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Global potential of integrated biorefineries for leaf protein and sugar: Producing sustainable food and preventing starvation in catastrophes

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Abstract

To accommodate population growth and shifting diets, the global protein supply must increase. Simultaneously, rising climate variability increases agricultural yield shocks, disrupting conventional crops. Worse, global catastrophes such as nuclear war or pandemics could collapse the global food system. Here, we turn to the potential of grasslands and plentiful legume biomass (e.g., alfalfa, clover) to address these challenges.

We demonstrate the potential and cost of integrated biorefineries for food production from biomass to obtain leaf protein concentrate (LPC), lignocellulosic sugar, and/or single-cell protein (SCP). These sustainable alternatives to conventional protein and sugar sources show remarkable global production potential: LPC+sugar could fulfill ~5% of the caloric requirements in one year, while LPC factories alone could fulfill global protein needs within 2 years. Combining LPC and SCP production enables food protein per hectare yields higher than any conventional food crop. Our crop modeling shows that LPC from grasslands could be more than enough to cover global calorie requirements. Even in extreme nuclear winter scenarios, grasslands could meet global protein requirements. However, this would require a large effort to multiply global legume biomass production several times over.

The product is affordable for global catastrophe response, at ~$1/kg (dry) of food, or a retail cost of ~$1-2/person/day to fulfill energy needs. Locations with long growing seasons, low biomass cost, and repurposable infrastructure minimize production costs. Future work should model tradeoffs with competing uses of land (food crops, grazing, etc.) to improve policy recommendations for crisis response.

Keywords

Global catastrophic risk; Existential risk; Resilient food; Food security; Leaf protein concentrate; Lignocellulosic sugar; Alternative Protein.

Abbreviations

ASRS, Abrupt sunlight reduction scenario

CAPEX, Capital expenditure

CEPCI, Chemical Engineering Plant Cost Index

DM, Dry matter

LPC, Leaf protein concentrate

NPV, Net present value

OPEX, Operational expenditure

SCP, Single-cell protein

Gt, Gigatonne (10^9 tonnes)

Tg, Teragram (10^{12} grams)

ha, Hectare

tpa, Tonnes per annum (metric tons per year)

USD, United States dollar

1 Introduction

The world's grasslands have a potential for food production that is much more massive than society currently exploits. Various constraints (steep/rocky/shallow soils, bad climate) complicate using them for growing crops that people can eat directly, so they are often used for grazing cattle or growing forages to feed cattle (Erb et al., 2016). However, we could grow much more food if we used these forage plants for food directly. Humans cannot digest these plants as ruminants do, but we can make food from them using industrial leaf protein extraction and biorefinery processes.

The world will need to produce 25–40% more food by 2050 to accommodate population growth (van Dijk et al., 2021). At the same time, increasing climate variability makes it almost certain that food production shocks unprecedented in contemporary history will take place, with a 10% loss in a given year almost certain to happen in this century (Bailey et al., 2015). In addition, it brings an increasing threat of climate tipping points that threaten modern agriculture, like the collapse of the Atlantic Meridional Overturning Circulation (Lenton et al., 2025). However, even larger food shocks are possible due to catastrophic events such as war, pandemics, infrastructure collapse, volcanic eruptions, etc. (Wescombe et al., 2025). The most severe of which is probably an abrupt sunlight reduction scenario (ASRS), such as a nuclear winter or volcanic winter that disrupts global crop production for years from a sudden reduction in temperature, sunlight, and precipitation (Xia et al., 2022). This type of agricultural disruption, which could arise from fires from nuclear explosions or sulfate aerosols from volcanic eruptions, could last for years, but there is less than one year of food storage globally (Denkenberger and Pearce, 2018). Preparing responses to these global catastrophes, such as the one developed in the current work, could help reduce existential risk to humanity.

To address these issues, a wide portfolio of options has been proposed to increase food production even in crisis situations, called resilient food interventions (García Martínez et al., 2025a) which could greatly mitigate famine (Rivers et al., 2024), including: crop relocation (Blouin et al., 2025), cropland expansion (Monteiro et al., 2024, 2025), seaweed (Jehn et al., 2024; Hinge et al., 2024), greenhouses (Alvarado et al., 2020), and high-tech industrial systems (García Martínez et al., 2024, 2025b). One of the latter involves the production of leaf protein concentrate (LPC), a sustainable protein-rich product that can be extracted from green leaves. Another one is the production of sugar from lignocellulosic biomass such as wood or plant residues (inedible stalks, husks, or leaves) (Throup et al., 2022), or single-cell protein (SCP) derived from this sugar. Combined production of LPC and sugar has significant potential to feed people more sustainably than we do now and even during food emergencies (García Martínez et al., 2025a).

Leaf protein concentrate is a protein-rich, nutrient-dense product made using the non-toxic, non-woody parts of selected plants. LPC can be consumed in a variety of forms, such as protein powder or concentrate, and is consumed primarily by monogastric animals, but also by people (Anoop et al., 2023). Large-scale production of LPC is often intended for use as a sustainable replacement for soybean meal protein in animal feed. For example, LPC has 57–85% lower emission intensity, 54–88% lower ocean acidification, and 74–89% lower eutrophication than soybean meal with the right system design (Gaffey et al., 2024). LPC has the potential to bridge nutritional deficits, including protein, and contains vitamins, minerals, and a combination of essential amino acids, making it a potential alternative to animal products. For example, it has significant potential to increase food security in Africa by producing more food from the same amount of crops, for example by covering a large share of Nigeria's food deficit (Ugwoke et al., 2023).

LPC has been produced on both household and industrial scales (Nagy et al., 1978), with several industrial and demonstration-scale plants producing feed, and is now gaining traction as an alternative protein source (Anoop et al., 2023). LPC has yet to be mass-produced globally for human consumption. Still, the last decade has seen a considerable increase in companies exploring leaf protein concentrate for the production of plant-based protein foods, including Leaft Foods, Rubisco Foods, The Leaf Protein Co, Grassa, Cosun, and Day 8.

LPC can be produced in biorefineries, factories that use a combination of physical and chemical steps to break biomass down into a variety of products in an integrated manner for increased efficiency (Ladero et al., 2025). The main byproducts of leafy biomass pressing to make LPC are a sugar-rich 'brown juice' and a lignocellulose-rich 'fiber press cake', which can be converted into a variety of products.

The concept of an integrated food biorefinery from green biomass has been hinted at in previous literature, with many authors proposing the extraction of LPC from fresh biomass for food use, integrated with the production of other outputs such as feeds, biochemicals, biomaterials, electricity, and biofuels (Corona et al., 2018; Santamaría-Fernández and Lübeck, 2020; Møller et al., 2021; Anoop et al., 2023). Some have studied the sugar production potential from the brown juice byproduct of LPC production (Andrade et al., 2023; Fetzer et al., 2024; Andrade et al., 2025), hinting at its potential food uses, or the production of single-cell protein from the brown juice sugars (Møller et al., 2021; Sørensen et al., 2025), a high-quality, sustainable protein source that can be used for food or feed (García Martínez et al., 2022b). Other authors have studied the production of food from lignocellulosic biomass, which the fiber-rich press cake byproduct of leafy biomass pressing is, to obtain single-cell protein (Voutilainen et al., 2021) or sugar products (Throup et al., 2022). However, to the best of our knowledge, an integrated biorefinery combining all of these processes to maximize food production has not been modeled before.

The goal of this project is to conceptualize a viable design for a biorefinery that produces the maximum amount of food energy and/or protein possible from leafy biomass, integrating these possibilities, and estimate its potential to be deployed at a global scale. We study the cost of deploying these biorefineries at scale in "business as usual" conditions, as well as doing so rapidly to respond to a global food crisis, using a nuclear winter as a model catastrophic scenario.

2 Methods

The integrated biorefinery, encompassing both LPC and lignocellulosic sugar production, was modeled based on studies carried out by Andrade and Ambye-Jensen (2022) and Tao and Davis (2017), as illustrated in Figure 1. While amenable biomass can be obtained from leafy crop byproducts (Meyer et al., 2023) or even tree leaves (Fist et al., 2021; Mottaghi et al., 2023; Pearce et al., 2019), we focus on perennial legumes that are much easier to obtain at scale with a stable high yield per hectare, have better protein quality, and provide multiple harvests per year while requiring no nitrogen fertilizer thanks to their natural nitrogen fixation. The leafy biomass, such as red clover or alfalfa, investigated in this study, is harvested and promptly transported to a nearby biorefinery to ensure immediate biomass processing, thereby minimizing nutrient degradation and preventing undesirable biological or chemical interactions. At the biorefinery, the biomass is first macerated to reduce particle size before wet fractionation. A mechanical process, carried out, for example, using a twin-screw press, separates the biomass into the fiber press cake and a protein-rich green juice. While the green juice is used for LPC production, the fiber fraction serves as the feedstock for sugar production.

For LPC production, the green juice is subjected to protein precipitation via heat coagulation. The juice is heated to 85 °C in a heat exchanger, after which a decanter centrifuge separates the LPC from the residual brown juice (BJ). The LPC is then dried to a dry matter content of approximately 95%, while the BJ is sent to an anaerobic digester for biogas production. Alternatively, the LPC could be post-processed into a different form, such as a chilled or frozen plant protein drink, and the BJ could be used as a fermentation media to produce single-cell protein.

For lignocellulosic sugar production, the fiber press cake feeds a dilute sulfuric acid pretreatment to hydrolyze hemicellulose into soluble sugars. The slurry is heated to 158 °C for 5 minutes to release C5 sugars from hemicellulose. After pretreatment, the hydrolysate slurry is flashed and held at approximately 130 °C in a secondary oligomer-conversion step for 20-30 minutes, then flashed again at atmospheric pressure with vapor at around 100 °C. The slurry is then conditioned to approximately 75 °C and sent to the enzymatic hydrolysis unit, which uses cellulase enzymes produced on-site in the biorefinery. This saccharification step is what liberates the sugar from the polymer structure, but there are also nonbiological processes that can produce the sugar, such as supercritical hydrolysis. The resulting hydrolysate, containing C6 sugars like glucose, C5 sugars like xylose, residual solids, and water, is processed through a filtration unit to separate the solids, primarily lignin, from the liquid fraction. The filtrate is then concentrated in an evaporator, yielding a product rich in fermentable sugars, while the residual solids are combusted in a boiler-turbogenerator. Finally, the sugar stream is purified to a dry food-grade product (Humbird et al., 2011; Throup et al., 2022).

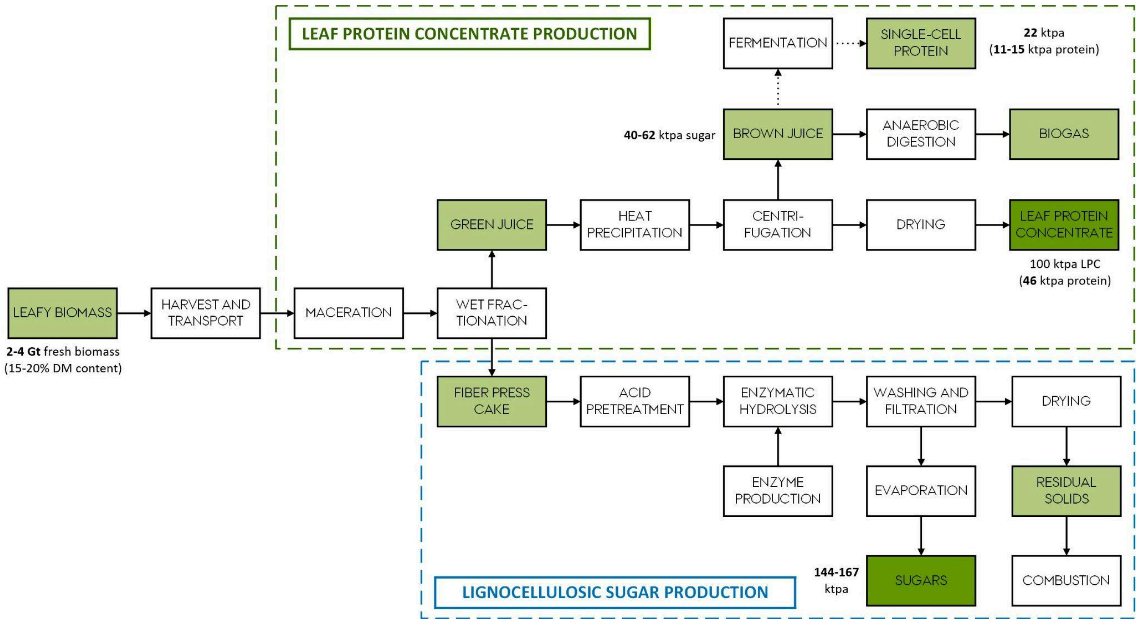

Figure 1. Integrated biorefinery concept for the combined production of leaf protein concentrate and lignocellulosic sugar. The dotted lines indicate alternative process routes. Mass flows are given for the design size proposed in this work.

