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How to find alternative crops for climate-resilient regional food production

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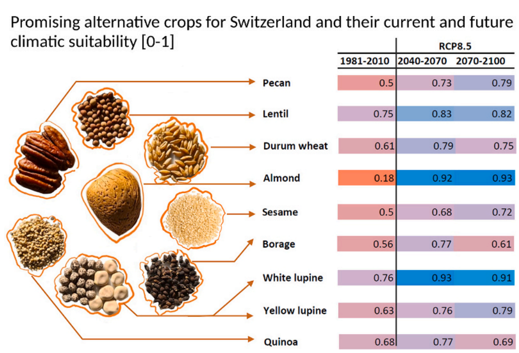
HIGHLIGHTS

- Innovative bottom-up screening approach identifies climate-adapted alternative crops.
- Almond, pecan, sesame, durum wheat, quinoa, lentil, lupine, and borage are identified.
- Identified crops provide essential nutrients and cover nutritional gaps in Switzerland.
- Selected crops can diversify existing production systems to improve sustainability.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Agricultural food production is both affected by and contributing to climate change. At the global scale, agri-food systems are responsible for one-third of total greenhouse gas emissions. With progressing climate change, the risks of crop failure increase. Thus, an urgent need is to reduce emissions from food systems while increasing their resilience to climate change. Enormous untapped potentials to achieve these dual goals lie in transforming agri-food systems towards more diverse, plant-based, and regional food production systems.
OBJECTIVE: In this paper, we present an innovative approach for identifying climate-adapted alternative food crops that could (1) help to diversify existing cropping systems and thus increase their climate resilience and can be (2) nutritious elements of plant-based regional diets with reduced emissions.
METHODS: The approach builds on the model ecocrop to select food crops that could benefit from regionally projected changes in climate. The model-based analysis is complemented with a literature review to examine the ecocrop results for their plausibility and provide a broader assessment of potentials for cultivation, utilization, and nutritional values of model-selected crops.
RESULTS AND CONCLUSIONS: The approach is applied to Switzerland, where we identify eight alternative crops with the potential to increase climate resilience while contributing to healthy human diets of regional consumers with benefits for climate mitigation (almond, pecan, sesame, durum wheat, quinoa, lentil, lupine, and borage). The literature review indicated that the increasing demand for many of these crops suggests great potential for regional marketing of crop products. The results produced in this study provide an initial guide for researchers

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and innovative farmers interested in experimenting with alternative crops in Switzerland, thus promoting climate-smart food system transformation from the production side.

SIGNIFICANCE: Using our unbiased bottom-up screening approach, we identified climate-adapted alternative crops that can provide essential nutrients, cover nutritional gaps in Switzerland, diversify existing production systems, and improve sustainability.

1. Introduction

With climate change, crop yield stability and food nutritional quality reductions are increasingly being observed, and further adverse effects are expected (IPCC, 2022). Driven by global warming, cultivation regions are shifting northwards and towards higher altitudes where cultivation potentials have previously been limited by low temperatures (European Environment Agency, 2019; Ceglar et al., 2019; Menzel et al., 2020). With that, possibilities for cultivating alternative crops in Northern regions are increasing and may even become necessities in the future. Besides being heavily impacted by changing climatic conditions, agricultural production systems also contribute to global warming. In 2020, global anthropogenic emissions were 52 billion tons of carbon dioxide equivalent (CO2eq), of which 31% came from agri-food systems. Agricultural production or farm-gate emissions (primarily from livestock production) were the most significant components of agri-food system emissions in 2020, with 46%, followed by post-production processes (35% from food waste and energy used in households, retail, transport, food processing, and packaging) and land use change (20%; FAO, 2022; Crippa et al., 2021a). Thus, a large scope exists for reducing greenhouse gas (GHG) emissions from agri-food systems through transformative food system changes (i.e., reduced livestock production and food transport and processing). With reductions in the consumption of meat and dairy products and an increase in the share of locally produced plant-based food, GHG emissions associated with the food system are likely to be reduced significantly (e.g., Springmann et al., 2016; Vicente-Vicente and Pior, 2021; Eisen and Brown, 2022). Food crop production systems would have to be diversified to provide all required macro- and micronutrients for healthy diets of regional communities and to buffer against adverse impacts of climate change.

Large potentials to increase the resilience of cropping systems to climate variability and change while benefiting healthy regional diets are expected from the cultivation of alternative crops (also termed minor crops, niche crops, underutilized or orphan crops in the literature, e.g., Kim, 2016; Tadele, 2019; Mabhaudhi et al., 2019; Kumar and Bhalothia, 2020; Ye and Fan, 2021; Kamenya et al., 2021; Gardner et al., 2021b). The uptake of alternative crop cultivation in practice is often hampered by the need for more knowledge about potentially suitable crops. To identify potentially suitable crops for a given region, researchers have so far mostly referred to literature knowledge and identified alternative crops of cultivation trials based on broad literature reviews (e.g., Georgakopoulos et al., 2016; Bilalis et al., 2017; Kakabouki et al., 2021). Recently, Gardner et al. (2021b) and Manners et al. (2020) have also utilized the generic model ecocrop to identify potentially suitable climate-resilient alternative crops. Manners et al. (2020) used the model ecocrop to simulate the future climatic suitability of several protein-rich crops currently cultivated in Europe. They specifically evaluated crops that reduce food-system-related emissions by replacing animal proteins and emphasized the spatial variability in climate change impacts. They found, that while the investigated crops (including chickpeas, lentils, beans, and quinoa) might benefit from expected climate conditions in northern Europe, the traditional system in the South might suffer (Manners et al., 2020). Gardner et al. (2021b) first conducted a stakeholder-based approach to select potentially interesting alternative crops and used ecocrop in a second step to assess their future climatic suitability in the UK.

All these studies, however, may be subject to biases depending on the availabilities of crop-specific studies, reports, and stakeholders' experience and knowledge. To overcome this subjectivity, this study utilizes the extensive global crop database by the FAO incorporated in the ecocrop model (Hijmans, 2020), which includes information on the climatic requirements of 1710 crops (similar to Gardner et al., 2021b and Manners et al., 2020). We systematically identify food crops with projected increasing climatic suitability under rainfed conditions by applying ecocrop to a selected case study region based on historic and climate projection data. This unprejudiced pre-selection of alternative crops is complemented with literature reviews to confirm or disprove the model-based pre-selection and to collect available information on regional cultivation experiences, possibilities of crop utilization, and nutritional values.

In this study, we test this newly combined approach for identifying alternative food crops, which could support the supply-side transformation towards a climate-resilient and more sustainable food system in a case study region in Continental Europe.

2. Case study

The approach is tested for the Swiss lowlands (Central Plateau), where the potential for cultivating alternative crops has not been systematically investigated despite increasing interest in alternative crop cultivation (Heine et al., 2018). While Swiss agriculture is likely to experience moderate adverse impacts of climate change in comparison to other regions such as the Mediterranean or the global South (e.g., Klein et al., 2014; CH2014 Impacts, 2014; Girvetz et al., 2019; Holzkämper, 2020) the Swiss agri-food system accounts for ~25% of the total national GHG emissions (Crippa et al., 2021a). Emissions from production account for the largest share (50%), while the contribution from food processing and retailing, in particular, are increasing (Appendix A.1). As already stated by Nemecek et al. (2018), the environmental impact of the Swiss food system could be reduced by over 50%, mainly by reducing feed imports, food imports, and animal production impacts. According to Bretscher et al. (2018), livestock production accounts for 85% of all emissions from the agricultural sector, and 60% of the arable land is currently used to grow fodder (Fig. 1). A shift towards more plant-based regional diets is a promising pathway towards increasing food system sustainability in general and Switzerland (Manners et al., 2020; von Ow et al., 2020; Frehner et al., 2022).

3. Data and methods

The study utilizes the simple mechanistic ecocrop model implemented in the R package dismo (Hijmans, 2020), which draws on a database of crop-specific thresholds determining temperature and moisture requirements for 1710 crops. Before the model application, we screened the ecocrop database to exclude all crops unsuitable for human nutrition or already commonly cultivated in Switzerland. The ecocrop model was then applied in the rain-fed mode for 651 edible crops to historical climate data for three stations in the Swiss Central Plateau (Switzerland's main agricultural production region). We also applied the model to downscaled climate projection data for these three sites (2 emission pathways, 10 model chains). The three MeteoSwiss stations, Zürich, Changins, and Basel, represent the primary agricultural production zone (Fig. 1). A very similar climate characterizes the stations; only Zurich has slightly lower average temperatures and higher summer precipitation. What all stations have in common, however, is that temperature increases, and precipitation decreases under ongoing climate change. This effect is amplified under RCP8.5 compared to RCP4.5 (CH2018, 2018). Only summer precipitation is shown in Table 1, as it significantly influences the harvest. As winter precipitation increases, the annual balance changes slightly (CH2018, 2018). Regarding the general edaphic conditions in the main arable zone (green areas in Fig. 1), deep loam, clay loam, or sandy clay loam dominate according to the Swiss Soil Dataset (Service Center NABODAT, 2022).

