% of the potential area) together with a second legume (additionally 12.5% of the potential area) at the same time in the crop rotation. That results in soybean with faba bean up to 600 m.a.s.l., faba bean with pea between 600 to 800 m.a.s.l. and pea only between 800 to 1300 m.a.s.l. Protein yield averaged the FAOSTAT yield data from 2016 to 2020 and protein content was taken from the Swiss Feed Database. The standard deviation is shown in brackets.

(25,803 ha), between 600 and 800 m a.s.l., faba bean (19,051 ha) and pea (9525 ha) and above 800 m a.s.l., pea only (1750 ha). In such a crop rotation, the total legume protein production would reach a total of 96,293 (± 15,004) t on 107,734 ha land (Table 3). This would be sufficient to replace 84 (± 13)% of the consumed meat protein in Switzerland with plant-based protein. However, the higher proportion of legumes in this crop rotation would require more research about soil health, due to the risk of "soil fatigue"[33]. A reduction of 70% of meat consumption was recommended to halve environmental impacts on food, especially reducing GHG emission and deforestation pressure due to soybean imports[5].

In scenario II, suitable permanent grassland was converted into additional arable land. In single cultivation, faba bean could substitute 55 (± 8)% of Switzerland's total meat protein consumption (Table 3). This production would correspond to an area of 460,826 ha for faba bean, i.e., 115,206 ha of production area with cultivation break. The combined protein production of the three legume species could reach 159,525 (± 24,992) t (on 181,479 ha), corresponding to 139 (± 22)% of Swiss meat protein consumption. In this scenario, the conversion of permanent grassland would increase the arable land by 49,939 ha (Supplementary Table 1). The legume production area in crop rotation would increase by 73,745 ha or 68.5% compared to scenario I.

Improved self-sufficiency of Swiss agriculture. With more grain legumes in the crop rotation, some non-legume crops would be partly replaced. The maximum production area for legumes in Switzerland was 181,479 ha for scenario II (Table 3). A 70% reduction of temporary grasslands (-87,775 ha) and fodder maize area (-32,793 ha) compared to the baseline, as well as of 8% of the permanent grassland (-46,230 ha, which could be converted to arable land) would be required to maximize legume production (Table 4). This would result in a total loss of 1,831,831 (± 4897) t DM roughage. The available concentrated feed equaled to 328,762 t DM according to equation (5) when minimizing feed import. At the same time, the mentioned production of 159,525 (± 24,992) t legume protein for fodder and food could be achieved.

The grain legume and roughage that could be produced on these defined areas were estimated and varied in order to assess the effects on the proportion of ruminants with reduced feed compared to the baseline ($r_{ruminants}$) and the proportion of monogastrics with reduced feed compared to the baseline ($r_{monogastrics}$). The self-sufficiency was optimized by balancing the produced grain legume protein into feed and food according to the equations (6) to (10). The feed composition and distribution between ruminants and monogastric animals was maintained. Imports of concentrated feed and animal protein were minimized. Under these conditions, the $r_{ruminants}$ and the $r_{monogastrics}$ decreased to 0.69 (± 0.002) and 0.66 (± 0.06), respectively (Fig. 3A and B). The gross and net self-sufficiency would increase from 55.6 and 49.3 % as in the year 2020 to 58.9 (± 1.2) and 58.4 (± 1.2)%, respectively (Fig. 3C). While animal gross production would decrease from 11,473 to 8580 (± 252) TJ, the plant gross production would increase from 11,228 TJ to 13,585 (± 351) TJ (Supplementary Table 2).

Under this improved self-sufficiency, 136,869 (± 56,952) t of concentrated feed, equalling about 68'000 t of legume protein, would be newly available from domestic production (Fig. 4A). The reduction in ruminants due to less available roughage would free up concentrated feed for monogastric animals: 62,309 and 86,428 t DM of cereals and side products (mainly soybean) per year, respectively (Table 5). However, compensating for the 632,500 t of concentrated feed imports would still reduce

Table 4 Reduction in roughage production when expanding grain legume production.

Animal	Feed	Feed item	Feed baseline (t DM)	Reduction in roughage area (ha)	Reduction in roughage (t DM)	Feed reduced (t DM)	Proportion
Ruminants	Roughage	Fodder maize	813,688 (± 53)	-32,793	-577,371	240,064 (± 666)	0.3 (± 0.001)
Ruminants	Roughage	Temp. grassland	1,484,415 (± 97)	-87,775	-1,053,301	437,950 (± 1,215)	0.3 (± 0.001)
Ruminants	Roughage	Perm. grassland	3,372,385 (± 27,925)	-43,937	-174,384 (± 1,154)	3,213,532 (± 26,991)	0.95 (± 0.001)
Ruminants	Roughage	Others	143,534 (± 9)	0	0	144,195 (± 117)	1 (± 0.001)
Monogastrics	Roughage	Fodder maize	11,128 (± 53)	0	-3,747 (± 665)	7,381 (± 666)	0.66 (± 0.06)
Monogastrics	Roughage	Temp. grassland	20,301 (± 97)	0	-6,836 (± 1,213)	13,465 (± 1,215)	0.66 (± 0.06)
Monogastrics	Roughage	Perm. grassland	46,120 (± 159)	0	-15,530 (± 2,755)	30,589 (± 2,755)	0.66 (± 0.06)
Monogastrics	Roughage	Others	1963 (± 9)	0	-661 (± 117)	1,302 (± 117)	0.66 (± 0.06)
Total Ruminants	Roughage	All	5,814,022 (± 28,084)	-164,505	-1,805,056 (± 1,154)	4,035,741 (± 27,389)	0.69 (± 0.002)
Total Monogastrics	Roughage	All	79,512	0	-26,775 (± 4,749)	52,737 (± 4,749)	0.66 (± 0.06)
Total	Roughage	All	5,893,534 (± 28,084)	-164,505	-1,831,831 (± 4,897)	4,088,478 (± 26,931)	0.69 (± 0.001)