2.1 Methodology overview

Two key metrics are estimated to characterize the potential of a resilient food: the ramp-up speed (how fast the production can be scaled over time) and the retail price (how affordable it would be during the catastrophe period). In addition, assessing the global availability of the relevant input resources is key to checking for potential bottlenecks to fast production ramp-up. Figure 2 contains an overview of the methodology used to estimate these metrics, which is described in depth in the following sections.

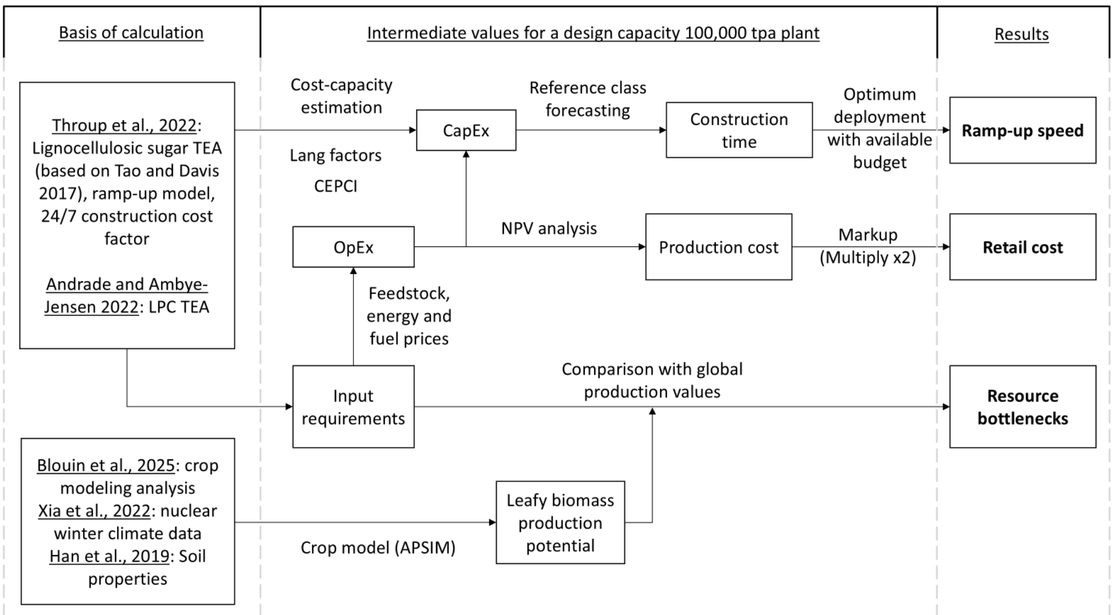

Figure 2. Methodology flowchart (CAPEX: capital expenditure, OPEX: operational expenditure, NPV: net present value, CEPCI: Chemical Engineering Plant Cost Index).

2.2 CAPEX, OPEX, and mass balances

To estimate the capital expenditure (CAPEX) of an "n-th factory" LPC+sugar biorefinery, we sum the capital cost of an LPC factory (Andrade and Ambye-Jensen, 2022) and the capital cost of a lignocellulosic sugar factory (Throup et al., 2022). The operational expenditure (OPEX) was similarly estimated by combining that of the two factories, minus the biomass cost of the sugar factory. Table 1 shows a summary of published capital cost estimates for LPC factories, indicating that the reference LPC factory is on the more conservative end of the capital estimates. There is a large uncertainty present in estimating the costs of a large-scale LPC+sugar food-grade production facility, as currently no available data exist on such a full-scale commercial-sized biorefinery. There exist semi-commercial and demonstration-scale LPC factories for feed and food uses (Jørgensen et al., 2021; Monagas, 2025). There also exist demonstration-scale facilities for lignocellulosic sugar production, as well as for producing and converting such sugars to ethanol, better known as second-generation biofuel factories (Throup et al., 2022). However, no biorefinery producing both products from a single feedstock has ever been built. Thus, we conservatively estimate that the cost of building such a biorefinery corresponds to the cost of building each biorefinery separately. In reality, there would be cost savings from shared systems, including feedstock admission, wastewater treatment, byproduct processing, office, laboratory, and site development. The capital estimate attempts to represent the cost of an "n-th factory" facility; we do not attempt to calculate the CAPEX of a costlier "first of a kind" biorefinery.

The reference LPC factory requires a CAPEX of $9.7 million at 5,600 tonne/year (tpa) capacity of LPC on a dry (DM) matter basis in 2021 (Andrade and Ambye-Jensen, 2022), whereas the reference lignocellulosic sugar factory requires a CAPEX of $574.9 million at 395,600 tpa (DM) capacity (Throup et al., 2022)—both including all relevant cost entries such as equipment, construction, warehouse, development, piping, prorateable expenses, field expenses, home office, project contingency, start-up, permits, and working capital.

The design capacity is set to 100,000 tpa LPC (DM), with the accompanying production of lignocellulosic sugar depending on the corresponding amount of fiber required to achieve this LPC design size. The reference factory was designed to operate for 6 months per year, corresponding to the growing season in Denmark, which is expected to be similar to the average for a majority of grasslands (Fischer et al., 2021). However, if the factory could be operated for longer, that would reduce factory CAPEX for the chosen design size, and vice versa. To estimate the capital cost of the reference LPC and sugar biorefineries when scaled to the design size, we use the power-sizing scaling technique as shown in Equation 1 (Sinnott, 2005), where C_1 is the unit cost at capacity Q_1, C_2 is the unit cost at capacity Q_2, and x is the cost-capacity exponential scaling factor. The capital money values were scaled to mid-2025 USD using the CEPCI.

$$C_2 = C_1 (Q_2/Q_1)^x \quad \textbf{(1)}$$

For the global catastrophe scenario, food is expected to be scarce after the first months in an ASRS, as food reserves run out (Denkenberger et al., 2017), making it preferable to increase food production as soon as possible. Fast construction methods are hereby proposed to reduce factory construction time, at the expense of increasing the capital expenditure. The most efficient post-catastrophe fast construction method available is to implement 24/7 construction, reducing overall construction time to 32% of the original at an increased labor cost of 47% as per (Throup et al., 2022), according to the methodology and values of (Hanna et al., 2007). This value has been conservatively incorporated in terms of a 47% increase in the capital cost of the factory to account for labor availability and other constraints. The CAPEX of the catastrophe scenario factories is thus increased by 47% from the baseline, for the purposes of estimating construction time and product costs.

Table 1. Literature review of previous techno-economic analysis of LPC production factories, including LPC yields, production capacity, and operating time assumptions, and results for capital efficiency and product selling price.

		Product yield		**Production capacity**		**Operating time**	**Capital efficiency (2025 updated)**	**Selling price (2025 updated)**
	Feedstock	kg crude protein/kg feedstock (DM)	kg LPC (DM)/kg feedstock (DM)	metric tonnes crude protein/year	metric tonnes LPC (DM)/year	hours/year	$/tpa LPC (DM)	USD/tonne LPC (DM)
Andrade 2022, conventional case	Grass clover mixture	0.092	0.186	2,784	5,628	4200	$1,820	899
Jørgensen et al. 2021, conventional case	Grass or grass clover mixture	0.089	0.180	1,781	3,600	4200	$1,017	462
Bals 2011, Mechanical pressing, Base case	Switchgrass	0.074	0.150	12,966	26,207	2160	$1,238	553
Bals 2011, Aqueous extraction, Base case	Switchgrass	0.062	0.124	10,778	21,786	8400	$1,832	553

In addition, a sensitivity analysis was run to explore the impact of four key parameters on the cost and ramp-up speed results. The LPC yield parameter varied between a conservative value of ~0.12 kg LPC (DM)/kg biomass (DM) (Bals and Dale, 2011) to a more optimistic 0.186 (Andrade and Ambye-Jensen, 2022); varying the yield this widely while keeping the design capacity constant results in significant variations in CAPEX. The fiber-to-sugar conversion yield was varied between 30-40%, representative of processes using effective pretreatment and enzymes or strong acids, such as modeled here (Cuevas-Aranda et al., 2024; Moncada et al., 2018). The cost-capacity exponent parameter was varied between 0.6-0.8, values based on highly mechanical processes like pulping, which is adequate for the current process (Sinnott, 2005). Finally, the OPEX was also varied to account for economies of scale using Eq. 1, with exponents between 0.8-1, i.e., from moderate savings with increasing scale to no savings.

The mass balances for the LPC section of the biorefinery are based on those reported for the reference LPC factory of (Andrade and Ambye-Jensen, 2022) and increased to the

100,000 tpa (DM) LPC design capacity, using the following ratios: 0.67 kg fiber press cake/kg biomass (DM) and 0.15 kg brown juice/kg biomass (DM). The mass balances for the lignocellulosic sugar section are based on the stream of fiber-press cake resulting from the leafy biomass pressing. The composition of the resulting sugar stream is based on that reported by (Tao and Davis, 2017). All the scenarios studied are summarized in Table 2.

Table 2. Summary of scenarios considered in this work for the main results (product cost and ramp-up speed), including relevant parameters.

Parameter	**Scenarios considered for sensitivity analysis of cost and ramp-up speed**	**Description**
Product	LPC-only	product = 100,000 tpa LPC
Ramp-up scenario	Regular conditions	20 years plant operation and normal construction
	Catastrophe conditions	6 years plant operation and 24/7 fast construction, higher CAPEX and product cost than regular conditions
Economic parameters of the factory	Optimistic factory parameters	LPC extraction yield=0.186 kg LPC/kg biomass (DM), high economies of scale with LPC CAPEX_x=0.6 and OPEX_x=0.8
	Pessimistic factory parameters	LPC extraction yield=0.12 kg LPC/kg biomass (DM), low economies of scale with LPC CAPEX_x=0.8 and OPEX_x=1
Lignocellulosic biomass to sugar yield	LPC+sugar	0.36 kg sugar (DM)/kg fiber press cake (DM)
Fiber press cake	N/A (same value for all scenarios)	0.67 kg fiber press cake/kg biomass (DM)
Brown juice byproduct	N/A (same value for all scenarios)	0.15 kg brown juice/kg biomass (DM)
Factory operational time (seasonal)	N/A (same value for all scenarios)	6 months/year
Type of cost estimate	N/A (same value for all scenarios)	N-th plant, cost for a mature industry

The SCP production potential of the LPC+sugar biorefineries can be estimated based on a set of relevant reported conversion yield values of sugars to SCP: 0.2 kg SCP/kg sugar (DM) for Torula from wood hydrolysate sugars (Voutilainen et al., 2021), 0.26 for Pekilo from sulfite spent liquor sugars (Voutilainen et al., 2021), 0.36 for Fusarium venenatum from glucose (Voutilainen et al., 2021), 0.37-0.48 for *C. utilis* from brown juice sugars (Sørensen et al., 2025), and 0.54 for yeast or microalgae from glucose (Good Food Institute et al., 2025). Modern industry standard yields for SCP of 0.36-0.54 were used for the design facility as well as a protein content of the SCP between 50% (Voutilainen et al., 2021) and 70% (Sørensen et al., 2025). The capital cost estimates do not include an SCP section, as the estimates for SCP production potential from brown juice or lignocellulosic sugar are illustrative. Instead, the total factory CAPEX is given for a process that converts the brown juice into biogas using an anaerobic digester, same as the reference plant (Andrade and Ambye-Jensen, 2022). The biogas produced from brown juice in the anaerobic digester present in the LPC-only factory could also be used to make SCP (García Martínez et al., 2022b) or provide process energy, but this is conservatively not included.

Estimates were also produced for how much milk could be obtained from the fiber press cake if it wasn't used for lignocellulosic sugar production, with a conversion rate of 5.93 kcal forage required per kcal of milk produced based on a forage only diet trial (Dong et al., 2015). The gross energy content of the fiber was considered comparable to alfalfa hay, at 4,862 kcal/kg fiber press cake (DM) (Feedipedia, 2012), and the milk composition was obtained from the USDA database (USDA, 2019).