Based on the model results, we selected crops that showed consistent increases in climate suitability estimates at all three stations, with both emission pathways and in two future projection periods (2040–2070, 2070–2100), which are not commonly cultivated in Switzerland. With that, we aimed to derive a robust subset of "alternative" food crops that could benefit from projected climate change in Switzerland without supplement irrigation. Climatic suitability for all candidate crops is also mapped for the whole country under current and projected future climate conditions to evaluate the expansion of possible cultivation zones. Finally, the selection of crops was complemented with additional information on nutritional content to evaluate the potential of candidate crops to contribute to healthy plant-based diets amongst the Swiss population.

3.1. Climate data input

For this study, we used the downscaled and bias-corrected climate projection data provided by CH2018 (2018) at daily resolution for three climate stations within the Swiss Central Plateau (Changins, Basel, and Zürich-Reckenholz) as input to the ecocrop model (Fig. 1). The data is available in daily resolution from 1981 until 2099. Parameters include daily minimum and mean temperatures, as well as daily precipitation. The CH2018 scenarios stem from an ensemble of Regional Climate Models (RCMs) provided by the European Coordinated Downscaling Experiment (EUROCORDEX). The RCMs translate the much coarser General Circulation Models (GCMs) to a level that adequately represents the main topographic properties of Switzerland (CH2018, 2018). Here, we use the ensemble mean of 10 different model chains (each consisting of a combination of a GCM and an RCM). Modeling and analysis in this work are based on the RCP4.5 and RCP8.5 scenarios. Maps of current and future climate suitability for selected crops were derived based on gridded CH2018 data at 2 km × 2 km resolution. We aggregated the daily climate input data to monthly mean temperatures (minimum and mean) and monthly precipitation sums for three different time horizons averaged over 30-year periods: a reference period of 1981–2010 and two future periods of 2040–2070 and 2070–2100.

Table 1
Observed and projected mean annual temperature and summer precipitation (June, July and August sum) at the three study sites shown in Fig. 1 (CH2018, 2018).

	Observations	RCP4.5		RCP8.5	
	1981-2010	2040-2070	2070-2100	2040-2070	2070-2100
Annual mean temperature [°C]					
Changins	10.37	12.08	12.73	12.39	14.2
Basel	10.46	12.15	12.43	12.73	14.21
Zürich	9.36	11.14	11.43	11.76	13.26
Summer precipitation [JJA sum in mm]					
Changins	236.5	200.1	190.8	190.9	157.4
Basel	254.6	242.3	236.1	230.1	205.8
Zürich	331	306	299.9	293.8	266.1

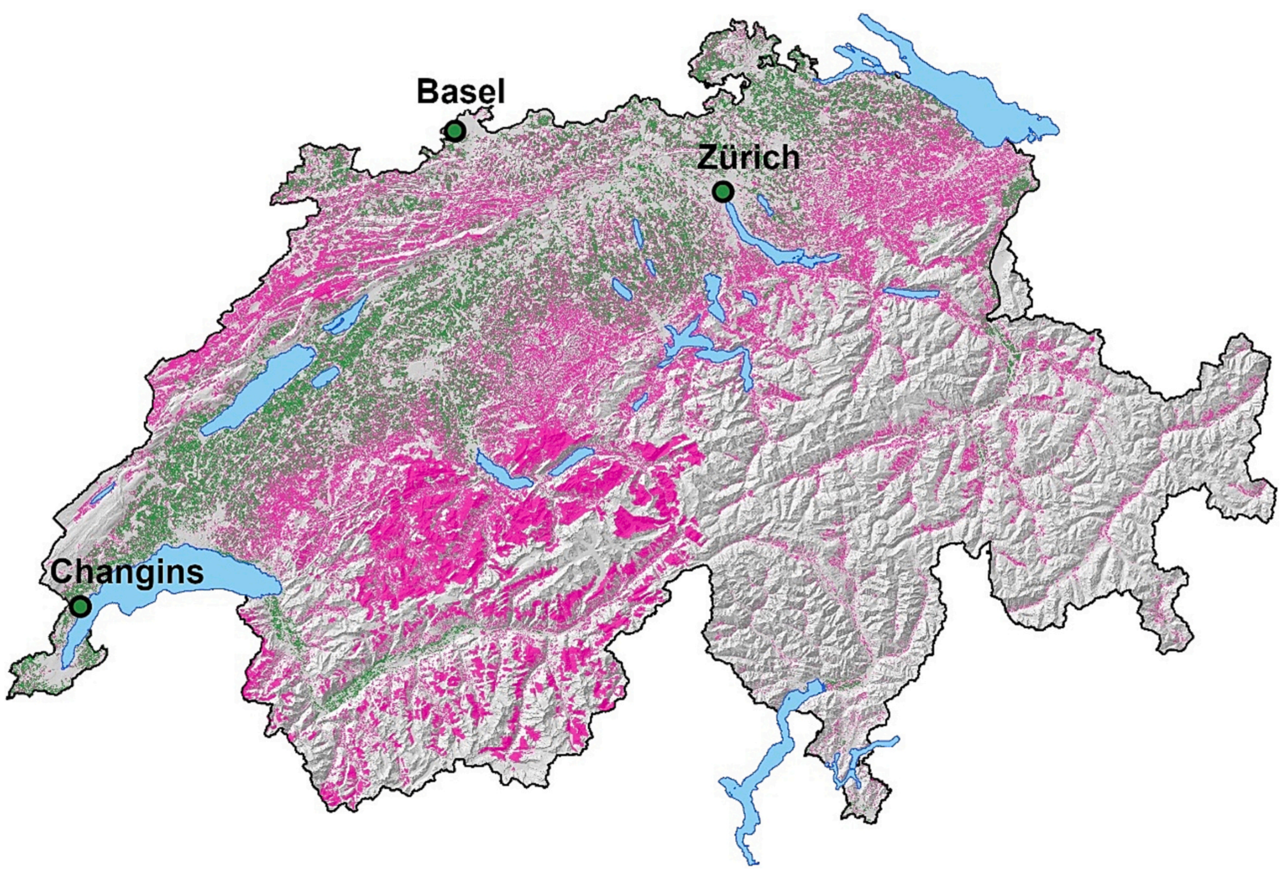

Fig. 1. Agricultural land in Switzerland in 2021, areas for fodder production (including pastures) are shown in pink, areas for plant food production in green (BLW, 2021). Digital elevation model in grey (Swisstopo, 2001). The three MeteoSwiss stations characterize the main agricultural production zone. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Ecocrop model

For quantifying the climatic suitability of alternative crops under current and future climate conditions, we used the ecocrop function and database included in the dismo package (v.1.1–4) by Robert J. Hijmans in R (1.2.5042; Hijmans, 2020). The database contains 1710 crops, defined by 35 parameters, including temperature and precipitation ranges, length of the growing season, and preferred soil conditions. This database is a unique and valuable source of expert-based model input data for a large and diverse number of crops. The ecocrop function determines the regional climatic suitability of crops and thus offers a first estimate of their suitability under the impacts of climate change (Manners and van Etten, 2018; Gardner et al., 2021b). Ecocrop simulates to what extent each month's (i) local climatic conditions (P) fall within the crop-specific thresholds of temperature and precipitation from the ecocrop database, assuming that each month is potentially the first month of the crop's growing season (Fig. 2; Ramirez-Villegas et al., 2013). We applied ecocrop in the rainfed mode, excluding crops relying on supplementary irrigation. The model requires monthly minimum and mean temperatures and monthly precipitation for a location (P) to compare with crop requirements from the ecocrop database. The parameters shown in Fig. 2 represent those requirements. The absolute limits of a crop are defined as Tmin/Tmax for temperature and Rmin/Rmax for precipitation. Topmin/Topmax and Ropmin/Ropmax determine a crop's optimal temperature and precipitation range. The parameter Tkill covers the possibility that monthly temperatures exceed a crop's absolute threshold. If the mean minimum temperature of a place is below Tkill +4 °C, then the model assumes that the Tkill temperature is reached during this month. In this case, the crop would not survive, and its suitability for that location would be zero. Eqs. 1 and 2 are calculated individually, and the results are multiplied into eq. 3, giving the crop the maximum achievable suitability. A value between 0 and 0.2 depicts unsuitability, 0.2–0.4 very marginal suitability, 0.4–0.6 marginal suitability, 0.6–0.8 suitability, and 0.8 until 1 high suitability (Table 2). The length of the growing season (y) is important under rainfed conditions. It determines the number of months (y) whose precipitation is accumulated. With a moving average, the precipitation sum of the following y months is assigned each month as a potential starting month. If this sum is below Rmin for all start months, then Rsuit is 0. In eq. 1, aT1 represents the intercept and mT1 the slope of the regression curve between Tmin, 0 and Topmin, 100; and aT2 represents the intercept and mT2 the slope of the regression curve between Topmax, 100 and Tmax, 0. In eq. 2, aR1 describes the intercept and mR1 the slope of the regression curve between Rmin, 0 and Ropmin, 100; and aR2 is the intercept and mR2 the slope of the regression curve between Ropmax, 100 and Rmax, 0 (Ramirez-Villegas et al., 2013).