Roughage dry matter (DM) for ruminants and monogastric animals was reduced according to scenario II compared to the baseline. The feed baseline averaged the actual production of the years 2016 to 2020. The reduction in roughage area and production as well as the new production quantities (feed reduced) when increasing grain legume production resulted in new proportions of roughage production for ruminant and monogastric animals compared to the baseline. Data for feed baseline was from Giuliani[32]. The standard deviation is shown in brackets.

Table 5 Reduction in concentrated feed when minimizing imports and expanding grain legume production.

Animal	Feed	Feed item	Feed baseline (t DM)	Import (t DM)	Legume feed new (t DM)	Reduction in conc feed (t DM)	Feed reduced (t DM)	Proportion
Ruminants	Concentrated	Cereal	204,046 (± 871)	0	0	-62,410 (± 167)	141,636 (± 883)	0.69 (± 0.002)
Ruminants	Concentrated	Side Products	283,032 (± 1208)	0	0	-86,569 (± 231)	196,463 (± 1,224)	0.69 (± 0.002)
Ruminants	Concentrated	Conc others	75,054 (± 2078)	0	0	-22,959 (± 735)	52,095 (± 1,347)	0.69 (± 0.002)
Monogastrics	Concentrated	Cereal	595,745	-344,076	0	-200,611 (± 35,580)	395,134 (± 35,580)	0.66 (± 0.06)
Monogastrics	Concentrated	Conc others	61,711	0	0	-20,780 (± 3,686)	40,930 (± 3,686)	0.66 (± 0.06)
Monogastrics	Concentrated	Side Products	303,806	-288,424	136,869 (± 56,952)	-102,304 (± 18,144)	201,502 (± 18,144)	0.66 (± 0.06)
Total Ruminants	Concentrated	All	562,133	0	0	-171,938 (± 857)	390,195 (± 857)	0.69 (± 0.002)
Total Monogastrics	Concentrated	All	961,262	-632,500	136,869 (± 56,952)	-323,696 (± 57,409)	637,566 (± 57,409)	0.66 (± 0.06)
Total	Concentrated	All	1,523,395	-632,500	136,869 (± 56,952)	-495,634 (± 56,948)	1,027,761 (± 56,948)	0.67 (± 0.037)

The reduction in concentrated feed dry matter (DM) for ruminants and monogastric animals when expanding grain legume production. The feed baseline production averaged the actual production of the years 2016 to 2020 of which the import of the year 2020 was substacted and parts of domestic grain legume production under scenario II (legume feed new) was added. The reduction in concentrated feed area and production as well as the new production quantities (feed reduced) when increasing grain legume production resulted in new proportions of concentrated feed production for ruminant and monogastric animals. Data for feed baseline was from Giuliani[32], the area data from BLW[19] and the import data from Agristat[20]. The standard deviation is shown in brackets.