2.3 Assessment of required resources

Assessing potential bottlenecks to the ramp-up potential of LPC+sugar first demands estimating the amount of LPC and sugar required to fulfill the food requirements of the global population and the equivalent in terms of the number of reference production factories. The amount of protein and calories available in LPC and sugar products, as well as the requirements for feeding one person, were compared to the world population. Then, the resources required to produce the necessary amount of LPC and sugar are quantified. The values used as a basis for the analysis are summarized in Table 3.

*Table 3. Basis of calculation for the resource availability analysis. *Some amount of food waste throughout the system is unavoidable, regardless of food crisis severity. However, a reasonably low value of food waste, 12%, was considered in the proposed scenario. This value was chosen because food waste is expected to be lower due to increased food scarcity. Moreover, the final LPC and sugar products are dry products, with a long shelf life, further reducing potential food waste* (Denkenberger and Pearce, 2014).

Variable	**Value**	**Unit**	**Source**
World population	8.2	billion people	(United Nations, 2025)
Recommended protein intake	60	g/person/day	(World Health Organization and United Nations University, 2007)
Expected food waste	12	% of calories produced	*
Average daily caloric requirement per person	2,100	kcal/person/day (=1.39 kWh)	(WHO, 2004)
Energy requirements of LPC production	3.3	kWh electricity/kg crude protein (alfalfa)	(Andrade et al., 2025)
	1.4	kWh thermal/kg crude protein (alfalfa)	

	4.7	kWh electricity/kg crude protein (red clover)	
	2.8	kWh thermal/kg crude protein (red clover)	
Global electricity consumption	27,064	TWh/year	(Statista, 2025)
Global natural gas production	4,142	billion m^3/year	(IEA, 2025a)
Net energy generation in the lignocellulosic sugar section	0.3	kWh/kg sugar	(Tao and Davis, 2017)

An accurate estimate of the caloric density and protein content in the final LPC and sugar products is central to forecasting how much of them would be required to fulfill the protein and caloric requirements of the global population. The macronutrient concentration profile of an LPC product from a single-stage extraction LPC process can be approximated as 45.6% protein, 13.9% fat, and 16.9% carbohydrates (DM basis), with the rest of the composition primarily comprised of ash, hemicellulose, cellulose, and lignin (Andrade and Ambye-Jensen, 2022; Andrade et al., 2025). Using typical Atwater factors, 4 kcal/g of protein and carbohydrate and 9 kcal/g fat (Atwater and Bryant, 1900), the caloric density of the LPC is estimated at 3,751 kcal/kg (DM) of LPC product. A caloric density of 3,311 kcal/kg (DM) sugar product obtained from the fiber cake is used (Throup et al., 2022).

The lignocellulosic sugar production process is net-energy positive from combusting lignin and organic byproducts of the process, providing 0.3 kWh/kg sugar produced (Tao and Davis, 2017).

2.4 Crop modeling

The global production potential of plant biomass amenable to LPC production is estimated through crop modeling simulations of the different scenarios studied: the current climate, an extreme nuclear winter scenario, and a less severe nuclear winter. We modeled red clover as a representative forage legume for this analysis. Red clover's taller growth habit makes it better suited to mechanical harvesting than white clover, and it serves as a reasonable proxy for other temperate forage legumes (e.g., alfalfa) that might be regionally optimal.

We used the Agricultural Production Systems sIMulator (APSIM) version 2024.10.7600.0 (Holzworth et al., 2018, 2014) to simulate red clover (cultivar Colenso) growth under baseline and nuclear winter conditions. APSIM is a process-based crop model that simulates plant growth through mechanistic representations of photosynthesis, respiration, phenology, and water/nutrient dynamics. The same modeling framework and climate data were used as in (Blouin et al., 2025), with simulations conducted at 1° × 1° spatial resolution.

Climate forcing data for nuclear winter scenarios were taken from (Xia et al., 2022), who simulated the climate effects of stratospheric soot injection. We analyzed two scenarios representing a 27 Tg and 150 Tg soot injection to the stratosphere, corresponding to a "central" severe nuclear winter scenario and an upper-bound extreme nuclear winter scenario, respectively. Soil properties were derived from the SoilGrids database (Han et al., 2019).

Simulations were restricted to current pasture areas using the dataset of (Mehrabi et al., 2025) as per Figure 3, which includes land used predominantly for grazing and forage cultivation while excluding untouched natural grasslands. We focused on pastures rather than cropland because cropland generally provides higher caloric returns through direct staple crop production (see the supplementary material for an illustrative comparison). Management practices represented low-input forage production without irrigation or nitrogen fertilizer application. However, note that the crop model assumes no P/K stress, which in practice means ideal P/K fertilization, and high alfalfa yields generally have significant P/K requirements (Megan Baker et al., 2024).

Harvest management used a threshold-based approach: cutting occurred when above-ground dry matter reached on average 2500 kg DM/ha, leaving 1000 kg DM/ha residual biomass to allow regrowth. Simulations spanned 15 years, with the first 5 years representing baseline climate conditions and the subsequent 10 years representing the nuclear winter period. For each grid cell, we calculated annual total harvested dry matter by summing all cuts within each year. In practice, large-scale LPC production would trade a small reduction in harvest efficiency for logistical feasibility. Rather than harvesting every field exactly at 2,500 kg DM/ha, harvests would be staggered across a larger catchment and scheduled to keep a near-constant factory throughput while maintaining short harvest-to-processing times (order of 6-12 h) for each load. Detailed harvest logistics optimization is beyond the scope of this study, but would be essential in real deployments.

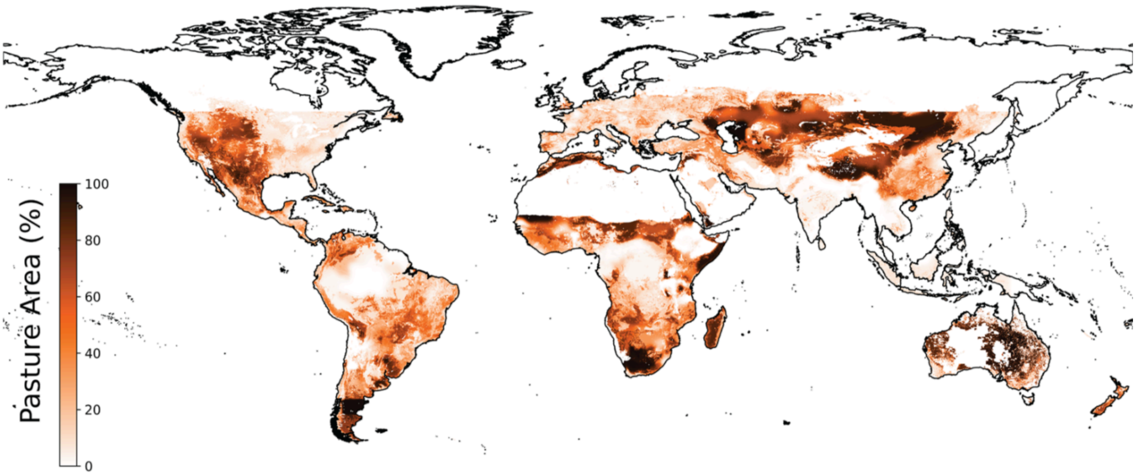

Figure 3. Pasture mask used in crop modelling. This is land in permanent meadows and pastures, which is used permanently (5 years or more) to grow herbaceous forage crops through cultivation or naturally (wild prairie or grazing land). This class includes the following: 1) grazing in wooded areas (e.g., agroforestry areas); 2) grazing in shrubby zones (e.g., heath, maquis, garigue); and 3) grassland in the plain or low mountain areas used for grazing, including land crossed during transhumance where the animals spend a part of the year (approximately 100 days) without returning to the holding in the evening (e.g., mountain and subalpine meadows) and steppes and dry meadows used for pasture. Material from: Z. Mehrabi, K. Tong, J. Fortin, R. Stanimirova, M. Friedl, and N. Ramankutty, Global agricultural lands in the

year 2015, Earth System Science Data, published 2025 by Copernicus Publications (CC BY 4.0 license, no changes made).

2.5 Ramp-up speed estimation

We define the ramp-up speed as the increase in installed food production capacity over time when continuously building as many food production factories as possible with the available resources. In the proposed catastrophe scenario, the ramp-up speed of LPC+sugar technology would likely be limited by the resources that could be effectively used, including but not limited to: raw materials, energy, qualified labor, and capacity for equipment construction. We roughly account for these constraints by limiting the budget that can be effectively applied to 24/7 construction of LPC+sugar biorefineries to a value of $489 billion per year (Damodaran, 2020), which is the capital expenditure on adjacent industries whose resources could be redirected, such as chemicals, power, pulp & paper, utilities, and beverages. It is uncertain if workers of other, less related industries could be retrained fast enough to build and operate LPC+sugar biorefineries. Thus, the average number of facilities that could be constructed in one year is obtained by dividing this total yearly CAPEX budget by the cost of a reference-size factory. Simultaneously, land preparation and legume biomass sowing would take place elsewhere to make the feedstock available at the time of factory completion.

The time taken to construct a facility can be modeled logarithmically from the cost of the facility. The construction time was estimated by reference class forecasting, using a logarithmic regression model based on data from previously built factories (Martin et al., 2006). The most efficient way to increase production capacity rapidly in this extreme scenario is 24/7 construction, which is estimated to reduce construction time to 32% of the original value (Throup et al., 2022). The number of facilities that could be built per construction "wave" is calculated by dividing the number of factories that can be built per year by the number of waves per year. For example, the first wave can be seen in the ramp-up graphs as the first step increase in food production, shortly followed by another increase representing the moment that the factory transitions from startup production to full production, and later by another increase that represents the second wave (see Ramp-up speed values section and supplementary material).

The startup period is the time of reduced production between mechanical completion and the start of operation. An average production capacity of 50% applies, and it is considered to last one-fourth of the construction time at regular speed (Humbird et al., 2011). Delays before factory construction also affect construction timelines; a value of 4 weeks is assumed, which is the time it took complex industries to convert and scale production of relevant supplies during the COVID-19 pandemic (Betti and Heinzmann, 2020). More details on ramp-up speed estimation can be found in (Throup et al., 2022) and (García Martínez et al., 2021c), including an example of the method in the supplementary material of the latter.

2.6 Economic analysis

A net present value (NPV) analysis was performed by calculating the required revenue for a standard unit of the LPC product when NPV equals zero, providing the break-even cost of the product. To estimate the timeframe of factory operation, six years was used. This conservative timeframe is shorter than those typical of chemical process facilities, and represents the period in which industrial food production factories could operate during an extreme food shock at costs lower than regular food production methods. This is representative of the duration for a period with little sunlight caused by a nuclear winter. The increased capital cost from 24/7 construction applies. At the end of the six years, the equipment was considered to be depreciated. In reality, some lower-priced food could be sold for longer, there would be some salvage value, or the systems could be built less expensively (less durably). Thus, this represents a conservative assumption. To account for the time value of money, a 10% discount rate was used, consistent with recommendations for economic analyses facing an absence of statistical data for the given technology (Short et al., 1995). The same analysis was performed for normal conditions outside of a catastrophe, namely a typical factory lifetime of 20 years and regular construction cost, for comparison and to understand the global potential of the process in a business-as-usual scenario. An income tax rate of 35%, a loan at 70% equity, an interest rate of 8%, and 10 years of payment were assumed.

3 Results and discussion

3.1 Mass balances

The design capacity of 100,000 tpa LPC (DM) requires 534,000-833,000 tpa biomass (DM), which after extraction results in a fiber press cake byproduct of 360,000-558,000 tpa fiber (DM) based on the expected yield range of 0.12-0.186 kg LPC (DM)/kg biomass (DM). This can be converted into lignocellulosic sugar at a conversion ratio of 0.3-0.4 kg sugar/kg fiber, resulting in an expected 144,000-167,000 tpa sugar (DM). The sugars in the brown juice are produced at a rate of ~0.15 kg sugar (DM) per kg biomass (DM), corresponding to 39,000-62,000 tpa sugar. Since the moisture content of red clover and alfalfa at harvest is typically between 75-80% (Undersander and Saxe, 2013), each design-size factory requires the harvest of approximately 2-4 million tonnes of fresh biomass per year. The biorefinery produces the most food mass when it maximizes LPC and sugar extraction from the biomass, at around 0.3-0.5 kg of food overall per kg biomass (DM).