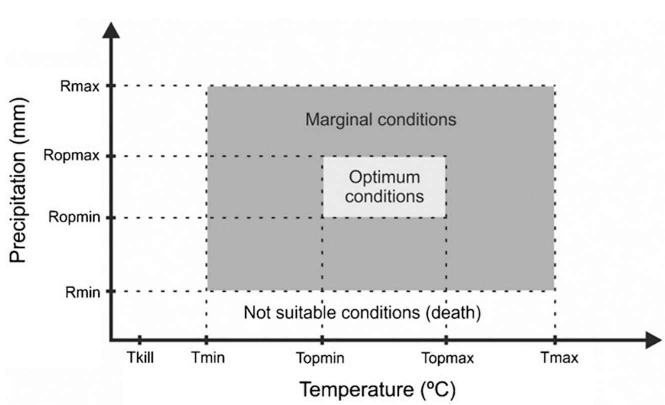

Fig. 2. Ecocrop's calculation of crop suitability as a function of temperature and precipitation in two-dimensional form. The parameters Rmax, Ropmax, Ropmin, Rmin, Tkill, Tmin, Topmin, Topmax and Tmax correspond to the crop's climatic requirements from the ecocrop database (adapted from Ramirez-Villegas et al., 2013).

Table 2
Suitability index according to Egbebiyi et al. (2020).

Suitability index	Value description
0–0.2	Unsuitable
0.2–0.4	Very marginally suitable
0.4–0.6	Marginally suitable
0.6–0.8	Suitable
0.8–1	Highly suitable

$$T_{suit} = \begin{cases} 0 & \text{Tmin-Pi} < \text{Tkill} \\ 0 & \text{Tmean-Pi} < \text{Tmin} \\ aT1 + mT1 * \text{Tmean-Pi} & \text{Tmin} \leq \text{Tmean-Pi} < \text{Topmin} \\ 100 & \text{Topmin} \leq \text{Tmean-Pi} < \text{Topmax} \\ aT2 + mT2 * \text{Tmean-Pi} & \text{Topmax} \leq \text{Tmean-Pi} < \text{Tmax} \\ 0 & \text{Tmean-Pi} \geq \text{Tmax} \end{cases} \quad (1)$$

$$R_{suit} = \begin{cases} 0 & \text{Rtotal-P} < \text{Tmin} \\ aR1 + mR1 * \text{Rtotal-P} & \text{Rmin} \leq \text{Rtotal-P} < \text{Ropmin} \\ 100 & \text{Ropmin} \leq \text{Rtotal-P} < \text{Ropmax} \\ aR2 + mR2 * \text{Rtotal-P} & \text{Ropmax} \leq \text{Rtotal-P} < \text{Rmax} \\ 0 & \text{Rtotal-P} \geq \text{Rmax} \end{cases} \quad (2)$$

$$\text{Suitability} = R_{suit}{}^{*}\ T_{suit} \quad (3)$$

3.3. Model application

As a first step, we categorized all crops within the ecocrop database following the FAO crop classification standards into cereals, vegetables, nuts and seeds, beverage and spice crops, legumes, sugar crops, fiber crops, and other (non-food) crops (World Program for the Census of Agriculture, 2010) (Appendix A.2). Since this work focuses on food crops, only edible crops were selected. This selection left 651 crops for which ecocrop was applied in rain-fed mode based on climate input data of ten model chains for a reference period (1981–2010) and two future periods (2040–2070 and 2070–2100) both for RCP4.5 and RCP8.5. Simulations were run for the three stations in the Swiss Central Plateau to identify a subset of crops with prospects of increasing climate suitability in the Swiss Central Plateau. At this step, the following selection criteria were applied:

1) The crop's climatic suitability is >0.6 in at least one of the two future periods.
2) The crop's climatic suitability in at least one of the two future periods is larger than in the reference period.
3) The crop must fulfill the first two criteria at all three stations to be considered a robust choice for the Swiss Central Plateau.

This selection step left 20 crops under RCP4.5 and 27 crops under RCP8.5. 18 crops overlapped under both scenarios, of which 12 were ultimately classified as "alternative" (tarragon, barley, rutabaga, horseradish, rye, and common bean were excluded because they are established). In this context, we define an *alternative crop* as one not yet widely cultivated in Switzerland. To evaluate a potentially remaining bias of the climate projection data, we ran the ecocrop model with historical climate data provided by MeteoSwiss. We compared the results with those obtained with projected climate data.

3.4. Spatial modeling

For the final subset of 12 alternative crops, ecocrop was again applied based on gridded climate projection data for the same projection periods and emission scenarios to quantify changes in the spatial extent of climatically suitable areas. The resulting matrices were exported into ArcGIS (v10.60), converted into raster files, and further into maps with spatial reference. The extent was then reduced using a number of additional factors and filters: Firstly, we evaluated climate suitability only within existing agricultural areas (orchards, vineyards, horticultural areas, arable land, natural meadows, home pastures, and alpine meadows; BFS, 2015). Secondly, we excluded areas with slopes >30% (Swisstopo, 2001). From the remaining area we selected only those patches with suitability values >0.6. The resulting maps show the spatial extent of suitable areas and their change over the future time periods.

3.5. Literature review

A literature review was conducted to complement the selection of identified crops with information relevant to determining each crop's potential for cultivation and utilization in Switzerland. Information on the expansion of cultivation zones was collected to provide insights into pedo-climatic site requirements for each crop, either confirming or rejecting estimates derived from the climate suitability analysis. Where available, we also sourced information on cultivation experiences from Switzerland from "grey" literature and field experts.

3.6. Nutritional content

To quantify the nutritional content of selected alternative crops, several databases were used to specify the content of 24 essential nutrients for each crop (Swiss food composition database; USDA food data central, FAO/INFOODS Food Composition Table for Western Africa, 2019; FAO/INFOODS Global food composition database for pulses – version 1.0, Public Health England, 2021). The content can be compared to the daily recommended allowances published by the Schweizerische Gesellschaft für Ernährung (2015).

4. Results and discussion

4.1. Climatic suitability

We identified twelve crops as climatically suitable alternative food crops for the central agricultural production zone: vanilla grass, crowfoot grass, quinoa, durum wheat, almond, pecan, sesame, lentil, white lupine, yellow lupine, buffalo gourd, and borage. Table 3 depicts the mean climatic suitability values over the three midland stations (values for each station shown in Appendix A.3). As Appendix A.4 shows, the remaining bias in the climate projection data is slight, as the differences between the climatic suitability values achieved with observed and projected climate data are minor.

The values for the reference period are almost identical under both emission pathways. In the near future (2040–2070), higher values are achieved under RCP8.5 compared to RCP4.5 in most cases (11/12). In 2070–2100, higher values are achieved under RCP8.5 in only 7 out of 12 cases, suggesting that some crops exceed the benefits of increasing temperature with RCP8.5. A high standard deviation indicates more significant regional differences in the climatic suitability of the crop. Several crops, such as crowfoot grass, almond, pecan nut, and sesame, are only marginally or very marginally suitable in the reference period. The climatic suitability of these crops increases in the future, especially that of almonds, which reach very high values (>0.8). Ecocrop projects vanilla grass, lentil, and white lupine achieve relatively high suitability values today as well adapted in the future. The standard deviation over the three periods is relatively high for almond, lentil, and borage, indicating more significant regional differences in suitability. The reason for the increased variability depends on the crop and its requirements. For example, almond has a suitability of 0 in the reference period in Zürich and about 0.25 for the other stations, resulting in a suitability value of 0.17 averaged over the three stations and a standard deviation of 0.12. (Table 3, Appendix A.3). Although all three stations have a similar climate, Zürich is slightly cooler (Table 1), which was probably the limiting factor here, given the temperature requirements from the database.

Fig. 3 depicts the suitable area for cultivation for each projection horizon and scenario, and Table 4, lists the potential cultivation area derived from the maps in Fig. 3. A slightly different pattern compared to station-based results can be observed for the grid-based results. The suitable area for cultivation increases in time and is highest for almost all crops under RCP8.5, especially in 2070–2100. The suitable acreage for borage decreases slightly in the second future period under RCP8.5 (Table 4). The suitable cultivation area for most crops extends from the southwest across the Central Plateau to the northeast. For some crops, areas in the Rhone (southwest) and Rhine valleys (at the eastern border), southern and central Switzerland are also classified as climatically suitable. For crowfoot grass, pecan, sesame, almond, and borage, the extent of areas with climate suitability >0.6 is very small under current climatic conditions (Table 4, Fig. 3). Under RCP4.5, extensive suitable areas for cultivation are only projected for quinoa, lentils, and white lupine, whereas under RCP8.5, they are projected for most crops. Higher elevated regions - currently mainly used as meadows - are no cultivation areas today. However, our investigations show that the potential area to

Table 3
Climatic suitability under RCP4.5 and RCP8.5 per period and crop (darker green colors indicate higher suitability). The values are averaged over the three Midland stations; column SD indicates the standard deviation over the three stations.