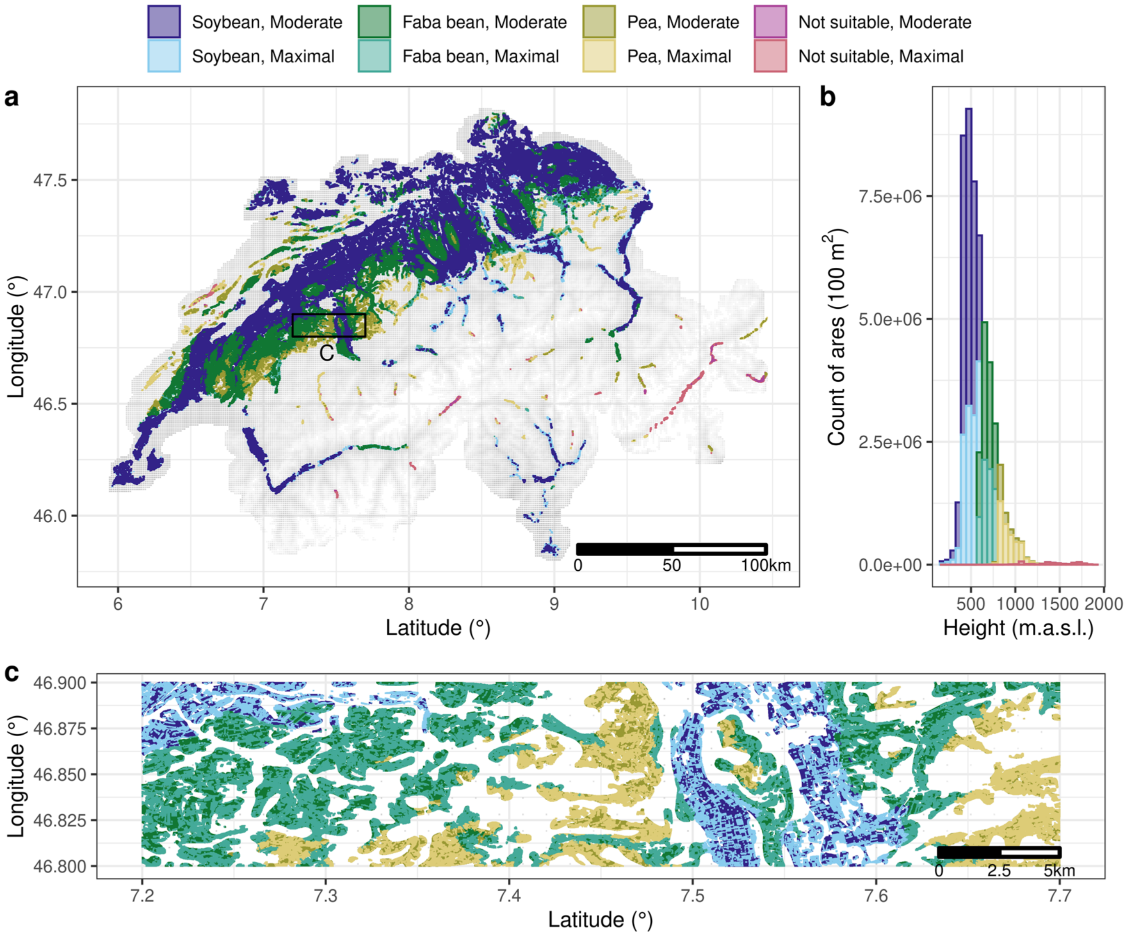

Fig. 2 Potential area for cultivation of selected grain legumes in Switzerland. The potential areas are defined by land suitability including soil properties, GDD and the maximum cultivation altitudes specific to soybean (purple), faba bean (green) and pea (yellow) on arable land (Scenario I, moderate; dark colors) and additionally including suitable permanent grassland (Scenario II, maximal; light colors). Not suitable areas due to GDD and altitude are displayed (pink), while not suitable areas due to land suitability were excluded. The areas are shown **a:** spatially distributed for whole Switzerland, **b:** as histogram counting ares (10 m × 10 m) and **c:** detailed for a region south of the city of Bern.

monogastric animal production. The reduction in animal production would decrease milk (-22,750 (± 158) t) and meat protein (-26,459 (± 3345) t produced and -15,486 t net import) which would be replaced by 91,090 (± 4649) t of grain legume protein for direct human consumption (Fig. 4B). This would result in a new protein diet of 37.8-44.0% grain legume protein, 32.2-32.7 % milk protein, 21.9-26.9 % meat protein and 1.9-2.6% egg protein. The baseline was approximately 54% milk and 46% meat protein (including meat and feed imports), i.e., meat protein consumption of the Swiss population would be halved.

Ecological impact. About 85% of GHG in Swiss agriculture is due to livestock production[3]. To a certain extent, climate gas emission can be decreased by technical optimization. However, the overall decrease in animal production is crucial regarding national efforts to decrease GHG emissions[3]. The estimated reduction of about 33 (± 0.04) % of livestock production, while increasing self-sufficiency, would contribute to those efforts. Furthermore, legumes in crop rotation reduce fertilizer needs for the legume itself and potentially for the following crop in the rotation[34]. Nitrogen oxide emissions and nitrogen fertilizer use is reduced when introducing legumes into the crop rotation[35]. Nitrogen fertilization for cereals after a legume can be reduced up to 30 kg ha^{-1} while still producing higher yields and up to 60 kg ha^{-1} under low nitrogen input[11]. In addition, legumes showed potential for carbon sequestration in general[34], and specifically as cover crop[12,34]. More studies are needed to investigate carbon sequestration in a crop rotation as suggested in this study. The conversion of permanent grassland into arable land likely would release CO_2 from soil organic matter[36] and increase erosion on steeper cultivation area. These effects should be minimized with adapted management and would be suitable only for minor permanent grassland areas. Permanent grassland will keep its value for agricultural systems, especially as swards at higher altitudes mixed with about 30-50% of forage legumes[37]. In this way, land that is not suitable for arable crops can be included to produce food through ruminants[37]. Even if temporary grassland would be largely replaced by legume cultivation, temporary grassland would be kept in some crop rotations, e.g., when the disease pressure from soil-borne pathogens is high. Lastly, a decrease in soybean imports would remove pressure on global deforestation and water-use.

Challenges for increased legume production. The cultivation of grain legumes is hampered by a number of factors along the agro-food supply chain. Grain legume production strongly relies on resilient varieties adapted to local climate and soil conditions[38]. The effect of intensified legume production in crop rotation needs to be studied in more detail, especially regarding the pea root rot complex, also called "soil fatigue"[33,39]. Pea lines, which show