A biorefinery setup to maximize protein production would instead use the fermentable sugars obtained from the saccharification process and in the brown juice to make single-cell protein. At a mass conversion ratio of 36-54%, the SCP potential of the sugar streams is 60,000-78,000 tpa SCP from the lignocellulosic sugar and ~22,000 tpa SCP from the brown juice, respectively, or a total SCP potential of 83,000-99,000 tpa SCP. For protein contents of 45.6% of LPC and approximately 60% of SCP, the resulting potential of pure protein production of an LPC+SCP biorefinery would be ~100,000 tonnes of protein per year, corresponding to ~190,000 tpa of protein-rich food. For an SCP yield of 0.36-0.54, this corresponds to an expected protein yield of ~100-200 g protein per kg of biomass (DM) processed into LPC and SCP. Alternatively, the fiber press cake can be fed to dairy cows at a rate of 6 kg to obtain 1 kg of milk (DM, 27% protein), resulting in an expected protein yield of ~100 g protein per kg of biomass (DM) processed into LPC and milk. Figure 4 summarizes the protein production potential of the biorefinery for different published values of sugar-to-SCP conversion applied to the target design biorefinery. All calculations in this section can be consulted in the supplementary spreadsheet.

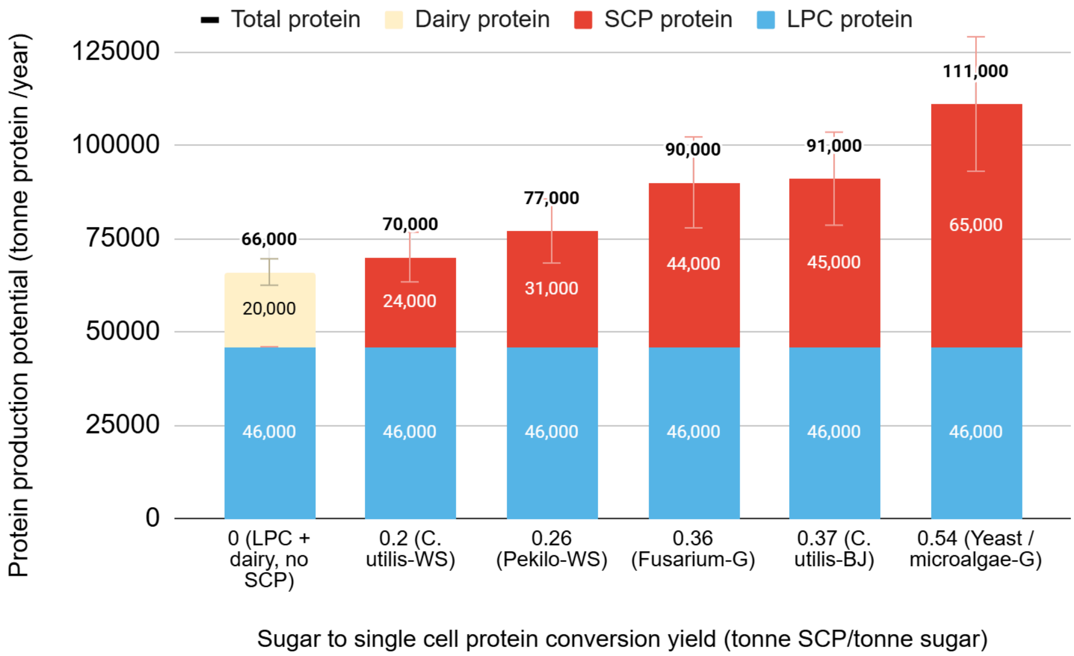

Figure 4. Protein production potential of the design capacity factory (100,000 tpa LPC) for selected values of sugar-to-SCP conversion (one for each column), and protein contents between 40-60% of the SCP mass (as represented by the uncertainty ranges). The amount of protein obtained per biorefinery is shown for both the protein that would be obtained from the sugar-to-SCP conversion (lignocellulosic sugars and brown juice sugars) and for the combination of SCP and LPC. The no-SCP case shows the protein yield of using the fiber press cake as feed for dairy cows. The columns represent relevant conversion yield values reported in literature for different combinations of organism and feedstock. Notes: WS=wood-derived sugars, BJ=brown juice, G=glucose. Candida utilis is a yeast used as feed, food, and flavoring. Pekilo is a mycoprotein from the fungus Paecilomyces variotii. Fusarium venenatum is a mycoprotein organism commonly used for vegan meat substitutes under the brand name Quorn. Yeast and microalgae are microorganism types with established uses in food and feed.

3.2 CAPEX and OPEX

Table 4 summarizes the factory CAPEX and OPEX results. The design LPC-only production capacity of 100,000 tpa LPC (DM) requires a CAPEX of $54-137 million, or $80-201 million when using 24/7 construction (all values updated to mid-2025 USD). The former is equivalent to a capital intensity of approximately $500-1,400/tonne of installed LPC capacity. The wide variation primarily stems from the uncertainty range of expected LPC yields (0.12-0.186 kg LPC/kg biomass) and economies of scale (x = 0.6-0.8 for capital cost, x = 0.8-1 for operational cost). The corresponding LPC-only OPEX is $60-164 million/year, primarily from the biomass cost—at 78% of the total OPEX (Andrade and Ambye-Jensen, 2022)—with the rest comprised by labor and maintenance, utilities, and other expenses (e.g., taxes/overheads). Details can be found in the supplementary spreadsheet.

The lignocellulosic sugar production requires an additional CAPEX of $342-458 million and an OPEX of $29-37 million. Combined, the reference LPC+sugar facility requires a CAPEX of $396-594 million and an OPEX of $71-180 million/year. The corresponding capital intensity is $1,600-2,200/tonne of installed capacity, or $2,400-3,300/tonne for 24/7 construction.

If there were a location with an adequate pulp and paper mill that could be repurposed for sugar production and a low distance to biomass amenable to LPC production, significant CAPEX savings could be achieved for the sugar section. For the chosen design capacity, the CAPEX for an LPC+sugar facility could be reduced from $582-874 million (using 24/7 construction) to an estimated $169-307 million by repurposing the existing pulp and paper facility (Throup et al., 2022).

Table 4. CAPEX and OPEX estimates for all factory configurations and scenarios considered.

Scenario	**Factory configuration**	**CAPEX (million USD)** Regular construction	Fast (24/7) construction	**OPEX (million USD/year)**
		Regular construction	**Fast (24/7) construction**	
Optimistic factory parameters: yield=0.186 kg LPC/kg biomass, high economies of scale with LPC CAPEX_x=0.6 and OPEX_x=0.8	LPC only	$54	$80	$60
	LPC+sugar	$396	$582	$71
	LPC+sugar (pulp and paper mill repurposing)	$115	$169	$71
Pessimistic factory parameters: yield=0.12 kg LPC/kg biomass, low economies of scale with LPC CAPEX_x=0.8 and OPEX_x=1	LPC only	$137	$201	$164
	LPC+sugar	$594	$874	$180
	LPC+sugar (pulp and paper mill repurposing)	$209	$307	$180

3.3 Energy requirements

Energy use would not be a significant limitation for ramping up LPC production. The electricity and fuel requirements vary depending on the type of biomass selected for LPC extraction, with alfalfa requiring ~40% less energy than red clover (Andrade et al., 2025). Fulfilling a global protein requirement of 0.2 Gt protein/y would require 658 TWh/y using alfalfa but 954 TWh/y using red clover. These correspond to 2.4-3.5% of the current global electricity consumption, lower than the requirement of other technologies for the catastrophe use case, such as hydrogen SCP (García Martínez et al., 2021c), microbial electrosynthesis (García Martínez et al., 2021a), or methane SCP (García Martínez et al., 2022b), but higher than synthetic fats from hydrocarbons (García Martínez et al., 2022a). The fuel requirements could be fulfilled with just 0.6-1.2% of global natural gas production. Even when trying to fulfill the entire global caloric requirement with LPC, it would take just around 10-15% of global electricity and 3-5% of global natural gas production.

A biorefinery design that combines LPC production with lignocellulosic sugar production could require less energy. The proposed sugar factory design includes a boiler to combust biomass byproducts (lignin, residual organics, sludge), as a result, the section produces more electricity than it requires, around 0.3 kWh/kg sugar (Tao and Davis, 2017). This would reduce the energy demand to fulfill global protein needs to ~8-13%.

Fuel requirements for harvesting are also not a significant limitation. A mechanized alfalfa harvesting life cycle assessment found a requirement of 282 MJ liquid fuel/tonne fresh alfalfa (Wiens et al., 2016), which, scaled to fulfill protein requirements, would mean 2-3 million barrels per day. This would be 2-3% of the global liquid fuel production of 107.4 million barrels per day (IEA, 2025b), or 7-11% to produce the equivalent of the global caloric food requirements. Some of this fuel requirement (~30%) could be obtained from a brown juice-based biogas stream.

3.4 Biomass production potential from crop modeling

Figure 5 shows modeled red clover yields on global pastures under baseline climate conditions, and under the 27 Tg and 150 Tg nuclear winter scenarios during year 2 (the worst year for agricultural production in a nuclear winter). Under the current climate, red clover achieves ~22 billion tonnes on the global pasture area of 2,774 Mha, for an average yield of 8.0 t/ha/y. While managed red clover systems in favorable conditions can achieve 9-18 t/ha/y (Frankow-Lindberg, 2017), our lower global average reflects the inclusion of marginal grazing lands at extreme latitudes, high elevations, and in semi-arid regions alongside highly productive temperate pastures. The result is consistent with other estimates, which propose a potential of 40 billion tonnes (DM) over 3.5 billion hectares, for a yield of ~11 t/ha/y, although the current actual production is about one third of this value (Askew, 2005).

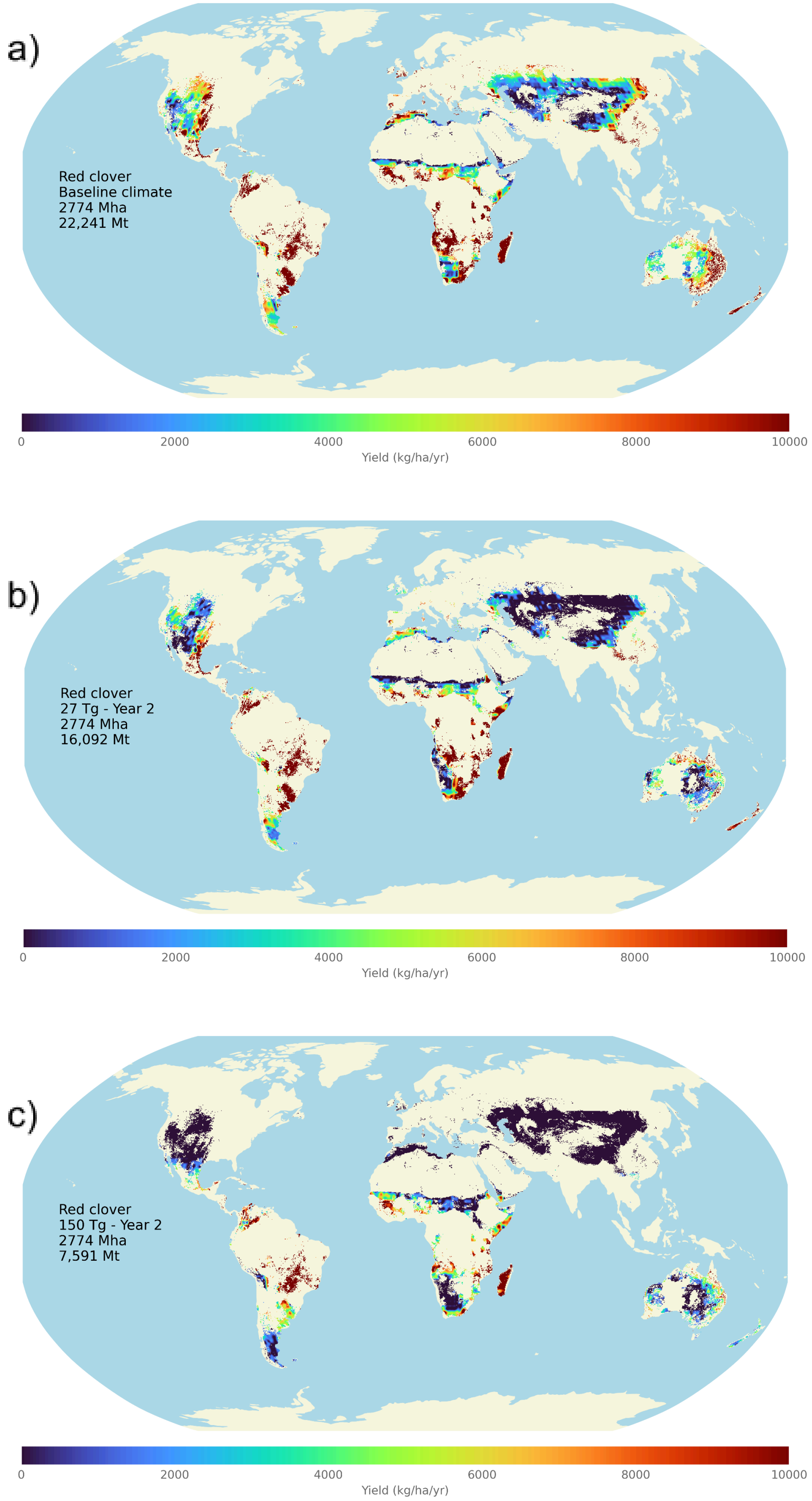

Figure 5. Yield of red clover biomass (kg DM/hectare/year) for the three scenarios modelled: a) current climate conditions, b) 27 Tg "central" nuclear winter, and c) 150 Tg extreme nuclear winter. Note that the visualizations show yield colors only in cells where there is over 50% pasture, for ease of reading.