Crop category		RCP4.5						RCP8.5					
		1981-2010	SD	2040-2070	SD	2070-2100	SD	1981-2010	SD	2040-2070	SD	2070-2100	SD
Spice crops	Vanilla grass	0.78	0.04	0.92	0.03	0.96	0.03	0.78	0.04	0.96	0.03	0.99	0.01
Cereals	Crowfoot grass	0.47	0.04	0.63	0.04	0.69	0.05	0.47	0.04	0.70	0.05	0.79	0.05
	Quinoa	0.68	0.04	0.77	0.02	0.76	0.01	0.68	0.04	0.77	0.02	0.69	0.06
	Durum wheat	0.62	0.08	0.72	0.04	0.78	0.03	0.61	0.08	0.79	0.05	0.75	0.09
Nuts and seeds	Almond	0.17	0.12	0.73	0.17	0.85	0.11	0.18	0.13	0.92	0.07	0.93	0.07
	Pecan	0.50	0.04	0.64	0.04	0.69	0.05	0.50	0.04	0.73	0.06	0.79	0.08
	Sesame	0.51	0.04	0.62	0.05	0.69	0.06	0.50	0.04	0.68	0.05	0.72	0.10
Legumes	Lentil	0.75	0.12	0.80	0.09	0.84	0.11	0.75	0.12	0.83	0.11	0.82	0.11
	White lupine	0.77	0.04	0.87	0.02	0.94	0.04	0.76	0.04	0.93	0.04	0.91	0.05
	Yellow lupine	0.63	0.03	0.73	0.03	0.76	0.03	0.63	0.03	0.76	0.03	0.79	0.01
Vegetables	Buffalo gourd	0.68	0.03	0.79	0.03	0.84	0.03	0.68	0.03	0.84	0.03	0.89	0.03
	Borage	0.56	0.04	0.70	0.04	0.73	0.03	0.56	0.04	0.77	0.03	0.61	0.15

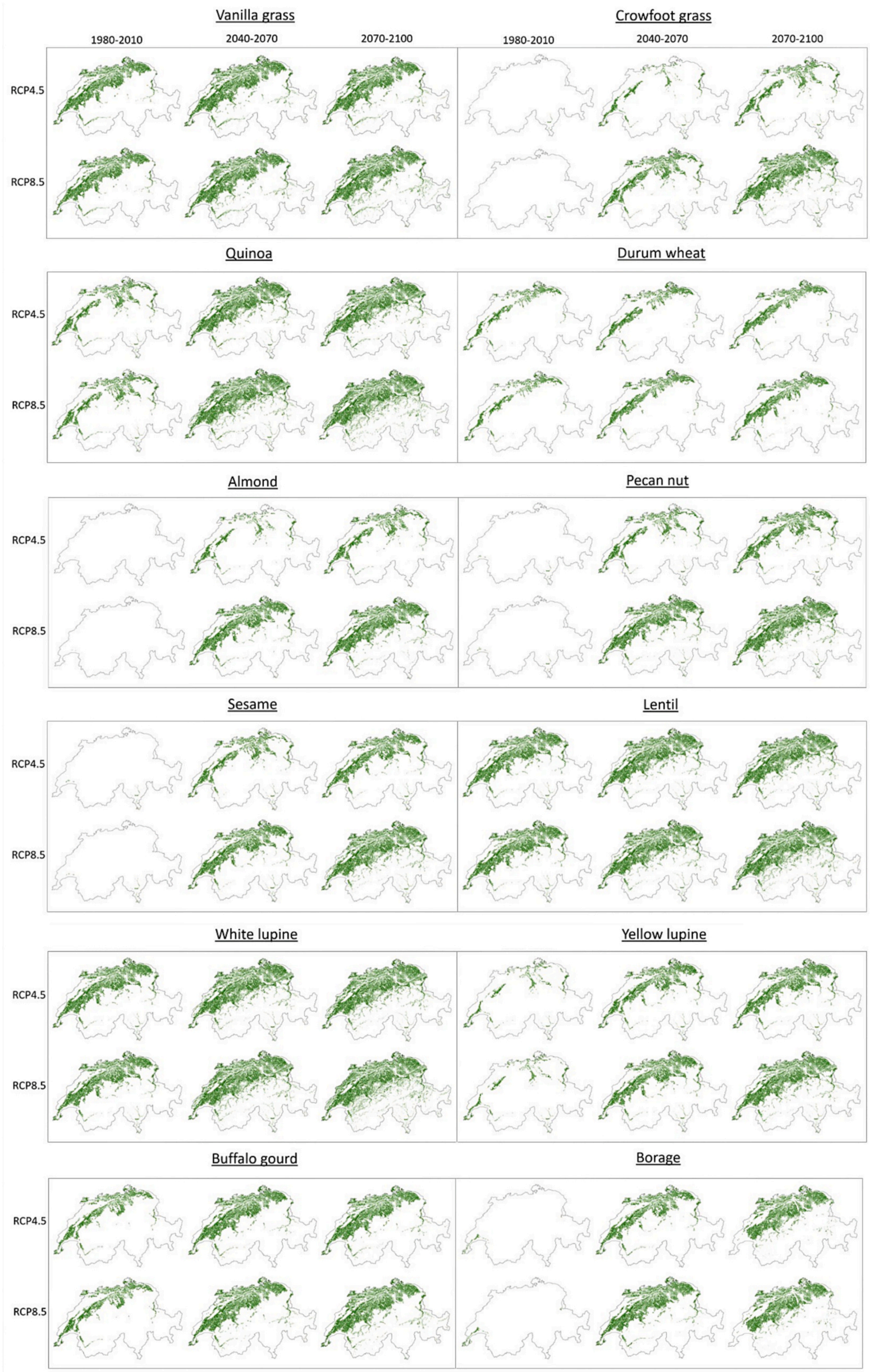

Fig. 3. Areas of climatic suitability (>0.6) on potentially arable land, excluding areas with slopes >30% for each crop, period, and scenario.

Table 4
Expansion of climatically suitable area (suitability score > 0.6) in km^2 by emission pathway and projection horizon.

		RCP4.5			RCP8.5		
Crop category		1981–2010	2040–2070	2070–2100	1981–2010	2040–2070	2070–2100
Spice crops	Vanilla grass	5836	6800	6886	5836	7096	7759
	Crowfoot grass	31	1445	3292	31	4203	7486
Cereals	Quinoa	3510	7424	7834	3666	8324	8661
	Durum wheat	2297	2898	3499	2231	3424	4123
	Almond	1	1994	3549	2	5830	6999
Nuts and seeds	Pecan	48	3309	4733	53	6399	7632
	Sesame	58	3579	5345	49	5849	7905
	Lentil	6544	7431	7797	6501	7773	8553
Legumes	White lupine	6220	7956	8287	6106	8405	8989
	Yellow lupine	1411	4782	5879	1343	5738	7444
Vegetables	Buffalo gourd	3793	6222	6246	3581	6481	7221
	Borage	124	4853	5693	162	6620	5889

be cultivated could expand towards higher altitudes (see Chapter 3.4).

4.2. Literature review on pedo-climatic requirements and prospects for utilization

4.2.1. Vanilla Grass (Hierochloë odorata)

Vanilla grass or sweet grass (*Hierochloë odorata*) is an herb with a sweet, vanilla-like taste, used as an aromatic to scent beverages or sweets (Leif et al., 2014). In North America, extracts from *Hierochloë odorata* are traditionally used as insect repellent (Cantrell et al., 2016). Thus, the plant may not be interesting from a food provisioning perspective.

Hierochloë odorata is distributed globally in North Asia, North America, and northern and eastern Europe, where it grows on rich, moist soils in full sun (Pukalskas et al., 2002; Leif, 2010). In Switzerland, *Hierochloë odorata* is known to occur naturally in subalpine regions and near surface waters (InfoFlora, 2022b). This contradicts the modeled high suitability for cultivating in the Central Plateau region already under current climatic conditions and an increase in climate suitability with rising temperatures and reductions in summer precipitation. Considering this and the distribution information from the literature (e.g., Pukalskas et al., 2002; Leif, 2010), it may be questionable if ecocrop's estimates are correct for this crop. Revisions of the minimum threshold moisture level in the ecocrop database (ideal minimum currently set to 250 mm) might be required for vanilla grass.

4.2.2. Crowfoot grass (Dactyloctenium aegyptium)

Crowfoot grass (*Dactyloctenium aegyptium*) is native to Africa, where it plays a vital role as a fodder plant in some regions but is also considered a famine food (Shemdoe et al., 2009). Crowfoot grass has recently reached the European continent and is considered an invasive weed in the Americas (Burke et al., 2003; Cerrato et al., 2021). Although the plant has been abundant in West Africa for the last decades, it is disappearing and being replaced by species with lower forage value in West African rangeland systems (Ouedraogo et al., 2021). This development suggests that the grass reached its environmental limits in its area of origin. Crowfoot has never been cultivated and thrives in various environments, from sandy to heavy soils, including alkaline and saline soils (Bogdan, 1977). *Dactyloctenium aegyptium* is one of the most drought-resilient grasses, as it can quickly grow and seed during the wet season (Skerman and Riveros, 1990).

The plants' high ability to cope with abiotic stresses makes them an interesting candidate for studying plant responses to extreme stress, as done, for example, by Maroco et al. (1997, 2000), potentially providing relevant insights for breeding more drought-resistant or drought-avoiding cultivars of dominant crops. However, the crop is unlikely to play a significant role as a food crop in Switzerland, especially since its introduction into Swiss farming systems holds the risk of spreading an invasive weed.