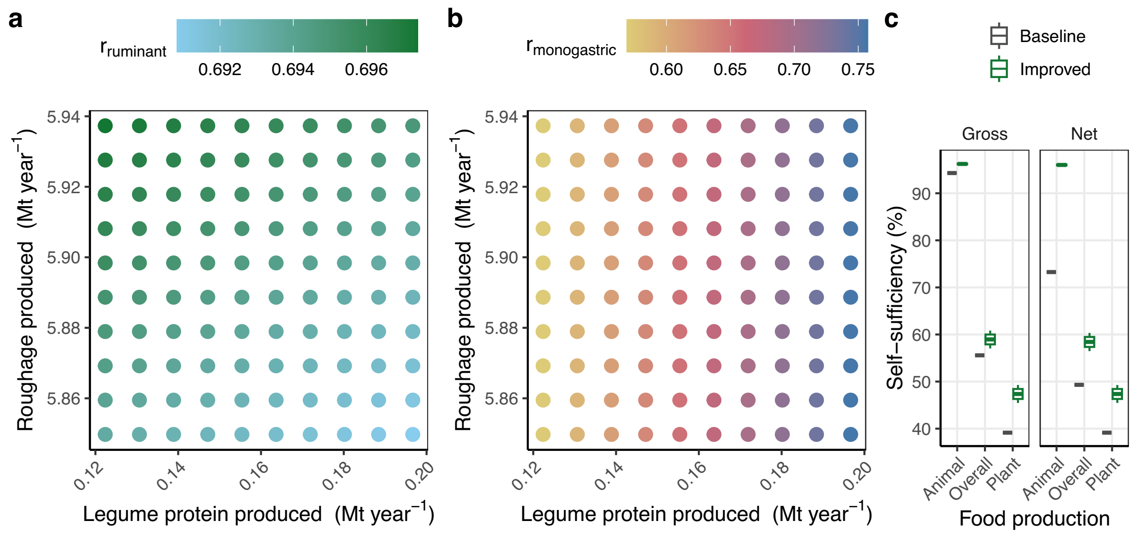

Fig. 3 Sensitivity analysis with varying grain legume and roughage production as inputs. a: The sensitivity of $r_{ruminants}$ and **b:** the $r_{monogastrics}$ was calculated under fluctuating grain legume protein and roughage production. The range was based on the maximum and minimum yield values in the years 2016 to 2020 (n=100). The production is in million tonnes of dry matter per year (Mt year^{-1}). The legume production area was maximized in expense of grassland and fodder maize. **c:** The gross and net self-sufficiency was improved with increased legume production and reduced imports compared to the baseline in 2020. In the case of improved gross self-sufficiency, feed imports were minimized while egg and meat import were set to zero. In the case of improved net self-sufficiency, imports (feed, egg and milk) were set to zero. The boxplot shows the median (bold line) and the upper and lower quartiles (box) of the self-sufficiency values with varying input (n=100 for improved gross and net self-sufficiency; n=1 for the baseline in 2020).

resistance against pea root rot complex[40], require adaption to local agricultural conditions. Additionally, the nutritional quality of grain legumes needs to be improved - while decreasing anti-nutritive substances.

To improve organization of an increased legume market, establishment of regional process centers to support legume production might be beneficial - similarly as implemented for the relatively highly subsidised Swiss sugar production. These process centers could also take care of the quality control and thus act as a link to fill the gap between farmers and industry. Consumer acceptance of plant-based proteins generally is still low, but steadily increasing according to a recent review including 91 articles[41]. Policy intervention to stimulate grain legume production in Europe was not successful so far[28]. Yet, in Canada and Australia, national approaches were successful since they included *"supply chains, and policy support as well as technical improvements of grain legume production such as breeding of new varieties and management development to improve yield stability"*[28].

Limitations of the study. Although based on empirical data, several assumptions limit our study: *i)* Estimates of the potential legume areas were based on GDD, soil types, characteristics and altitudes. The yield was approximated as average over the areas. However, more detailed evaluation and yield predictions as, e.g., shown by Guilpart, Iizumi and Makowski[21] need to be performed, including other climatic factors, such as precipitation or erosion risks. This could slightly change the resulting numbers for the protein production, but would most likely not affect the main conclusions of this study. In fact, the variation for $r_{ruminants}$ and self-sufficiency was around ± 6 and ± 1.2% with varying yield over the years, respectively (Table 5, Supplementary Table 2). *ii)* The focus of this study was on proteins. For other nutrients, like fat, results would differ. The protein quality of legume species is generally lower compared to animal-based proteins and was adjusted based on an averaged Digestible Indispensable Amino Acid Score (DIAAS). However, the DIAAS varies depending on food preparation and meal composition, e.g., mixing faba bean with corn and potato improves the protein quality such that it is comparable to meat[42,43]. Micronutrients such as iron, zinc, magnesium and vitamin B12, which are present in grain legume and/or animal protein were not considered in this study[44,45]. *iii)* The assessed crop rotation is only one possibility of many and will rely on many factors, e.g., the proportion of maize and grass in the ruminant feed composition. *iv)* More studies are needed to assess economical impacts of increased legume production, especially when changing from grassland to crop production. However, the three investigated legumes are economically competitive with winter wheat in Switzerland: Zorn and Lips[27] estimated a remuneration of 61, 37, 52 CHF h^{-1} for soybean, faba bean and pea, respectively, while it was 46 and 2 CHF h^{-1} for winter wheat and fodder barley, respectively. Soybean can also be competitive against soybean fodder imports when process chains are established[27]. Overall, the results of this study give an estimation on the potential of legume-based protein production in Switzerland. To which extent this can be realized and how this will affect real-life sustainability of national farming efforts depends on an interplay of policy, food industry, consumer behavior, ecology and agriculture[46].

Conclusion

The qualitative expert assessment showed that the potential of grain legume cultivation in Switzerland is high. Various experts along the value chain see an increasingly important role for the production of plant-based proteins as meat substitutes. Soybean, faba bean and dry pea are particularly interesting for cultivation in Switzerland. In addition to progress in breeding (yield stability, disease resistance, competition with weeds, site adaptation), this also requires interactions among the agri-food chain between society, agriculture and industry.