The 27 Tg "central" scenario shows moderate yield reductions, especially in the Northern Hemisphere (e.g., Great Plains, Eurasian Steppe), for an overall yield of 5.8 t/ha/y (-28%). The extreme 150 Tg scenario reveals much more severe impacts, with near-total production collapse across most of the Northern Hemisphere, for an overall yield of 2.7 t/ha/y (-66%). Only tropical and Southern Hemisphere regions maintain significant productivity, though even these areas experience substantial yield reductions. Integrating yields across the global pasture mask weighted by fractional pasture coverage, we estimate a potential harvest of 16.1 Gt red clover (DM) in year 2 of the 27 Tg scenario and 7.6 Gt in year 2 of the 150 Tg scenario.

Global grasslands could provide enough legume biomass for LPC production even in the worst-case scenarios, given adequate management. Since it takes ~3 kg biomass (DM) to produce 1 kg of food via LPC+sugar, and ~2 Gt of this food combination to produce the equivalent amount to the caloric requirement of the global population, the amount of biomass needed would be around 6 Gt. This means that leveraging all global grasslands for red clover production would be enough to reach this threshold in the current climate and in the 27 Tg and 150 Tg nuclear winter scenarios. This would more than suffice to fulfill the global protein requirement, at ~3 Gt of biomass (DM) via LPC, or 1-2 Gt via LPC+SCP. Regardless, it is not possible to achieve a healthy diet from just LPC+sugar or LPC+SCP, and producing this much protein is more than enough to make a very significant difference to global food production in an agricultural catastrophe scenario. Figure 6 compares how much of global food and protein requirements could be produced from grassland biomass using 10%, 30%, and 100% of global biomass at the modeled yields during the catastrophic scenarios.

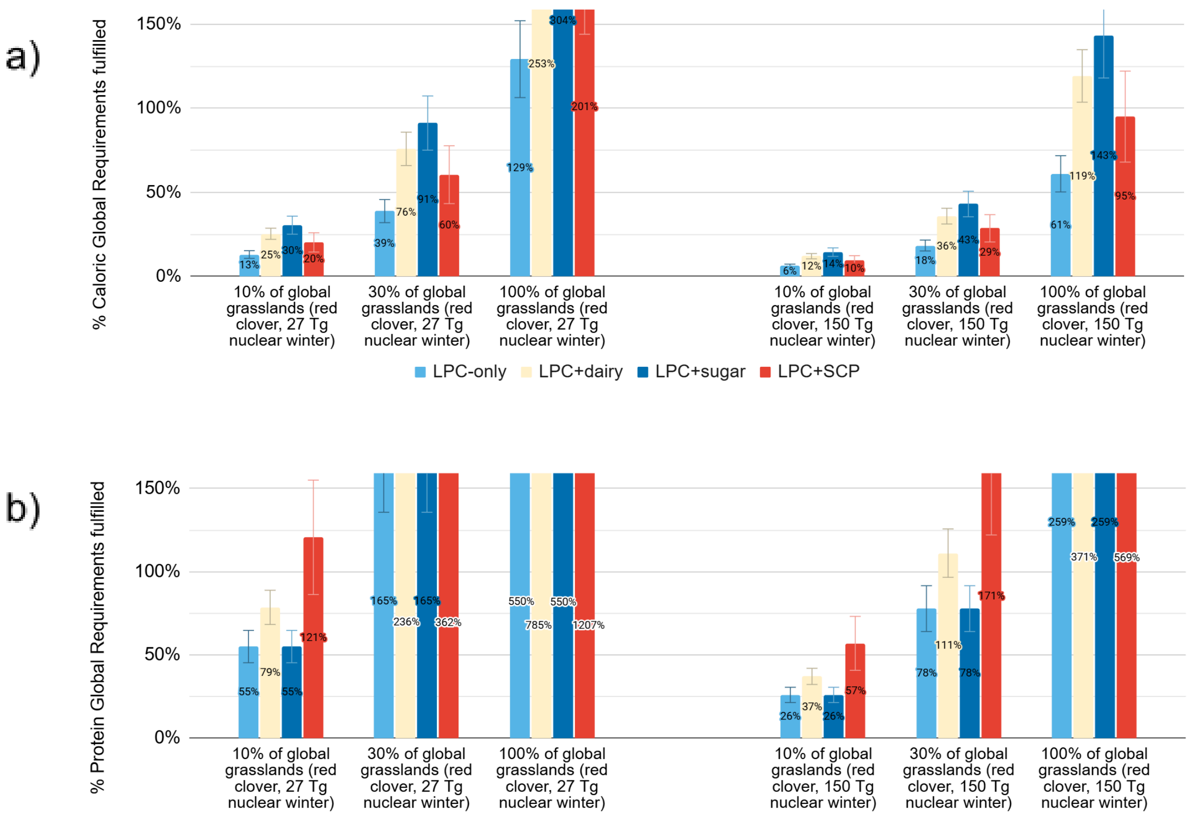

Figure 6. Global potential of grasslands to produce food in catastrophic scenarios via LPC and associated technologies at the modeled red clover yields and a 15% LPC conversion yield. a)

global caloric requirements fulfilled at 10%, 30% and 100% of grassland utilization, for both nuclear winter scenarios: 27 Tg "central scenario" and 150 Tg "extreme scenario". b) global protein requirements fulfilled at 10%, 30% and 100% of grassland utilization, for both nuclear winter scenarios: 27 Tg "central scenario" and 150 Tg "extreme scenario".

However, uncertainty remains regarding how many of the world's grasslands could be converted to leafy legume farms at short notice. To address this, we present other scenarios: 1) Global alfalfa production is ~0.25 Gt (DM) (IMARC Group, 2025), if only that amount of biomass were available, that would provide approximately ~9% of the global protein requirement via LPC at a 15% yield. 2) Global grass consumption by livestock equals 2.4 Gt (Wolf et al., 2021), if that amount of biomass could be replaced by legumes with a 15% LPC yield, that would provide ~80% of the global protein requirement. However, note that if the biomass currently obtained from those lands was used without changing it to LPC-efficient biomass such as red clover, the yield would be lower, perhaps comparable to values around 0.075 kg LPC/kg biomass (DM) obtained for various leaves suboptimal for LPC production (Meyer et al., 2023), roughly halving protein production while probably keeping sugar production at a similar level. 3) No more than 30% of global grasslands can be converted to legume cultivation at the estimated yield. The above scenarios are summarized for the current climate in Figures 7a and 7b.

The 8.0 t/ha/y average yield of leafy legume biomass on rainfed grasslands in the current climate results in protein yields of 0.4-0.7 tonne protein/ha from LPC, or 0.8-1.7 tonne protein/ha when maximizing the protein production via LPC and SCP, at 0.36-0.54 kg SCP/kg biomass (DM). The latter is higher than "good soybean yields" for rainfed cropland, of 0.5-0.9 tonne protein/ha, from 1.5-2.5 tonne soy/ha/y (FAO, 2025a), and comparable to the average global yield of 0.95 tonne protein/ha, from 2.7 tonne soy/ha (FAO, 2025b); all estimates based on a protein content of 0.4 kg protein/kg soybean and 13% moisture. For reference, soybeans are typically considered the food crop with the highest protein yield per unit of land (Messina, 2022). In well-managed lands, alfalfa can beat the protein yield per unit of land of soybeans via LPC+SCP: the 18 tonne alfalfa/ha/y obtained in California converts to 1.9-3.9 tonne protein/ha/y via LPC+SCP, whereas the impressive 5 tonne soybean/ha in Nebraska translates to ~1.7 tonne protein/ha. This is comparable to the protein yield per unit of land of SCP from beet sugar at ~2.7 tonne protein/ha/y (Leger et al., 2021). Achieving higher protein yields per unit of land requires much higher energy consumption systems, such as microbial protein bioreactors or vertical farming (García Martínez et al., 2025b; Järviö et al., 2021; Leger et al., 2021). The protein yields per unit of land are summarized in Figure 7c. Details can be found in the supplementary spreadsheet.

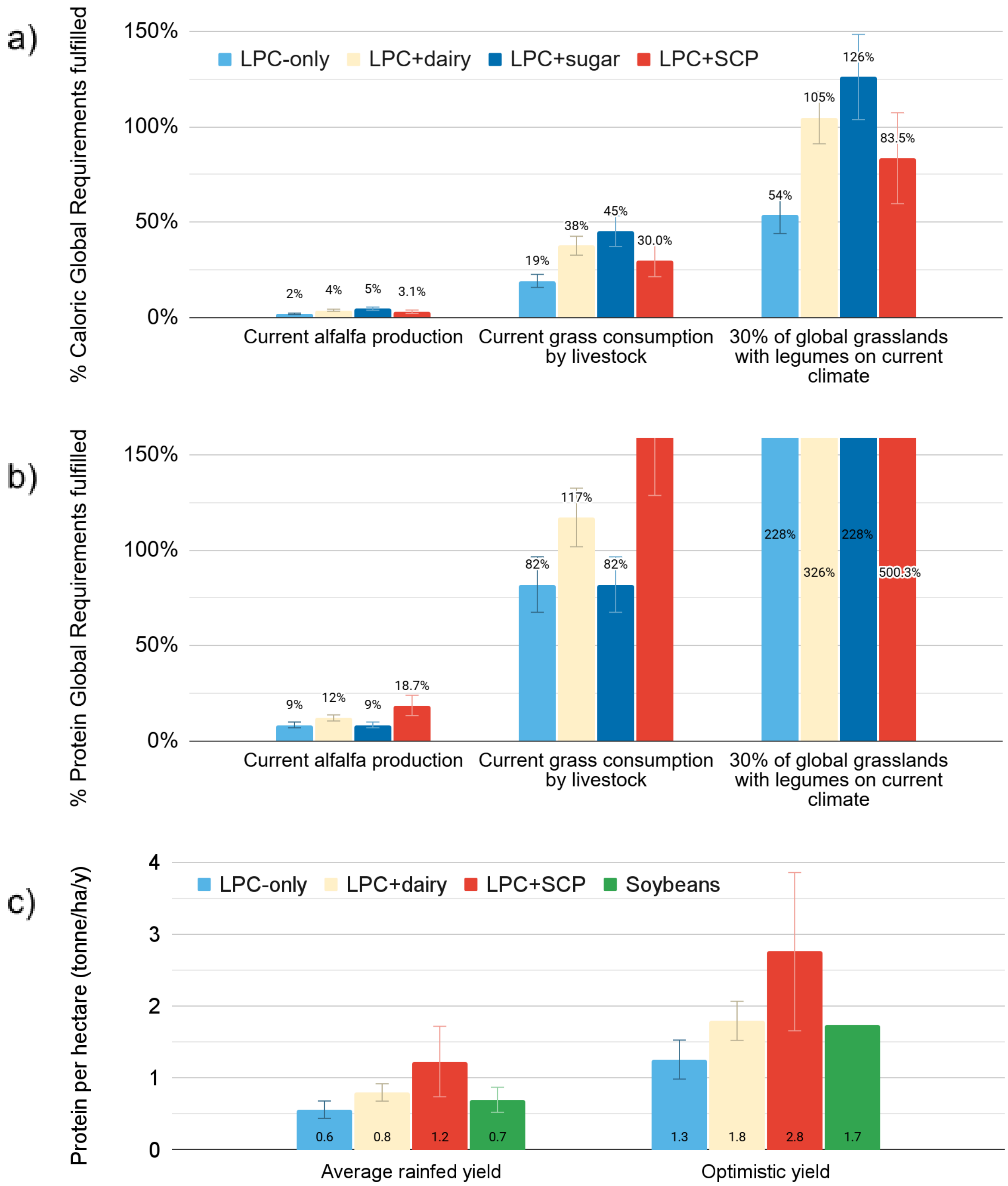

Figure 7. Production potential of food from grassland biomass in the current climate, from leaf protein concentrate, lignocellulosic sugar, and single cell protein, all assuming a central LPC yield of 15%. a) shows it in terms of the global caloric requirements, b) shows it in terms of the global protein requirements, while c) shows the protein yield per unit of land including a comparison with soybeans. Note that the soybeans are grown in higher quality lands compared to the biomass for LPC.