4.2.3. Quinoa (Chenopodium quinoa)

Quinoa is a stress-tolerant pseudo-cereal that has been cultivated along the Andes of South America for the last 7000 years in variable environmental conditions (Vega-Galvez et al., 2010). The crop has gained considerable attention for its recognized health benefits as a gluten-free, high-protein ingredient in stews, salads, or even ground into flour for pasta, bread, and other baked goods (e.g., Jancurová and Minarovičová, 2009; Bazile et al., 2016; De Bock et al., 2021). While the main producing countries are still Bolivia and Peru today, the cultivation areas have expanded to other South American countries, but also the US, China, France, and Canada (Bazile et al., 2015).

The crop is resistant to cold, salt, and drought stress (Angeli et al., 2020). As Hinojosa et al. (2019) report, quinoa shows a high plasticity in response to high temperatures, even though pollen viability is affected by heat stress. Quinoa grows on rocky and nutrient-poor soils and is drought resistant due to its deep rooting system and high water use efficiency, which make it an ideal crop for increasingly drought-prone agricultural soils in Europe (Jacobsen et al., 2012). However, intensive rainfall and heavy soils pose unfavorable conditions for quinoa (Bachmann and Maciejok, 2018). Therefore, areas in Switzerland with rather heavy soils and wet years could pose unfavorable conditions.

Quinoa is grown experimentally or on a small scale, e.g., on a farm near Bern (north-western Switzerland), where yields of 1–2.5 t/ha are obtained. According to the farmer (personal communication), cultivation is challenging because quinoa has low, competitive vigor and should be sown early and in areas with low weed pressure. A cold and wet spring can lead to crop failure. However, the crop requires little nitrogen fertilization (80 kg/ha) and no irrigation. Field trials by the Strickhof Research Centre and Agroscope have also achieved 1–2.5 t/ha, depending on variety and fertilization (Levy et al., 2019,Strickhof, 2018).

These reports and trials paint a positive picture of the potential for quinoa cultivation in Switzerland and confirm our model results, which indicate high climatic suitability. Bachmann and Maciejok (2018) state that yield processing is complex and expensive, especially for small quantities, which might be an implementation barrier. The increasing international demand has affected the price, so quinoa has become partly unaffordable for the local population in South America (Bachmann and Maciejok, 2018). Therefore, Swiss label organizations like IP-Suisse and Biofarm welcome and support the cultivation of Swiss quinoa.

4.2.4. Durum wheat (Triticum durum)

Durum wheat, primarily used to make pasta, bulgur, and couscous, originated in sub-Saharan Africa and is now a global food and cash crop (Sall et al., 2019). Today, its cultivation areas expand across North and Central America, Africa, and Asia (Curtis, 2002), while the largest commercial producer of durum wheat in Europe is Italy, followed by France (Ranieri, 2015).

Unlike bread wheat, durum wheat is primarily grown where rainfall is more limited (300 to 500 mm; Curtis, 2002). The crop is also adapted to high temperatures, but on the other hand, it is sensitive to cold conditions and requires an average of >250 h of sun during the harvest-preceding month (Lidon et al., 2014). The summer variety can be sown from February to March, depending on the soil, since it must be warm enough (Roth and Erkens, 2018). An area with little weed pressure should be selected for cultivation, as durum wheat shows low competitive strength, especially at the early stages of development. Because the crop is susceptible to several fungal diseases, such as fusaria (more so than bread wheat), quality definitions also require control of fungal phytopathogens (Lidon et al., 2014; Roth and Erkens, 2018). Sufficient nitrogen fertilization is recommended to achieve the protein contents crucial for pasta production, especially in the early stages of development (Lidon et al., 2014; Morari et al., 2018). Low competitive strength, susceptibility to fungal diseases, and fertilizer requirements pose challenges for management in the context of sustainable agriculture in Switzerland. Fig. 3 shows that durum wheat is only suitable in a narrow band from west to east, characterized by consistently lower rainfall. However, particularly in dry locations with coarser soils, durum wheat could produce more reliable yields than bread wheat (Salzmann, 2022).

4.2.5. Almond (Prunus dulcis)

The nuts of the almond tree are considered particularly healthy and are either consumed directly or processed, for example, into milk, marzipan, and ingredients for cosmetics ((Verma and Ahmed, 2009; Ahmad, 2010). The perennial crop originates from the Levant region and is cultivated on all continents today, with the greatest production regions being North America, Africa, Europe, and Asia (Lamichhane, 2014; Browicz and Zohary, 1996). In Europe, almonds are mainly grown in Spain (Lorite et al., 2020), but to a lesser extent in other Mediterranean countries such as Italy (Verma and Ahmed, 2009). However, according to Reutimann et al. (2020), almonds can grow in Switzerland in similar areas as grapevine and apricots. In Valais in southwestern Switzerland, almond trees occur wild and are also successfully cultivated in small quantities (Reutimann et al., 2020). In the ecocrop database, however, almonds' minimum temperature (Tmin) is set to 7 °C, Tkill to 4 °C. As a reminder, the crop is considered unsuitable if the average minimum temperatures fall below Tkill +4 °C. This is inconsistent with Reutimann et al. (2020) and Parker and Abatzoglou (2018), who describe almonds as winter-hardy and very well-tolerant of minus temperatures. Therefore, the ddatabase entries for almonds might underestimate the temperature range of the trees and, thus, their climatic suitability.

The winter-hardy crop is traditionally associated with marginal land (García-Tejero et al., 2018) and adapted to various soil-water conditions. Almonds thrive in areas with precipitation as high as 600 mm per year and dry-land areas (Yadollahi et al., 2011). Ahmad and Velma et al. (2009) reported that deep, well-drained loamy soils are best, while heavy and waterlogged soils are least suitable.

Soil degradation and high erosion, which are common risks in traditional almond orchards, can be limited through cover cropping with co-benefits for soil water retention and soil organic carbon sequestration (Ramos et al., 2010; Garcia-Franco et al., 2015; Almagro et al., 2016). Since it is a perennial crop, there may be options to introduce the tree in agroforestry systems (e.g., alley cropping with co-benefits both for climate mitigation and adaptation; Wolz et al., 2018).

A possible limitation of cultivation in Switzerland compared to the Mediterranean region is the higher humidity, which could favor diseases such as monilia (Reutimann et al. 2020). Lamichhane (2014) highlights the importance of disease risks for almonds and recommends breeding resistant cultivars and planting mixtures of intercropping varieties as suitable disease management strategies in the long term. Despite possible difficulties in cultivation and the competition in quality and price compared to imports, it could be marketed as a "Swiss almond" (Reutimann et al. 2020).

4.2.6. Pecan (Carya illinoinensis)

Pecans, also known for their healthy components, come initially from southern North America, where they were first cultivated commercially in the US. Nowadays, its cultivation expands towards South America (Uruguay, Argentina, Chile, Peru, and Brazil), China, South Africa, and Australia (Freiberg et al., 2021; Zheng et al., 2021). In Europe, pecan is grown on a small scale in the Mediterranean region, for example, Sicily (Italy) or Andalusia (Spain) (Benucci et al., 2012).

According to Fronza et al. (2018), pecan prefers deep and well-drained soils with a high level of nutrients and good water-holding capacity. Poorly drained soils are unfavorable as excess moisture causes stress to the root system (Fronza et al., 2018). The crop is susceptible to pests like *phylloxera* or fungi like *Fusicladium effusum*. Since there is no method yet to control the disease, cultivars with a higher resistance should be considered (Fronza et al., 2018). As for almonds, pecan cultivation in agroforestry systems is reported to have beneficial effects on soil properties (i.e., decreased bulk density, increased porosity, nutrient availability, and enzyme activity; Wang et al., 2022). Exploring the possibilities of co-cropping pecan and commercial truffles is a subject of ongoing research (e.g., Freiberg et al., 2021; Habtemariam et al., 2021; Grupe et al., 2021). So far, there are no reports of pecans being grown in Switzerland, but choosing the right location, especially regarding soil water conditions, is critical.

4.2.7. Sesame (Sesamum indicum)

Sesame (*Sesamum indicum L.*) is one of the oldest oilseed crops with high seed oil quality (Wei et al., 2009). While the use of edible seeds is commonly well known, the plant leaves can also be consumed during food scarcity (Qiu et al., 2012).

Sesame originates from Africa (Sharaby and Butovchenko, 2019) and can be found in all tropical to warm-temperate regions today (Pusadkar et al., 2015). The central production regions are China, India, Myanmar, Sudan, Central America, and other tropical and subtropical countries (Namiki, 2007). In Europe, only Italy produces small quantities of sesame (FAOSTAT).

Sesame is a chilling-sensitive plant that thrives best in high temperatures (around 25 °C) and requires 90 to 120 days without frost to be commercially grown (Sharaby and Butovchenko, 2019). The annual crop requires well-drained, sandy loam soils; sunny positions are favorable, while heavy rains might increase the risk of fungal diseases (Sheahan, 2014). According to Sheahan (2014), sesame is very drought tolerant, requires only one heavy irrigation or rainfall event before establishment, and should be harvested before frost.

In Switzerland, the soil requirements are met in many places. However, there is no indication of successful sesame cultivation in Switzerland yet. Nevertheless, the potential for cultivation could emerge with increasing temperatures.