The quantitative study showed that there is also a great cultivation potential that has not yet been exploited. Legume protein could be produced in Switzerland in quantities exceeding the currently consumed meat protein. Parts of fodder production (70% of temporary grassland and fodder maize area) could compensate for the increased legume production area. This would decrease the ruminant and monogastric production by 33

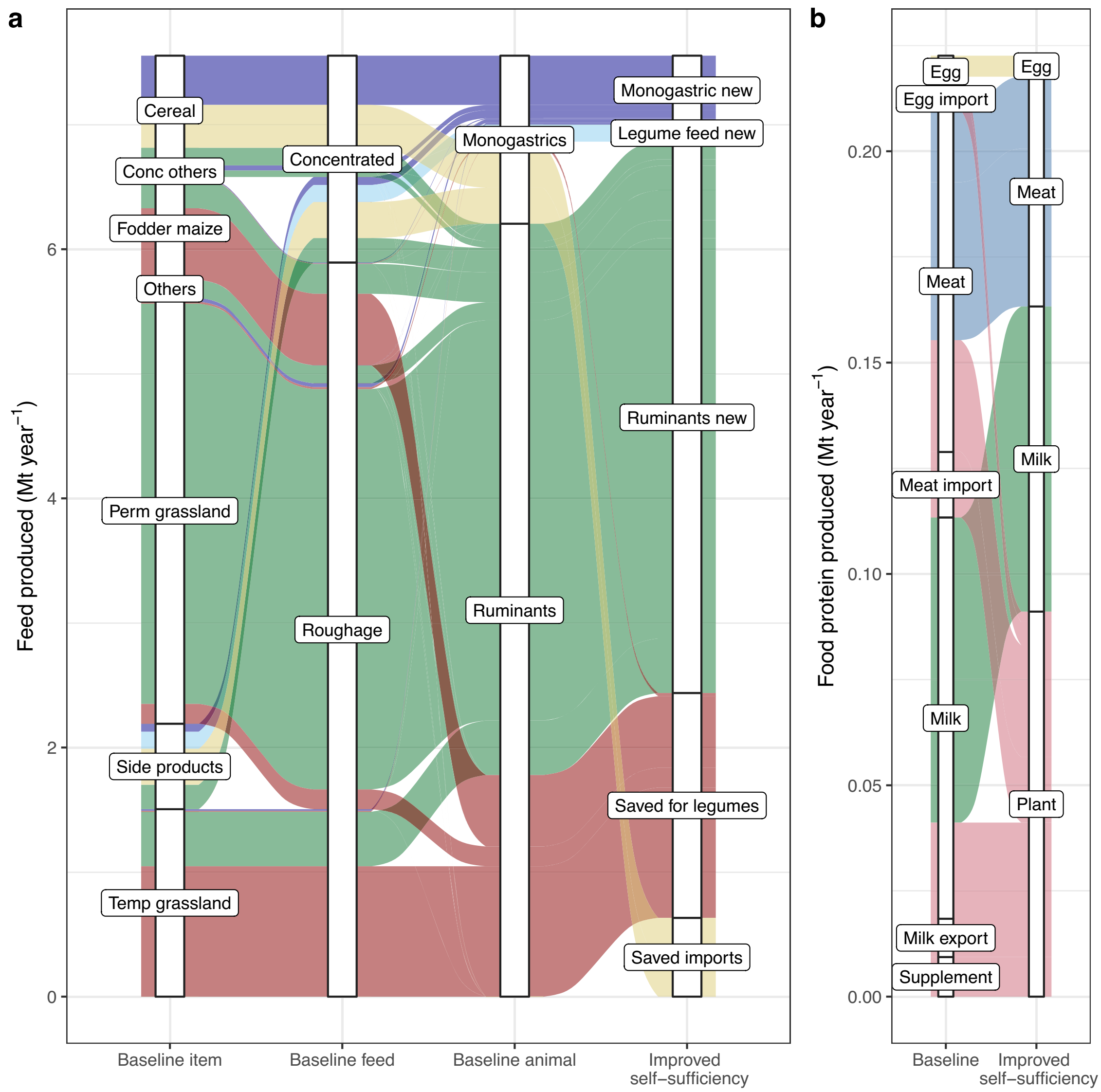

Fig. 4 Changes in agricultural production in Switzerland with improved self-sufficiency. a: Changes in feed production when improving self-sufficiency compared to the baseline. The legume production (saved for legumes) was maximized in expense of fodder maize, temporary (Temp) and permanent (Perm) grassland. Feed imports were minimized (saved imports). Grain legume protein of domestic production was partially used for feed (legume feed new) and food. **b:** Changes in food protein produced when improving self-sufficiency. Egg and meat imports were cut, and domestic egg, meat and milk protein were partially replaced by ramped up production of grain legume protein. The production is shown in million tonnes of dry matter per year (Mt year^{-1}). The values for roughage production, legume feed new and plant-based food protein production are averaged values of the roughage and legume protein production ranging between the years 2016 to 2020. Milk export and supplemental protein refers to the amount of plant-based protein which is additionally required to replace animal protein based on DIAAS.

(± 0.04) % and reduce the import of concentrated feed by more than 600,000 t. This represents one promising option to substantially increase the sustainability and self-sufficiency of Switzerland's agriculture.

Methods

Qualitative analysis. A mixed-methods study of experts along the food value chain was carried out to gather existing expertise and information on grain legume cultivation in Switzerland. First, qualitative data was collected with interviews, which were conducted with 15 experts. In a second step, additional data was collected with a survey, which was conducted with 29 experts (Supplementary Table 3). For expert selection, categories of experts along the agri-food chain were identified to obtain a good overview of the various stages from production to consumption. The categories were advisor, breeder, researcher, food processor and farmer. The experts were chosen by the criteria, that they are working in Switzerland and have experience with grain legumes from their everyday work.