3.5 Ramp-up speed values

The construction time for a reference-size LPC+sugar biorefinery is estimated at 86-90 weeks, and at 28-29 weeks when using 24/7 construction. The ramp-up speed for the scenario in which the global budget for chemical and related industries can be effectively redirected to fast construction of LPC+sugar factories is shown in Figure 8 for both the global caloric requirements and global protein requirements. Results are given for a leafy biomass to an LPC yield of ~0.15 kg LPC/kg biomass, the average of the expected ranges. At the end of the first year of 24/7 construction, around 5% of the caloric requirements could be fulfilled by LPC+sugar biorefineries, translating to ~10% of the protein requirements. If building LPC-only factories, the global protein requirement target could be achieved in 1-2 years, if sufficient biomass could be harvested. This is because LPC-only factories are significantly less capital-intensive than LPC+sugar or sugar-only facilities, though they require more than twice as much biomass/land per unit of food than LPC+sugar. Additional ramp-up scenarios can be found in the supplementary material.

For illustrative purposes, assuming unlimited capital and no bottlenecks, a capital cost of approximately 3-5 trillion USD would be required for building the amount of LPC+sugar biorefineries required to fulfill the caloric requirements of humanity. This would take a construction time equivalent to building one reference-scale production factory at around 16 months to full production. This capital investment is significantly lower than what was spent on, for example, COVID-19 stimulus checks, at 17.2 trillion USD (O'Malley, 2021).

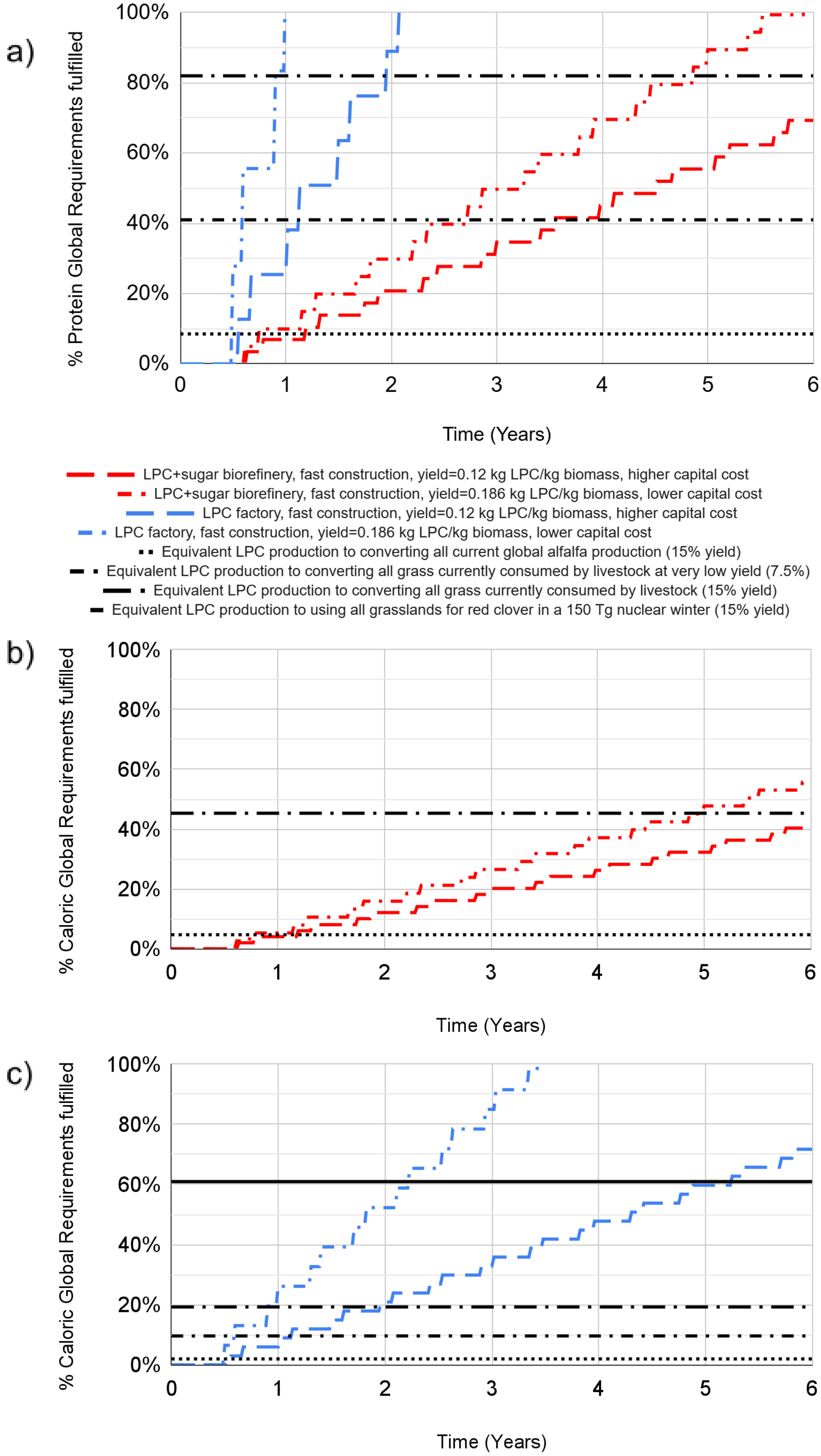
a)
% Protein Global Requirements fulfilled
100%
80%
60%
40%
20%
0%
0
1
2
3
4
5
6
Time (Years)
LPC+sugar biorefinery, fast construction, yield=0.12 kg LPC/kg biomass, higher capital cost
LPC+sugar biorefinery, fast construction, yield=0.186 kg LPC/kg biomass, lower capital cost
LPC factory, fast construction, yield=0.12 kg LPC/kg biomass, higher capital cost
LPC factory, fast construction, yield=0.186 kg LPC/kg biomass, lower capital cost
Equivalent LPC production to converting all current global alfalfa production (15% yield)
Equivalent LPC production to converting all grass currently consumed by livestock at very low yield (7.5%)
Equivalent LPC production to converting all grass currently consumed by livestock (15% yield)
Equivalent LPC production to using all grasslands for red clover in a 150 Tg nuclear winter (15% yield)
b)
% Caloric Global Requirements fulfilled
100%
80%
60%
40%
20%
0%
0
1
2
3
4
5
6
Time (Years)
c)
% Caloric Global Requirements fulfilled
100%
80%
60%
40%
20%
0%
0
1
2
3
4
5
6
Time (Years)

Figure 8. Ramp-up speed of factory deployment as a function of the global food requirements fulfilled over time. Results shown reflect the use of the budget of similar industries, at 24/7 construction speed, and for optimistic (yield=0.186 kg LPC/kg biomass, lower capital cost) and pessimistic (yield=0.12 kg LPC/kg biomass, higher capital cost) factory parameters. a) share of global protein requirements fulfilled over time via fast construction of LPC-only factories and LPC+sugar biorefineries—does not include uses of the fiber press cake as feed. b) share of global caloric requirements fulfilled over time via fast construction of LPC+sugar biorefineries. c) share of global caloric requirements fulfilled over time via fast construction of LPC-only biorefineries. The three different proposed scenarios of biomass availability are depicted as fixed values of production limits: 1) all current alfalfa production, 2) all current forage production—at expected yield and at very low yield—and 3) all grasslands at 150 Tg catastrophe scenario; with no conversion of sugar to SCP. Note that the line for scenario 3 is off the chart for (a) and (b) because it provides over 100% of protein requirements and 100% of caloric requirements when doing LPC+sugar.

3.6 Food price

The NPV analysis was performed to estimate the break-even cost of an LPC product and an aggregated (on a weight basis) LPC+sugar product for different scenarios. The expected cost in an ASRS was estimated by limiting the factory life to 6 years and accounting for the additional cost of 24/7 construction. For comparison, the product cost in regular conditions (20 years of lifetime and regular construction cost) was also obtained. For each of the two scenarios, product costs were calculated under both high (pessimistic) and low (optimistic) operating and capital cost assumptions, providing upper and lower bounds for the cost per kg. Results are shown in Figure 9. A markup of 100% was applied to estimate the retail cost to consumers of the LPC + sugar product, accounting for distribution and other additional costs (McCray, 2010). The results are shown in Table 5.

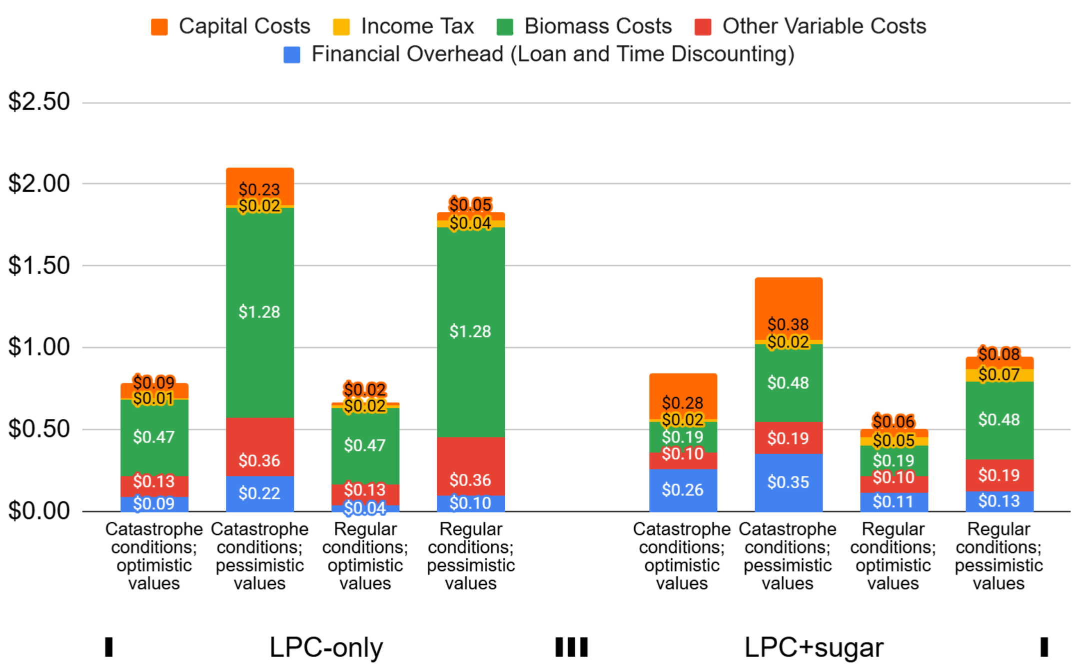

Figure 9. Breakdown of the contributions to the wholesale production cost incurred per kg of product obtained, for an LPC-only factory (left-side values), and an LPC+sugar biorefinery (right-side values). Regular conditions means 20 years plant operation and normal construction, catastrophe conditions means 6 years plant operation and 24/7 fast construction. Optimistic values means: yield=0.186 kg LPC/kg biomass, high economies of scale with CAPEX_x=0.6 and OPEX_x=0.8. Pessimistic values means: yield=0.12 kg LPC/kg biomass, low economies of scale with CAPEX_x=0.8 and OPEX_x=1.