4.2.8. Lentil (Lens culinaris)

Lentils are a source of high-quality micro-and macronutrients and a staple food in many countries and are often used in soups, stews, or vegetarian substitutes (Cokkizgin and Shtaya, 2013; Reif et al., 2020). Cultivation in Switzerland was abandoned in the late 1940s, and knowledge about it was lost (Strickhof, 2019). However, the areas under cultivation are increasing again in Switzerland, but demand can still not be met with the limited supply (Agroscope, 2023). Lentils are mainly cultivated from temperate to tropical regions in South Asia, North America, and Eastern Africa (Cokkizgin and Shtaya, 2013).

Lentils grow in sunny positions and require medium-heavy soils with a fine surface (Huxley, 1992, as cited in Fern, 2022). They are suitable for mixed cropping, where they benefit from support crops such as peas (Blatter et al., 2020)

Lentils should be cultivated on weed-free fields and be sown early. Due to their root nodules, the lentils can fix atmospheric nitrogen and do not require further nitrogen fertilization (like all legumes). The legumes are adapted to various soil conditions but prefer sandy loams, while heavy soils can lead to yield reductions (Cokkizgin and Shtaya, 2013).

In Switzerland, lentils of the green variety "Anicia" are currently cultivated in north-western Switzerland, where they are reported to require little maintenance and to be tolerant to dry conditions (Anonymous farmer, personal communication). At the farmer's site, lentils are grown together with camelina, which covers the soil and reduces weed pressure; thus, yields of 1–1.5 t/ha could be achieved. According to the farmer, lentils are a niche product, but thanks to existing demand, they can be marketed through regional or organic labels (such as Biofarm or ProSpeciesRara). The Strickhof Research Centre conducted field trials with "Anicia" and "Beluga" varieties in north-western Switzerland. The crops did not require any care and produced good yields of 2.2–2.9 t/ha, depending on the supporting crop (Strickhof, 2019). Based on these results, we anticipate prospects for cultivating in Switzerland as generally promising for lentils.

4.2.9. White/yellow lupine (Lupinus albus/Lupinus luteus)

Lupine is often known as a forage crop, but the seeds can also be used for human consumption, such as in the Mediterranean region, where it is part of the diet (Sedláková et al., 2016). Due to their high protein content, lupines are a promising substitute for meat in vegetarian diets, complementing the soybean and gaining increasing importance in recent years, especially in Europe, the demand for lupine as a substitute product has increased (Sedláková et al., 2016; Prusinski, 2017; Heine et al., 2018; Palanisamy et al., 2019). Due to its high nutritional value and technological properties, lupine is used as a technological food, and ingredient in many processed products (snacks, bakery, meat, and dairy products; Villa et al., 2020). However, with the increasing inclusion of lupine products in human foods, the allergenic potential of lupine seeds has become clear (Guillamon et al., 2010). The white and yellow lupine originated in the Mediterranean region and is now also common in South America, southern Africa, and southern Europe.

Both lupines have lower temperature requirements than soybeans and grow best in acidic soils, as they are very susceptible to lime (Biasio, 2020; Hijmans, 2020). Because of their deep roots, they can tolerate dry conditions and should preferably be grown in sunny locations (Huxley, 1992, cited in Fern 2021). Like all legumes, lupines do not require additional nitrogen fertilization. White lupine does not compete well with weeds. It is very susceptible to anthracnose, which is why resistant varieties such as "Frieda" or "Sulimo" are recommended, especially when it comes to organic farming (Frick et al., 2002). The Strickhof Research Centre conducted field experiments in northwestern Switzerland for different varieties in 2019 and 2020, where yields of 3.4–4.2 t/ha were achieved (Carrel and Zingg, 2020), suggesting strong potential for cultivating lupines in Switzerland.

4.2.10. Buffalo gourd (Cucurbita foetidissima)

Buffalo gourd is a pumpkin species originating from semi-arid North America and Mexico (Bemis et al., 1978). The flesh, starchy root and the oily seed can be consumed (Zhang and Halaweish, 2003). While the crop has several characteristics that are subject to various research investigations (e.g. its extreme drought resistance), it is not commonly cultivated. It is, however, known to have been occasionally consumed by native Americans, although the flesh is reported to be bitter (DeVeaux and Shultz, 1985). Also, nutritional information on buffalo gourd is lacking from food composition databases suggesting that the crop is unlikely to play a role as a food crop in Switzerland and in general.

4.2.11. Borage (Borago officinalis)

Parts of the annual herbaceous plant, such as the tender leaves, can be consumed either raw, cooked like spinach, or as a spice, and the flower can be prepared as an infusion for medicinal purposes (Gupta and Singh, 2010; Seifzadeh et al., 2020; Morton, 1992). However, these uses are more prevalent at home than commercial cultivation (Gupta and Singh, 2010; Seifzadeh et al., 2020). Today, borage is mainly grown as an oilseed, as it is the richest plant source of gamma-linolenic acid (GLA), which is used as an extremely valuable dietary or nutritional supplement and is used to treat various diseases (Gupta and Singh, 2010; Asadi-Samani et al., 2014; Galambosi et al., 2014).

Borage is likely to originate from the Mediterranean region but is now cultivated worldwide (Gupta and Singh, 2010). The main producers are the UK, Canada, and New Zealand (Galambosi et al., 2014).

The plant is very cold-resistant and grows well on moist soils with good drainage in weedy areas and in full sunlight (Asadi-Samani et al., 2014). The most appropriate fertilizer rate is 250 kg of nitrogen per hectare, but adequate amounts of phosphorus and potassium are also required (Asadi-Samani et al., 2014). A challenge for low-cost cultivation remains the mechanization of harvesting, as seeds mature unevenly over a long time (Galambosi et al., 2014).

In Switzerland, *Borago officinalis* occurs naturally; distribution records from InfoFlora cover large parts of the Swiss Central Plateau (InfoFlora2022a). This suggests that the ecocrop underestimates the current climate suitability for this plant.

4.3. Nutritional content

Table 5 shows a summary of the nutritional content information collected from the different food composition databases for the identified crops, as described in section 3.6. Nutritional information is lacking for vanilla grass and crowfoot grass and is available only partially for buffalo gourd. However, for the other crops identified in this study, A.2 (table describing the relevance of the listed nutrients) suggests that they provide good sources of all macronutrients and also of most micronutrients, except the ones that can generally not be derived from plants (i.e., vitamins B12 and D).

Vanilla grass (*Hierochloe odorata*) is an aromatic herb with traditional use both in Europe and northern America. Little is known about its nutrition properties. However, given its use as a spice crop, no important nutrient contribution is expected. Crowfoot grass (*Dactyloctenium aegyptium*) grain is still a traditional food plant consumed in several parts of Africa. Little is known about its nutrition properties. Quinoa (*Chenopodium quinoa*) has a very high protein content compared to other cereals and also contains high levels of carbohydrates, vitamins such as B2 and B6, as well as minerals like potassium, chloride, magnesium and iron. Durum wheat (*Triticum durum*) is a tetraploid species of wheat and is the hardest of all wheats; it is used to produce dry pasta. It contributes to the carbohydrates and protein intake, and it provides more fibers than common wheat. It contributes to thiamin, niacin, vitamin B6, potassium and iron intake, although the latter is little bioavailable. Almond (*Prunus amygdalus*) and sesame (*Sesamum indicum*), but most of all pecans (*Carya illinoinensis*), contain high amounts of fat. Almonds and sesame also contain a considerable amount of protein. In terms of vitamins and minerals, sesame contains high amounts of vitamin B1, B6, niacin, calcium, magnesium, phosphorus, iron, iodide, and zinc. Almonds contain vitamin B1, B2 and E, as well as potassium, magnesium, and phosphorus in larger amounts. Pecan provides moderate amounts of zinc and beta-carotene. Beta-carotene functions as an antioxidant and can be converted to vitamin A by the human body. Lentils (*Lens culinaris*) contain high quantities of various nutrients, for instance, they provide large amounts of proteins and carbohydrates (most of which as fibers) besides important micronutrients such as thiamin, pantothenic acid, vitamin B6, and folate, as well as phosphorus and iron. Both types of lupines (*Lupinus albus*, white, *and Lupinus luteus*, yellow) are very similar in nutrient content. They provide extraordinarily high amounts of proteins as well as fiber and in addition various essential micronutrients such as folate, iron, zinc, potassium, and vitamins B1 and B6. Unlike white lupine, yellow lupine also provides beta-carotene. Lupine can thus be considered a highly nutritional food crop. Buffalo gourd (*Cucurbita foetidissima*) flesh and seeds are a source of carbohydrates and fibers and provide significant amounts of potassium, calcium, and iron. Borage (*Borago officinalis*) is rich in vitamins A and C, and it contributes fairly to potassium and sodium intake.

Table 5
Summary of nutritional composition of the selected crops. Daily recommended allowances from the Swiss Society for Nutrition SSN (2015) and the Swiss food composition database by the Federal Food Safety and Veterinary Office (2021).