The interview procedure was based on central principles of qualitative interviews[47]. The experts were asked ten questions according to an interview protocol, which we designed based on an extensive literature research (Supplementary Table 4). Literature research was done by consulting scientific articles about legumes in general, but also by consulting articles published and projects carried out in Switzerland. The questions were about assessing the current status of legume production, potential today and in future, possible research of interest and possible measures as well as about disadvantages and advantages for producers (farmers). The interviews took place in person, online via Zoom or by telephone and were conducted in English or Swiss German, depending on the expert's preference. The interviews were recorded, anonymised, fully transcribed, and then analysed. For this, statements in the transcripts were coded for content and assigned to the respective question to allow for more detailed analysis. The interviews lasted between 30 and 60 minutes each.

In a next step, the insights obtained from the interviews were used to design a 17-question survey (Supplementary Table 5). For this part of the study, we used a quantitative approach. Participants were given multiple options to choose from. For this part, 15 additional experts in the different categories were recruited, resulting in a total of 30 invited experts. For the categories of advisors, breeders, researchers and processors, two additional people from the respective areas were invited for the study. For the category of producers, seven additional people were added to the sample to be able to distinguish between organic and conventional production systems. One person from the processing sector who participated in the preliminary study did not participate in the survey, resulting in a final sample size of 29 responsive experts. The survey was carried out using an online tool, and took about 25 minutes to complete.

Ethical statement. The interviews and survey were approved by the ETH Ethics Committee under number *EK 2021-N-196*.

Agricultural production in Switzerland. The data for agricultural area was taken from fao.org/faostat (FAOSTAT) and BLW[19]. The total used animal fodder in Switzerland in 2020 were used according to the statistical service of the Swiss Farmers' Union (AGRISTAT) - an official institution of Swiss public statistics[32]. Of the total concentrated feed, 63.1% are fed to monogastric animals ($Concentrated_{monogastric,total}$) and 36.9% to ruminants ($Concentrated_{ruminant,total}$), i.e., 961,262 t and 562,133 t DM, respectively[32]. Regarding animal species, the concentrated feed is mainly fed to pigs (36.3%) and cows (25.1%). Of the total roughage, a major part of 98.6% accounting for 5,797,253 t DM in 2020 was fed to ruminants ($Roughage_{ruminants,total}$), while the part fed to monogastrics was minor ($Roughage_{monogastric,total}$= 79,512 t DM). Concentrated feed accounted for 8.3% of the ruminant diet, compared with 81% for monogastric animals[32]. The feed imports were taken from the AGRISTAT supply balance report[20].

Animal protein consumption by the Swiss population. Meat, milk and egg protein consumption for 2020 in Switzerland were taken as baseline. Meat (in retail weight) consumption was 447,482 t in 2020, i.e., on average 51 kg per capita[19]. Thereof, 15.24 kg and 35.68 kg were associated to ruminant and monogastric animals, respectively (www.proviande.ch/de/der-fleischmarkt-in-zahlen). The net import of meat amounted to 71,880 t retail weight. The protein content of ruminant and monogastric meat was approximated with 0.214 t (based on cattle meat) and 0.216 t (based on pork meat) protein per t of meat according to the Swiss Food Composition Database (naehrwertdaten.ch), respectively. Hence, 24,479 t and 56,339 t of ruminant ($Protein_{ruminants,meat}$) and monogastric ($Protein_{monogastric,meat}$) protein were produced from Swiss agriculture, respectively, and 15,486 t of meat protein was net imported. Regarding milk, 8586 TJ were produced in Switzerland of which 748 TJ were net exported[48]. The milk composition was approximated with 284 kJ per 100 ml (107.5 g) with 3.2% protein content according to the Swiss Food Composition Database (naehrwertdaten.ch). This corresponded to 103,999 t milk protein produced in 2020, 94,939 t of milk protein consumed in Switzerland ($Protein_{monogastric,milk}$), and 9060 t were net exported. Regarding the consumption of eggs, 327 TJ were produced by laying hens in Switzerland and additional 252 TJ were net imported[48]. The egg composition was approximated with 648 kJ 100^{-1} g^{-1} with 14% protein content according to the Swiss Food Composition Database (naehrwertdaten.ch). This corresponded to 12,941 t of egg protein consumed in 2020, of which 7497 t were produced in Switzerland ($Protein_{monogastric,egg}$) and 5444 t were net imported.

The protein originating from ruminants ($Protein_{ruminants,total}$) for human consumption was calculated as follows:

$$Protein_{ruminants,total} = Protein_{ruminants,meat} + Protein_{ruminants,milk} \quad (1)$$

and the protein originating from monogastric animals ($Protein_{monogastric,total}$) as follows:

$$Protein_{monogastric,total} = Protein_{monogastric,meat} + Protein_{monogastric,egg} \quad (2)$$

The total consumption of protein originating from eggs, milk and meat in Switzerland in 2020 ($Protein_{food,total}$) was calculated according to:

$$Protein_{food,total} = Protein_{monogastric,total} + Protein_{ruminants,total} + Protein_{import,net} \quad (3)$$

where the $Protein_{import,net}$ summed up the net protein import of egg (5444 t), milk (-9060 t) and meat (15,486 t).

Production potential. For the quantitative study, cultivation area for three legume species, soybean, summer faba bean and summer pea, was estimated based on suitable land available in Switzerland. Suitable land for the legume species production was defined according to three criteria: production potential of the land, GDD and altitude.