Table 5. Retail cost of the LPC + sugar product for different cost scenarios in U.S. dollars per kilogram of LPC + sugar (DM) product aggregated on a weight basis. The low end of the intervals represents the optimistic operational and economic values, the high end the pessimistic values. The two top rows represent the costs per kg of product, the two bottom rows represent the same values given in units of "cost per person", referring to the cost of purchasing 2,100 kcal

	Catastrophe conditions						**Regular conditions**					
	24/7 construction, 6 year operation						**Regular construction, 20 year operation**					
	LPC only			**LPC+sugar**			**LPC only**			**LPC+sugar**		
wholesale production cost ($/dry kg)	$0.79	-	$2.11	$0.85	-	$1.43	$0.67	-	$1.83	$0.51	-	$0.98
retail cost to consumers ($/dry kg)	$1.58	-	$4.22	$1.70	-	$2.86	$1.34	-	$3.66	$1.02	-	$1.96
wholesale production cost ($/person/day)	$0.44	-	$1.18	$0.51	-	$0.86	$0.38	-	$1.02	$0.31	-	$0.59
retail cost to consumers ($/person/day)	$0.88	-	$2.36	$1.02	-	$1.73	$0.75	-	$2.05	$0.61	-	$1.18

The product cost of the factory scenario where only LPC is produced is simply given in $/kg (DM) LPC, but for the factory scenario obtaining both LPC and sugar, the product cost is given in units of $/kg (DM) of the combined LPC and sugar products, which is approximately 40% LPC and 60% sugar by mass. This means in regular conditions it costs $0.61-1.18 to produce ~0.4 kg of LPC and ~0.6 kg of sugar through the combined process, or ~$1-2 to produce about a kg of each. In catastrophe response conditions (24/7 construction, 6 years of plant operation), the estimated retail cost to consumers for fulfilling their daily caloric requirement (2,100 kcal/person/day) is affordable for the majority of the global population, at $1-2/kg/person/day. This indicates a noticeable potential of LPC to contribute to the affordability of ASRS diets, being on the lower cost end of resilient foods (Asal et al., 2025).

The food price results present a large variation depending on the key factors of the sensitivity analysis, namely biomass-to-LPC yield and economies of scale, with the latter including the biomass cost. The ranges proposed for these factors alone result in CAPEX and OPEX values that vary by more than 100%, producing comparable variations in price. This highlights the uncertainty in how well equipment and biomass supply costs scale, as well as the importance of operational costs. In fact, the highest cost in most scenarios is the cost of biomass, indicating lower biomass supply costs would be crucial to achieve affordable LPC production (growing, harvesting, transport, storage, etc).

Even though the current work does not study the costs and unit economics of SCP production, a recent meta-analysis indicates that the cost of sugar-based SCP production is ~2.5 $/kg SCP (DM), with a capital efficiency of ~7,400 $/tpa, at a scale of 32,000 tpa (Good Food Institute et al., 2025), comparable to the SCP scale of the design facility if it included SCP production (See Figure 4).

3.7 Biomass supply

Another key supply factor significantly affecting CAPEX and unit economics is the growing season of legume biomass. The selected 6-month growing season could be longer (or shorter) than this in many places, but conservatively, we assume that in a nuclear winter scenario, the seasonal legume biomass production would not run longer than 6 months. Locations with very short growing seasons would not be a fit for economical LPC production. For example, a 3-month growing season would produce half the LPC for the same capital investment at a higher product cost.

Transporting several million tonnes of biomass per season from the field to each biorefinery in a short time is no small feat. Protein degradation is considerable even with modest delays between harvest to processing: a 12-hour delay reduces extractable crude protein content by 5-10% (Andrade et al., 2024). The harvest method also matters; digestible protein after 12h falls by 10% in mowed biomass but as high as 40% in chopped biomass (Lærke et al., 2025). Other relevant factors include the number of harvests, plant maturity, weather, and storage period (if any). Overall, the factory must be fairly close to a large area of harvestable biomass, which constrains the number of adequate locations. It takes ~0.1-0.3 million hectares to supply a 100,000 tpa LPC biorefinery at a yield of 2.7-8.0 tonne biomass (DM)/ha. Future work should evaluate how the availability of adequate sites constrains the global potential of LPC biorefineries.

Ensiling the biomass may appear to be an alternative to create a stable raw material for year-round operation, as is commonly done for animal feed. However, it considerably degrades the digestible protein content and makes LPC separation more challenging, creating a final product with degraded nutritional and sensory properties (Rinne, 2024). This can be partially limited through optimized ensiling techniques, additives, and moisture control, but these may not suffice to produce food-grade products. Other techniques for achieving a stable biomass supply include drying and freezing (Ayanfe et al., 2023). However, they are energy-intensive solutions, and address the issues only partially. While preserving protein better than ensiling, the drying and freezing technique is impractical at a biorefinery scale and still requires additional steps, such as rehydration or controlled thawing before extraction (Rinne, 2024). More research on the topic is warranted.

Repurposing pulp and paper mills and similar infrastructure is a promising way to reduce capital costs for biorefineries. While most mills are probably near forests, it is unclear how many sit in regions adequate for supplying the large quantities of legume biomass needed. There exist global databases of pulp and paper mills (Sheikh et al., 2025), biorefineries (ENEA, 2025), and even breweries (Stueven, 2025), which could be used in future work to elucidate the highest potential retrofits.

3.8 Consumer preference and food safety

There are open questions about the consumer acceptability of LPC. Its taste, typically bitter and grassy, is a clear barrier to adoption (Furia et al., 2025). However, companies are currently aiming for the release of food-grade LPC products with improved taste and organoleptic properties. For example, the company Leaft Foods is commercializing a "green protein" product, which they describe as: "Leaft Blade®, a green protein-based product with minimal flavorings, has found good acceptance with consumers excited about the nutrition-first positioning". Using a green protein product directly is a crucial consideration for affordability, because extracting the neutral-tasting protein fraction of leaf proteins incurs considerably lower protein yields per unit of biomass and much higher purification costs (Furia et al., 2025; Møller et al., 2021).

A good sensory experience of LPC is crucial for any effort in commercializing it as a food or using it for crisis response in a global crisis, as even food aid must be culturally appropriate to be effective (Koçak et al., 2025). Research to achieve this without costly separation and losses includes optimizing operational conditions (Furia et al., 2025; Møller et al., 2021). It may also include commercial additive products (PPTI, 2025; Gelin et al., 2022) and fermentation techniques (Nisov et al., 2024), interventions used for food ingredients derived from oilseed byproducts that minimize or mask off-flavors and bitterness, but may not have been applied to LPC yet.

LPC contains antinutrients that can be toxic at high intakes (saponins, L-canavanine, phytate, and tannins). However, for alfalfa LPC exposures to these are well below levels of concern, with no adverse effects in volunteers after consuming 5 g/kg of body weight (Milana et al., 2025), which is over half of a person's daily caloric intake. For other LPC sources, such as red clover, there are no dedicated safety dossiers to the best of our knowledge. On the other hand, alfalfa LPC is naturally high in many nutrients of concern for disaster scenarios (Asal et al., 2025; Pham et al., 2022), including vitamin A, vitamin K, calcium, and iron, with some LPC products reporting even significant vitamin B12 (Leaft Foods, 2025).

Regarding lignocellulosic sugars, food safety precedents and concerns are discussed in (Throup et al., 2022). For example, toxins like furfural and other furan derivatives need to be strictly controlled during separation. Lignocellulosic sugar food-grade products were briefly commercialized by Comet Bio, for use as drop-in replacements to corn syrup.

3.9 Comparative potential of LPC for ASRS response

Compared to other ASRS-resilient foods based on industrial production, LPC and LPC+sugar biorefineries are fairly affordable and quick to ramp up, as per the comparison in Figure 10. However, their dependence on adequate climatic conditions makes them more vulnerable to shocks compared to those using non-plant feedstocks such as single-cell proteins from gas fermentation (e.g., from methane or hydrogen), or synthetic fats from hydrocarbon feedstocks (García Martínez et al., 2024). LPC is also more land- and water-intensive than these options, but less energy-intensive. All of these options compete for similar industrial capacity resources (raw materials, energy, qualified labor, and capacity for equipment construction), so future work could assess the optimal option based on regional needs and resource availability.

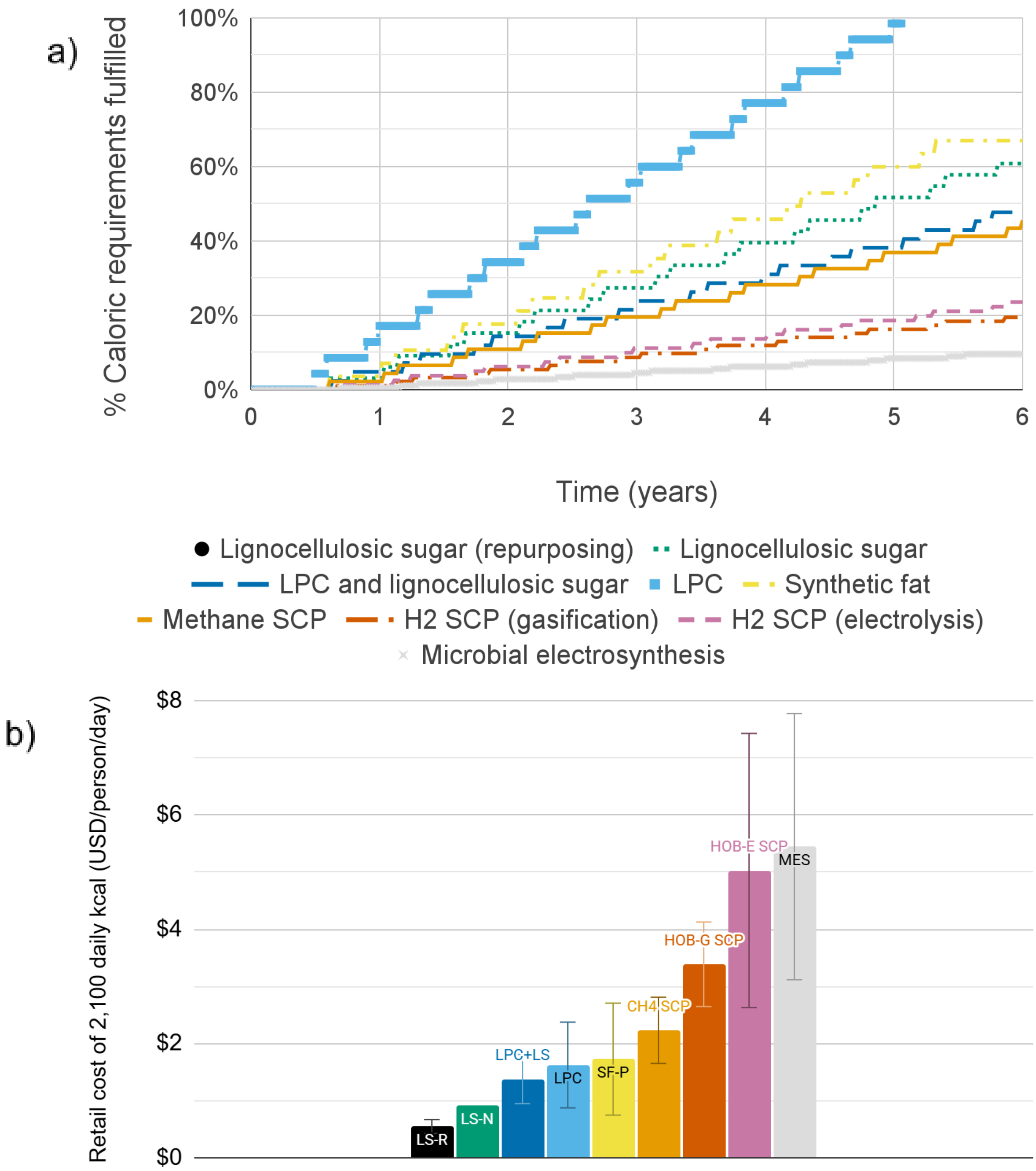

Figure 10. a) Ramp-up speed of various non-agricultural food production sources for deployment using 24/7 construction after a global agricultural catastrophe. Values are given in terms of the amount of caloric requirements of the global population (at 2,100 kcal/person/day) fulfilled over time by the factory deployment, on a 2020 basis (Damodaran, 2020), for the average of expected capital cost of the factories, and assuming a low food waste value of 12%. Note that the values are given for each food source assuming all industrial resources are used for each process, and not distributed among the different options. The LPC results are based on

the middle of the range CAPEX values. b) Retail cost to consumers for fulfilling the equivalent of one's daily calorie requirements in catastrophe conditions, estimated as twice the breakeven production cost. Data from (García Martínez et al., 2021b, 2021a, 2022a, 2022b; Throup et al., 2022) and this work.