Crop Category		Fat (g)	Carbohydrates (g)	Fiber (g)	Protein (g)	Vitamin A (mcg-RAE)	Vitamin B1 (mg)	Vitamin B2 (mg)	Vitamin B6 (mg)	Vitamin B12 (mcg)	Niacin (mg)
		Nutritional quality (component values per 100 g edible portion)									
Spice crops	Vanilla grass	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Crowfoot grass	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Cereals	Quinoa	5	62	6.6	15	1	0.4	0.3	0.4	0	0.5
	Durum wheat	1.4	78	3.4	12	1	0.1	0.1	0.1	0	2.2
	Almond	50	4	13	26	0	0.2	0.4	0.2	0	2.1
Nuts and seeds	Pecan nut	72	14	9.6	9.2	8	0.7	0.1	0.2	0	1.2
	Sesame	50	12	12	21	0	0.7	0.1	0.4	0	5.8
	Lentil	1.5	45	17	24	2	0.5	0.1	0.2	0	2.5
Legumes	White lupine	8.8	13	32	33	0	0.4	0.2	0.2	0	2.9
	Yellow lupine	5	4.7	35	41	0	0.4	0.2	0.4	0	2.5
Vegetables	Buffalo gourd	18	27	21	NA	NA	NA	NA	NA	NA	NA
	Borage	0.7	3.1	NA	1.8	210	0.1	0.3	0.1	0	0.9
		Daily recommended allowances (women)									
		35*	50*	30	48	700	1	1.1	1.4	4	12
		Daily recommended allowances (men)									
		30*	50*	30	57	850	1.2	1.4	1.6	4	15

* % of daily energy intake

According to the Federal Food Safety and Veterinary Office FSVO (2021b) the Swiss population is well supplied with most important minerals and vitamins. However, parts of the population do not consume enough folate, iodide, vitamin D, iron, and magnesium, but also potassium, calcium, and vitamin C. Several of the crops we identified are excellent sources of many of these deficient nutrients: lentils and quinoa, but especially lupines contain large amounts of folate; borage is a good source of vitamin C; yellow lupine, sesame, and buffalo gourd provide magnesium; lupines, lentils, and quinoa contain larger amounts of potassium; and calcium can be supplied especially by sesame, and almonds (Table 5).

4.4. Benefits of the approach

The approach tested in this study proved to have a strong potential to identify region-specific candidate food crops suitable for emerging climate conditions. Unlike most other studies exploring cultivation potentials for alternative crops in a particular region, which start with a pre-defined list of candidate crops (e.g., Georgakopoulos et al., 2016; Bilalis et al., 2017; Kakabouki et al., 2021; Manners et al., 2020; Gardner et al., 2021b), our study takes an unprejudiced approach. By screening all 651 edible crops in the ecocrop database for current and future climatic suitability, we circumvent any possible pre-selection bias that may bias the results of review-based and participatory studies of alternative cropping potentials. Our approach thus opens the scope for identifying alternative crops with significant potential for cultivation that are undiscovered until now, while building on extensive knowledge resources contained in the ecocrop database. Our work highlights the high value of crop databases such as ecocrop and advocates for studies to revise the database, as ecocrop results for one crop were found to be implausible at the literature review stage (i.e., vanilla grass). The literature search also revealed that the nutritional value of crowfoot grass and vanilla grass is undocumented, vanilla grass is only suitable as a spice, and buffalo gourd has rather moderate nutritional value and almost no actual documentation of consumption. Following the additional evaluation by the literature review, we can now exclude these candidates as alternative food crops.

Like Gardner et al. (2021b), we complement our quantitative model results with qualitative data. By employing the Delphi method and interviewing multiple experts to derive an initial list of alternative crops, Gardner et al. (2021b) also account for non-climatic factors that influence agricultural decisions. By complementing the model results with a comprehensive literature review, our approach offers similar advantages and thus represents an alternative or even a complementary strategy.

4.5. Limitations of the approach

The effect of CO2 fertilization, which may have an impact especially on C3 crops, cannot be represented with ecocrop. We are screening for crops that are suitable under rainfed conditions, where water-use efficiency is vital. The adaptation capacity of C3 crops regarding the increase in duration and intensity of summer droughts with climate change increases due to the reduction in stomatal conduction related to elevated CO2 levels (Manderscheid et al., 2018). The suitability of the identified crops (all C3 crops) might increase relative to C4 crops in the future. However, such advantages may be consumed by adverse impacts of climate extremes and increasing pest pressure (Grünig et al., 2020).

Results derived from the ecocrop model seem plausible for most crops (except vanilla grass), considering available information on current distributions and information from the literature. Nevertheless, we noted that suitability estimates for almonds and borage are likely underestimated with ecocrop. This highlights a need to revise and update the ecocrop database to maintain and improve its applicability. Although the ecocrop database is a very valuable and unique source of information, most of the data was collected in the 1990s. To maintain our unbiased framework, we left the inputs to the database unchanged, partly because we would then have had to review the entries of all 651 food crops. Since 2022, ecocrop has been updated and integrated into a modeling framework provided by the FAO, a step we very much appreciate to maintain and improve this great source of knowledge in the future.

As a general limitation, interannual variability and influences of short-term extremes, which are expected to become more frequent in the

Folate (mcg)	Pantothenic acid (mg)	Vitamin C (mg)	Vitamin D (mcg)	Vitamin E activity (mg-ATE)	Potassium (mg)	Sodium (mg)	Chloride (mg)	Calcium (mg)	Magnesium (mg)	Phosphorus (mg)	Iron (mg)	Iodine (mcg)	Zinc (mg)
Nutritional quality (component values per 100 g edible portion)													
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
115	0.8	0.5	0	4	800	9.6	110	80	280	330	8	1.6	2.5
57	0.4	0	0	0.4	150	1.2	87	17	27	100	0.9	5.1	2.2
48	0.5	0	0	29.6	760	1.3	40	270	240	510	4.8	2	6
22	0.9	1.1	0	4.3	410	0	15	70	121	277	2.5	NA	4.5
115	0.3	0	0	1.7	500	7.7	10	940	330	570	8.6	10	8.5
150	1.4	6.8	0	0.3	860	1.7	84	57	96	400	8	0.7	3.6
360	0.8	4.8	0	NA	956	11	NA	176	162	373	4.7	NA	5.2
370	0.8	4.8	0	NA	1150	9	NA	NA	280	726	8.6	NA	7
NA	NA	NA	NA	NA	4500	140	NA	420	190	360	10	NA	4.1
13	0.0	35	0	NA	470	80	NA	93	52	53	3.3	NA	0.2
Daily recommended allowances (women)													
300	5	95	20	12	4000	1500	2300	1000	300	700	15	200	8
Daily recommended allowances (men)													
300	5	110	20	15	4000	1500	2300	1000	350	700	10	200	14

future, cannot be accounted for with ecocrop. It is, therefore, still being determined to what extent the listed crops could cope with increasingly variable climate conditions. This aspect requires more intensive research efforts in the future to validate results from this study (possibly based on observed yield data and mechanistic crop models), as also concluded by Gardner et al. (2021a). Future analyses are needed to address these crucial aspects and to identify possibilities to overcome existing agronomic and socio-economic implementation barriers, such as limited availability of regionally adapted varieties, plant protection methods, logistic constraints to harvest collection, and difficulties with emerging value chains (Meynard et al., 2018). Crops identified in this study could lead to a transformation towards more sustainable and climate-resilient agro-food systems only if they are complemented by behavioral changes on the consumer side (Poore and Nemecek, 2018). While health benefits are seen as possible promoters of dietary shifts towards plant-based products, limited knowledge about how to prepare meals with alternative ingredients was identified as an inhibiting factor with high relevance when it comes to the utilization of alternative crop products (Joyce et al., 2012; Hoek et al., 2017; White et al., 2022).

5. Conclusions

This work presents an innovative model and review-based approach for identifying suitable alternative crops to diversify cropping systems. Expanding the portfolio of cultivated food crops could increase climate resilience of food cropping systems, while providing healthy nutrition for regional plant-based diets and thus reducing GHG emissions from the agri-food system. While the approach applied here is transferable to other countries or regions, the analysis results apply to the Swiss Central Plateau and, at most, to neighboring regions with similar climatic and socio-cultural conditions. For Switzerland, we could identify eight alternative food crops that may benefit from projected climate change while also providing essential macro- and micronutrients for more plant-based regional diets.

Many of the identified crops are already being cultivated at very small scales in Switzerland, which confirms their potential as alternative crops. Although this is the first indicator of existing demand and lupines have great potential from a nutritional perspective, demand is still relatively small, which could pose an implementation barrier for farmers. This barrier is lower for quinoa, durum wheat, almond, pecan, and lentil. Evidence of cultivation efforts in different regions of Switzerland, as reported in the review section 4.3, confirms that these crops can be cultivated in Switzerland and are already perceived as alternative crops from a commercial perspective. However, additional marketing efforts may be needed to promote less familiar crops (i.e., lupine and borage) and facilitate their acceptance on both the consumer and producer side.

Legumes such as lupine and lentils are promising sources of proteins, which are essential if we reduce meat consumption to minimize GHG emissions and other environmental impacts. Like durum wheat, quinoa provides proteins and a large share of carbohydrates. Almond, pecan, and sesame provide high amounts of fat and macro- and micronutrients. At the same time, borage is a good source of vitamins A and C. Overall, the identified crops cover all important macro- and micronutrients (except for vitamins B12 and D, which are only contained in animal products). They may thus contribute to closing nutritional gaps in the Swiss population, such as a deficiency of folate, vitamin C, or magnesium. All identified crops have in common that they are robust to a wide range of environmental conditions, and many may be successfully cultivated on poorer soils and at higher elevations (such as quinoa and lentils). This expands the range of possible cultivation regions for food production in Switzerland towards regions mainly used for fodder production.