As a first criterion, agricultural land was selected if it had very good to moderate production potential and if it had a slope of less than 25% according to the digital soil map of Switzerland[49]. The production potential was described by the following six soil characteristics: soil depth, soil skeleton, water storage capacity, nutrient storage capacity, water permeability and waterlogging[49]. Based on the combination of these characteristics, the land was classified as very good, good, moderate and insufficient for agricultural production. The digital soil map was provided by *geodienste.ch* including the agricultural land use based on assessments of the federal government and the cantons.

Growing degree days (GDD). The sum of GDD throughout the growing season, at which the specific legumes show ideal growth and development, was used as a second criterion for cultivation. Based on the literature, a threshold of 1500°Cd for the GDD sum (GDD_{sum}) with a base temperature ($Temp_{base}$) of 6°C was chosen for soybean[31], 1600°Cd with a base temperature of 4°C for faba bean[50] and 1300°Cd with a base temperature of 4.4°C for pea[51,52]. The GDD was calculated as the following:

$$GDD_{sum} = \sum_{i=Sowing}^{Harvest} (Temp_i - Temp_{base})\,[Temp_i > Temp_{base}] \quad (4)$$

where $Temp_i$ is the daily temperature average of the i^{th} day which has higher $Temp_i$ than $Temp_{base}$ values starting form sowing until the harvest. Temperature data were provided by MeteoSwiss, the Swiss Federal Office of Meteorology and Climatology, with averaged daily temperature displayed in 1x1 km gridded tiles in the Swiss national coordinate system CH1903/LV03 (EPSG:21781)[53]. The period from sowing to maturity was considered to be maximally 150 days: For soybean from April 19 to September 16 and for faba bean and pea from March 20 to August 17. The sowing date was chosen, when the ten day average was above two times the base temperature to account for colder climate in higher altitudes. To account for seasonal differences, the GDD_{sum} was averaged over the years from 2016 to 2020.

Altitude. The third criterion was the altitude above sea level at which certain legumes can still be grown in Switzerland (Table 2). The recommendations for altitude were not recently updated[22,54]. Therefore, we compared GDD over the growing season of the three legumes from the period of 1986 to 1900 with 2016 to 2020 in steps of 100 m altitude. As a consequence of the generally increased temperature in the last 30 years, the maximum altitudes were elevated by 100 m for each of the three legumes (Table 2).

Extraction of suitable land. The digital soil map was first filtered for agricultural land with very good to moderate production potential using Geographic Information system (GIS) (QGIS version 3.20). The agricultural land was selected according to two scenarios differing in the use of temporary and permanent grassland. The filtered agricultural land data was rasterized with a 10 x 10 m pixel resolution with altitude information and as geotiff imported to R Project (R version 4.1.3). The GDD data was assigned to each pixel corresponding to the same location. Then, the potential area for each legume was extracted using the specific GDD and maximum altitude as threshold.

Scenario I. In scenario I, potential legume production area was estimated based on arable land that is currently used for crops and temporary grassland. The required cultivation breaks, three years for soybean and faba bean and six years for pea, were taken into account.

Scenario II. In scenario II, suitable permanent grassland (less than 25% slope inclination with the same suitability parameter as in Scenario I) were added to the potential legume production area on arable land in scenario I. Permanent grassland includes natural or semi-natural grassland which is often associated for conservation of hay and silage, also known as meadows.

Crop rotation on extracted suitable land. Both scenarios were evaluated with one legume (single) or with two legumes cultivated at the same time (combined) in crop rotation. According to national regulations, soybean and faba bean have three and pea six year cultivation break due to 'soil fatigue'. Therefore, cultivating one and two legumes resulted in a maximum use of 25% and 37.5% of the potential area, respectively. The legume combinations differed in their production area depending on the altitude: Below 600 m a.s.l., soybean (25% of this area) and faba bean (12.5% of this area), between 600 and 800 m a.s.l., faba bean (25% of this area) and pea (12.5% of this area), above 800 m a.s.l., pea only (12.5% of this area).

Plant-based protein yield and quality. Regarding fluctuations in grain legume production, different yield values were evaluated based on the FAOSTAT data from 2016 to 2020, ranging between the minimum and maximum values in ten equal steps. The protein content was taken from the Swiss feed database (Table 2). The protein content was multiplied with yield per ha and with the potential areas extracted in scenario I and II. This resulted in ten values for $Protein_{legume,total}$ for each scenario. The produced grain legume protein was then compared to the protein meat consumption in Switzerland in 2020 ($Protein_{monogastric,meat}$+$Protein_{ruminants,meat}$). It has been estimated that soybean, faba bean and pea protein replace 1, 0.6 and 0.8 kg of animal protein based on the DIAAS[43].

Feed and food protein balance. A new feed and protein balance was analyzed under the assumption that parts of the current fodder production areas were replaced by the identified legume production area and that imports of concentrated feed and animal protein were minimized. The new feed balance was analyzed for the two main feed parts, concentrated feed and roughage.

The import of soybean oil cake (side products) and cereals were set to zero accounting for 288,424 and 344,076 t DM (in cereals included: cereal seeds = 286,463 t; rice fractures = 57,613 t DM), respectively[20]. Hence, the imports for concentrated feed ($Concentrated_{monogastric,import}$) were reduced by 632,500 t DM. In a first step, this import cuts were assigned to monogastric animal production, resulting in the net concentrated feed available for monogastric animals ($Concentrated_{monogastric,net}$):

$$Concentrated_{monogastric,net} = Concentrated_{monogastric,total} - Concentrated_{monogastric,import} \quad (5)$$

which equaled 328,762 t DM in 2020.