The specific results from this study provide a valuable basis for innovative Swiss farmers interested in exploring alternative, climate-smart production forms and for regional development initiatives interested in fostering local production and marketing of farm products. Further work should focus on increasing the confidence in model estimates (e.g., collecting yield information from diverse possible sources in Switzerland and its neighboring countries, refining crop-specific thresholds in the ecocrop database, and complementing ecocrop estimates with estimates based on process-based crop models). Systematic field trials with alternative crops in different biogeoclimatic regions of Switzerland would provide essential evidence on realistic cultivation potentials. While such evidence would be beneficial for refining estimates of cultivation potentials as quantified in our study, maps of regional differences in cultivation potentials could be highly informative for the planning of further field trials.

CRediT authorship contribution statement

Malve Heinz: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft. **Valeria Galetti:** Conceptualization, Methodology, Supervision, Formal analysis, Writing – original draft.

Annelie Holzkämper: Methodology, Validation, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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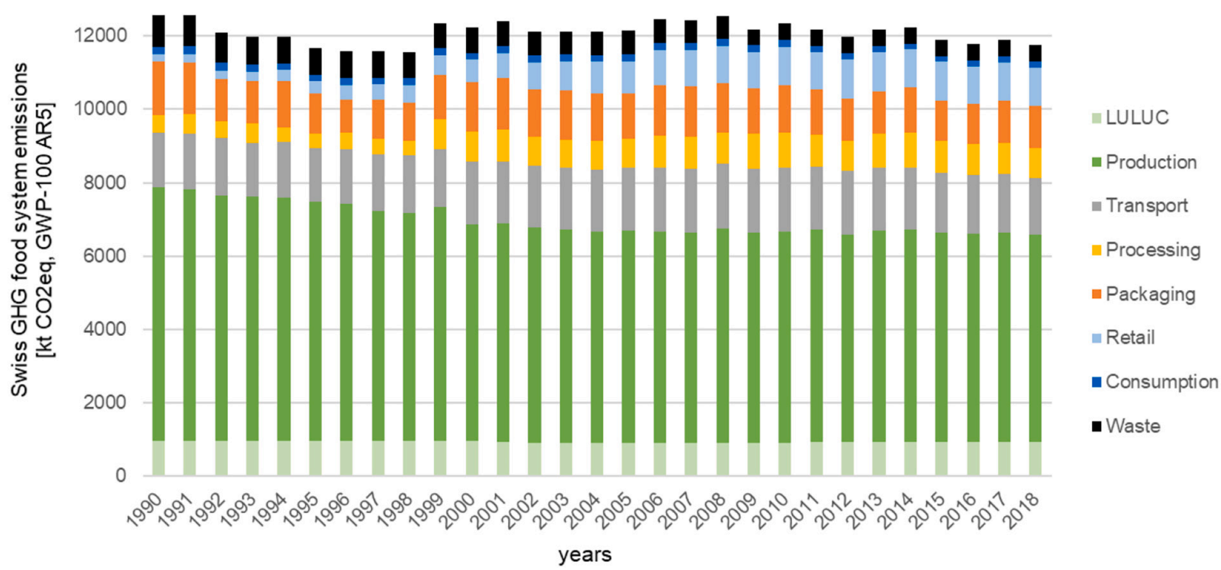
Appendix A

A.1. GHG emissions from the Swiss food system



Development of GHG emissions from the Swiss food system from 1990 to 2018 (LULUC = land use and land use change; data source: Crippa et al., 2021b).

A.2. Categorization of crops

Categorization of crops and examples, following the World Program for the Census of Agriculture, 2010.

Categorization of crops	Examples
Cereals	maize, wheat, rice
Vegetables	lettuce, onion, herbs
Fruits and Nuts	dates, apples, almonds
Oilseed crops	soybeans, olives, rapeseed
Root and tuber crops	potato, cassava, yams
Beverage and spice crops	coffee, tea, pepper
Leguminous crops	chickpeas, lupins, beans
Sugar crops	sugar beet, sugar cane
Grasses and fodders	–
Fiber	cotton, jute, hemp
Other crops	medical or ornamental crops, toxic or addictive plants

A.3. Climatic suitability at all three stations and periods under RCP scenarios 4.5 and 8.5

	RCP4.5									RCP8.5								
	Changins			Basel			Zürich			Changins			Basel			Zürich		
Crops	1981–2010	2040–2070	2070–2100	1981–2010	2040–2070	2070–2100	1981–2010	2040–2070	2070–2100	1981–2010	2040–2070	2070–2100	1981–2010	2040–2070	2070–2100	1981–2010	2040–2070	2070–2100
Vanilla grass	0.809	0.946	0.986	0.811	0.93	0.974	0.73	0.87	0.91	0.804	0.987	0.996	0.806	0.98	0.98	0.73	0.92	1
Crowfoot grass	0.502	0.665	0.727	0.504	0.65	0.711	0.41	0.57	0.62	0.496	0.736	0.833	0.498	0.721	0.721	0.41	0.63	0.83
Quinoa	0.706	0.774	0.751	0.71	0.784	0.768	0.63	0.74	0.77	0.71	0.752	0.617	0.713	0.77	0.77	0.63	0.8	0.68
Durum wheat	0.694	0.781	0.818	0.513	0.673	0.761	0.65	0.72	0.76	0.692	0.841	0.664	0.501	0.723	0.723	0.65	0.8	0.87
Almond	0.236	0.914	0.995	0.262	0.768	0.823	0	0.5	0.73	0.26	0.998	0.954	0.279	0.827	0.827	0	0.94	1
Pecan	0.547	0.697	0.766	0.506	0.607	0.666	0.44	0.61	0.65	0.552	0.81	0.869	0.505	0.679	0.679	0.45	0.7	0.82
Sesame	0.552	0.686	0.762	0.519	0.572	0.625	0.45	0.61	0.69	0.545	0.728	0.699	0.513	0.617	0.617	0.45	0.7	0.85
Lentil	0.863	0.857	0.886	0.579	0.672	0.681	0.81	0.86	0.94	0.862	0.888	0.836	0.575	0.682	0.682	0.81	0.93	0.95
White lupine	0.793	0.903	0.984	0.796	0.85	0.921	0.71	0.86	0.9	0.788	0.986	0.857	0.79	0.9	0.9	0.71	0.91	0.97
Yellow lupine	0.636	0.737	0.763	0.663	0.755	0.784	0.6	0.69	0.72	0.635	0.771	0.785	0.661	0.79	0.79	0.59	0.73	0.8
Buffalo gourd	0.701	0.816	0.866	0.703	0.805	0.853	0.64	0.75	0.79	0.697	0.873	0.882	0.698	0.856	0.856	0.63	0.8	0.93
Borage	0.588	0.725	0.757	0.593	0.722	0.743	0.5	0.64	0.68	0.593	0.799	0.421	0.596	0.793	0.793	0.5	0.73	0.62

A.4. Results for the reference period

Comparison of impact on model results between observed and modeled climate data for the reference period 1981–2010 as input for ecocrop. The last three columns show the mean value over all three stations. With the exception of a few crops, the results are very consistent.

	Reference period 1981–2010											
	Changins			Basel			Zürich			mean		
Crops	observed	RCP4.5	RCP8.5	observed	RCP4.5	RCP8.5	observed	RCP4.5	RCP8.5	observed	RCP4.5	RCP8.5
Vanilla grass	0.78	0.81	0.80	0.78	0.81	0.81	0.71	0.73	0.73	0.76	0.78	0.78
Crowfoot grass	0.46	0.50	0.50	0.46	0.50	0.50	0.38	0.41	0.41	0.43	0.47	0.47
Quinoa	0.73	0.71	0.71	0.74	0.71	0.71	0.65	0.63	0.63	0.71	0.68	0.68
Durum wheat	0.70	0.69	0.69	0.48	0.51	0.50	0.68	0.65	0.65	0.62	0.62	0.61
Almond	0.35	0.24	0.26	0.45	0.26	0.28	0.00	0.00	0.00	0.27	0.17	0.18
Pecan	0.57	0.55	0.55	0.50	0.51	0.51	0.48	0.44	0.45	0.52	0.50	0.50
Sesame	0.51	0.55	0.55	0.51	0.52	0.51	0.42	0.45	0.45	0.48	0.51	0.50
Lentil	0.87	0.86	0.86	0.57	0.58	0.58	0.85	0.81	0.81	0.76	0.75	0.75
White lupine	0.76	0.79	0.79	0.76	0.80	0.79	0.68	0.71	0.71	0.73	0.77	0.76
Yellow lupine	0.64	0.64	0.36	0.68	0.66	0.66	0.63	0.60	0.59	0.65	0.63	0.54
Buffalo gourd	0.67	0.70	0.70	0.67	0.70	0.70	0.61	0.64	0.63	0.65	0.68	0.68
Borage	0.61	0.59	0.59	0.63	0.59	0.60	0.53	0.50	0.50	0.59	0.56	0.56

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