Fodder maize (green and silage maize) and temporary grassland cultivation area in Switzerland were reduced to make land available for legume production. The yield of temporary grassland was approximated with 12 t ha^{-1} reached by intensive production[55]. Therefore, the total roughage production from the temporary grassland on 125,393 ha, was reduced according to the required area for legume production in Scenario I. The roughage reduction from permanent grassland (in t DM) was calculated proportional to the area of converted permanent grassland (in ha) in Scenario II. The decrease in fodder maize (in t DM) was calculated proportionally to the decrease in fodder maize area (in ha) with the quantity produced in 2020 as baseline[19].

Considering the reduced roughage and minimized feed imports, the $Protein_{legume,total}$ was balanced between feed and food determining $r_{ruminants}$ and $r_{monogastrics}$. With increased plant-based protein consumption, the new balance for the amount of plant-based protein food ($Protein_{legume,food}$) was defined as follows:

$$Protein_{legume,food} = (Protein_{food,total} - Protein_{monogastric,total} * r_{monogastric} - Protein_{ruminants,total} * r_{ruminants})/c_{DIAAS} \quad (6)$$

where c_{DIAAS} is the average DIAAS of the three legume species weighted according to their production quantity in order to correct for differences in protein quality of plant-based protein compared to animal protein. A part of $Protein_{legume,total}$ compensated for the reduction in egg, milk and meat protein for human consumption ($Protein_{legume,food}$). The resulting plant protein surplus was used for animal feed ($Concentrated_{legume,feed}$):

$$Concentrated_{legume,feed} = (Protein_{legume,total} - Protein_{legume,food}) * 2 \quad (7)$$

where $Protein_{legume}$ was divided by the protein content (factor 0.4 resulting in grain yield) and multiplied by the factor 0.8 to convert from t DM grain yield to t DM soybean oil cake[21]. This resulted in factor 2 to convert from t protein to t DM oil cake in order to partly replace imported feed with domestic production.

Together with the concentrate feed remaining from the ruminants, the new balance for concentrated monogastric feed ($Concentrated_{monogastric,new}$) is:

$$Concentrated_{monogastric,new} = Concentrated_{monogastric,net} + Concentrated_{legume,feed} + Concentrated_{ruminant,total} * (1 - r_{ruminants}) \quad (8)$$

The $r_{monogastrics}$ is determined by:

$$r_{monogastric} = Concentrated_{monogastric,new} / Concentrated_{monogastric,total} \quad (9)$$

The $r_{ruminants}$ is calculated with:

$$r_{ruminants} = (Roughage_{ruminants,total} + Roughage_{monogastric,total} * (1 - r_{monogastric}) - Roughage_{ruminants,red}) / Roughage_{ruminants,total} \quad (10)$$

where $Roughage_{ruminants,red}$ is the reduced roughage for ruminants due to the reduction in fodder area.

Finally, combining equations (6) to (10) allows to determine $Protein_{legume,total}$, $r_{ruminants}$ and $r_{monogastrics}$. All variables are in t DM, except $r_{ruminants}$ and $r_{monogastrics}$ which represent proportions.

Sensitivity analysis. The sensitivity of $r_{ruminants}$ and $r_{monogastrics}$ was investigated by varying grain legume ($Protein_{legume,total}$) and roughage production ($Roughage_{ruminants,total}$+$Roughage_{monogastric,total}$). The roughage production values ranged between the maximum and minimum values in the years 2016 to 2020 in ten equal steps[32]. The proportion of roughage and concentrated feed distributed between ruminants and monogastric animals was kept constant. The $r_{ruminants}$ and $r_{monogastrics}$ were calculated with each combination of the ten protein and the ten roughage production values. This resulted in 100 values for each calculated variable, indicating its sensitivity to the varying input values. The import and consumption values were taken from 2020 as they were relatively stable over the last years.

Self-sufficiency calculation. The energy values of total food production and food production using domestic fodder only were divided by the food consumption to calculate gross and net self-sufficiency, respectively. For the baseline, food production and consumption in terra joules (TJ) for Switzerland in the year 2020 were taken[48]. For the improved self-sufficiency, the consumption of egg, milk and meat was reduced by $r_{ruminants}$ respective $r_{monogastrics}$ according to the 100 runs of the sensitivity analysis. Additionally, the imports of egg and meat were set to zero. The reduction in animal protein consumption was compensated by the produced grain legume protein. The replaced protein had the same proportion of the three legume species as the quantities they were produced. Energy values for soybean (1600 kJ 100^{-1} g^{-1}) and pea (1400 kJ 100^{-1} g^{-1}) were available from the Swiss Food Composition Database (naehrwertdaten.ch) and were reviewed for faba bean (1425 kJ 100^{-1} g^{-1}) by Dhull et al.[56]. The energy value of meat (899 kJ 100^{-1} g^{-1}) was taken as average of ruminant and monogastric production[48]. In order to calculate the improved net self-sufficiency, the sensitivity analysis was repeated by replacing all imports of concentrated feed consisting of 369,067 t side products and 388,755 t cereals in 2020[20].

Reporting summary. Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The digital soil map was provided by *geodienste.ch*. The spatial data for potential grain legume cultivation and the data to generate the tables is available on https://doi.org/10.3929/ethz-b-000639755.

Code availability

The code is available on GitLab: https://gitlab.ethz.ch/kellebea/swisslegumeprotein/.

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Author contributions
B.K., A.H., A.W. designed the study; C.O., J.A., A.H. designed the expert survey; C.O. carried out and analyzed the interviews and survey; B.K., M.C. performed the spatial analysis; B.K. wrote the manuscript, with substantial contributions from all co-authors. All authors reviewed the final manuscript.

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