LPC's considerable land requirement limits its potential for ASRS response. Cropland would be better used for crops in the absolute vast majority of cases, particularly crops better adapted to ASRS climate conditions like lower temperatures (Blouin et al., 2025)—see the supplementary material for details. Hence, the current work focused on grasslands; however, that does not necessarily mean that LPC is always a more efficient food production method for grasslands compared to cropland or other uses of land. Many grasslands may produce more food per hectare by cultivating short-growing season crops (e.g., spinach), and at times even staple crops like wheat, despite the low yields, as long as sufficient agricultural inputs (fertilizers, pesticides, herbicides, etc.) are available. Grazing dairy cattle may be a better option in regions where local industrial capabilities or agricultural inputs are in short supply. However, this optimization is beyond the scope of this work, which focuses on elucidating the biophysical potential of producing LPC and lignocellulosic sugar production from legumes, as well as the associated product cost and ramp-up speed.

Often, there are practical reasons for not growing crops on current grasslands, other than simply low crop yield, including: difficult machinery access due to slopes/stones/terraces, soil type/depth, erosion risk, hydrology limits, short/erratic seasons, regular frosts, regulations, etc (Csikós and Tóth, 2023). These also apply to LPC to varying degrees, but there are reasons why perennial legumes (e.g., alfalfa and some clovers) can be better than cropping on such lands: less tillage, lower input requirement (e.g., nitrogen fertilizer, pesticide), wider harvest window with multiple cuttings (delaying clover or alfalfa cutting comes with limited consequence, compared with the much more time-critical wheat harvest), better machinery fit where stony/rough fields complicate use of row-crop combines but are tolerated by forage harvesting/mowing machines, deeper roots for moisture against droughts (in alfalfa), continuous ground cover to handle heavy rain, etc (Fernandez et al., 2019). Regarding regulatory limits, it would likely be easier to cultivate legumes than food crops in pasture land in many cases due to the changes made to accommodate leguminous grass counting as "grassland management" rather than land-use change, potentially bypassing impact barriers of erosion/peat disturbance/soil cover/nutrient rules more easily than food monocrop rotations, and considered less disruptive to biodiversity, for example in European regulation (DAERA, 2017). Whereas in some cases, like protected semi-natural grasslands or other conservation restrictions, regulations would potentially remain a barrier to the use of grasslands for either LPC or food crops even in crisis situations (Cuadros-Casanova et al., 2023).

3.10 Future work

Competing options for land use and agricultural inputs could result in a moderate contribution of LPC to catastrophe response, even if factory buildup and biomass harvesting could be ramped up successfully. A future study aiming to answer the question of how to maximize calories or other nutrients in nuclear winter at affordable costs should provide an integrated assessment of which land-based method of food production would be optimal for different regions in nuclear winter (e.g., short/medium/long growing season crops, LPC, grazing, other food production, intercropping, cover cropping), including practical factors (slope, rockiness, soil types, agricultural input requirements, irrigation needs, water logging, etc.), and techniques to increase production (multiple cropping, land expansion, etc). Regional needs also condition what the optimal biorefinery configuration would be. If biomass is limited but capital is abundant, an LPC+sugar biorefinery maximizes food production, and an LPC+SCP biorefinery maximizes protein. If biomass is plentiful but industrial capability is scarce, LPC-only with feeding fiber press cake to livestock may be a better choice. This analysis would provide a rigorous basis from which to make policy recommendations to institutions in different regions that contextualize the use of LPC and the circumstances in which it would be best, ahead of crisis scenarios.

As described in the Biomass Supply section, future work could also extend the biophysical estimate of biomass potential performed here by researching the availability of sites where it would be feasible to source enough leafy biomass, to better understand how logistics constrain the potential of LPC biomass for food production. This could include identifying sites where significant CAPEX savings may be possible, such as the subset of these locations with pulp and paper mills that could be repurposed for sugar production. It could also include scenarios of varying international cooperation through different degrees of agricultural equipment sharing to prepare land for legume cultivation, as was done in previous work on cropland expansion (Monteiro et al., 2024, 2025).

Future research could also include more in-depth modeling of biomass nutrient content based on climatic conditions, as crude protein content in red clover and forage grasses is temperature-dependent. Higher temperatures result in lower protein content per kg of biomass (Lee et al., 2017), whereas cold temperatures inhibit growth and biomass yield per hectare. Relatedly, it could study the location-dependent effect of how growing season duration affects capital efficiency and product cost on a case-by-case basis. For example, selecting only areas where the growing season is around 6 months could result in significantly lower global biomass estimates. In addition, future work would benefit from more in-depth uncertainty analysis such as Monte Carlo simulations for key parameters including growing season length, LPC yield, and biomass cost.

Future modeling efforts should also ensure that capital and product costs reflect those of a food-safe, consumer-adequate product. For example, high-heat concentration/drying increases shelf life but can denature leaf proteins (especially Rubisco), darken colour, and reduce lysine availability. The choice of purification method determines the antinutrient content and, to a large extent, the organoleptic properties of the final product (Anoop et al., 2023).

Future work should create generalist open source front-end engineering design packages to better characterize the global potential of biorefineries and expedite crisis response. This would result in a more precise estimate of the cost of a combined LPC+sugar biorefinery. It could also explore other biorefinery configurations, for example, one that includes the capital and operational costs of producing SCP or of extracting the brown juice sugars. The sugars from the brown juice could be extracted using a variety of processes, for example, a nanofiltration membrane treatment that retains approximately 93% of the sugar while concentrating from a 4.7% DM content to 27.2% (Andrade et al., 2023). Further research on affordable LPC downstream operations for preserving it in good condition to ship around the world as food aid would also be beneficial. Additional work on biorefinery strategies for nuclear winter response could incorporate the disruptions of nuclear war on industrial systems, which could destroy 3% of global industry and reduce global industrial output by 25% via cascading effects (Blouin et al., 2024) and significantly reduce renewable energy inputs (Varne et al., 2024).

4 Conclusions

Leaf protein concentrate can be produced at scale for $0.67-1.83/kg (DM), and when combined with lignocellulosic sugar production, it takes around $2/kg to produce about a kg of each, with considerable variation depending on the LPC yield and the cost of biomass. In catastrophe-response conditions, the estimated retail cost to consumers for fulfilling their daily caloric requirement is fairly affordable compared to alternatives, at ~$1-2/person/day. Grassland locations with long growing seasons, low biomass cost, and short harvest-to-factory distance should be prioritized, especially if they contain a pulp and paper mill that could be repurposed for lower CAPEX.

The ramp-up time of LPC is 1-2 years to fulfill the minimum protein requirements of the global population, but global biomass cropping and harvesting would need to increase considerably. LPC+sugar biorefineries could fulfill ~5% of the caloric requirements by the end of the first year after the ramp-up starts. Energy and financing would likely not be limiting factors, as fulfilling the entire global caloric requirement with LPC would take less than 15% of global electricity, less than 5% of global natural gas, less than 11% of liquid fuel, and a small fraction of global spending. However, biomass supply could be a significant limitation. Crop modeling results indicate that in the current climate, the planet's grasslands could provide up to ~22 Gt/y of legume biomass for LPC, which would be reduced to ~16 Gt/y in a "central" nuclear winter scenario and ~7.6 Gt/y in an extreme one. However, this would require a massive increase in legume cultivation from current values. For example, the current production of alfalfa is only ~0.3 Gt/y, and all grass fed to livestock amounts to 2.4 Gt. For comparison, ~3 Gt would be needed to fulfill the global protein requirement via LPC, or ~1-2 Gt via an LPC+SCP biorefinery.

The sugars from the saccharification process and the brown juice byproduct could be used to produce food in the form of protein-rich SCP instead of sugar, for an overall protein yield of 0.7-3.1 tonne protein/ha (current climate), comparable to or higher than that of typical soybean production.

Future work should engage with the tradeoffs between using land for LPC, traditional crops, grazing, and other uses; as well as using industrial capacity for LPC vs other options like SCP. This would result in a better understanding of the potential of LPC production at scale for global food shock response, and more rigorous policy recommendations for crisis response tailored to regional needs. Creating generalist open source front-end engineering design packages for food biorefineries would help estimate costs more precisely and expedite crisis response.

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CRediT author statement

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SUPPLEMENTARY MATERIAL

Global potential of integrated biorefineries for leaf protein and sugar: Producing sustainable food and preventing starvation in catastrophes

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Supplemental ramp-up speed values

Figures S1 and S4 compare the ramp-up speed between all scenarios of an LPC-only factory design, in terms of global caloric requirements and global protein requirements, respectively. Figures S2 and S5 show the same results, but for a combined LPC+sugar biorefinery design. Figures S3 and S6 compare the ramp-up speed between an LPC-only factory design and a combined LPC+sugar biorefinery design, only for 24/7 construction values of deployment speed and capital investment.

Note that the regular construction speed eventually overtakes 24/7 construction due to its lower resource intensity, but takes much longer to start producing food, which makes it worse in the advent of a catastrophe. The overtaking in cumulative production takes longer than overtaking in instantaneous monthly production shown on the graphs. Furthermore, since demand will eventually cap production, this is an additional reason that fast construction is superior.

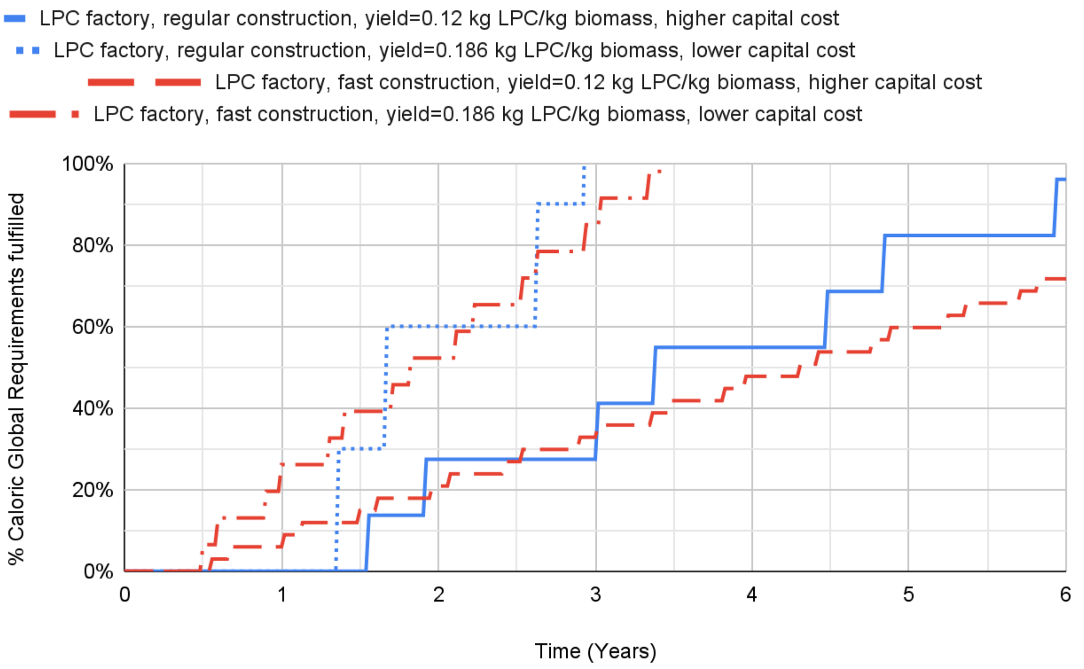

Figure S1. Expected ramp-up speed of LPC production in terms of the global caloric requirements fulfilled over time for an LPC-only factory.

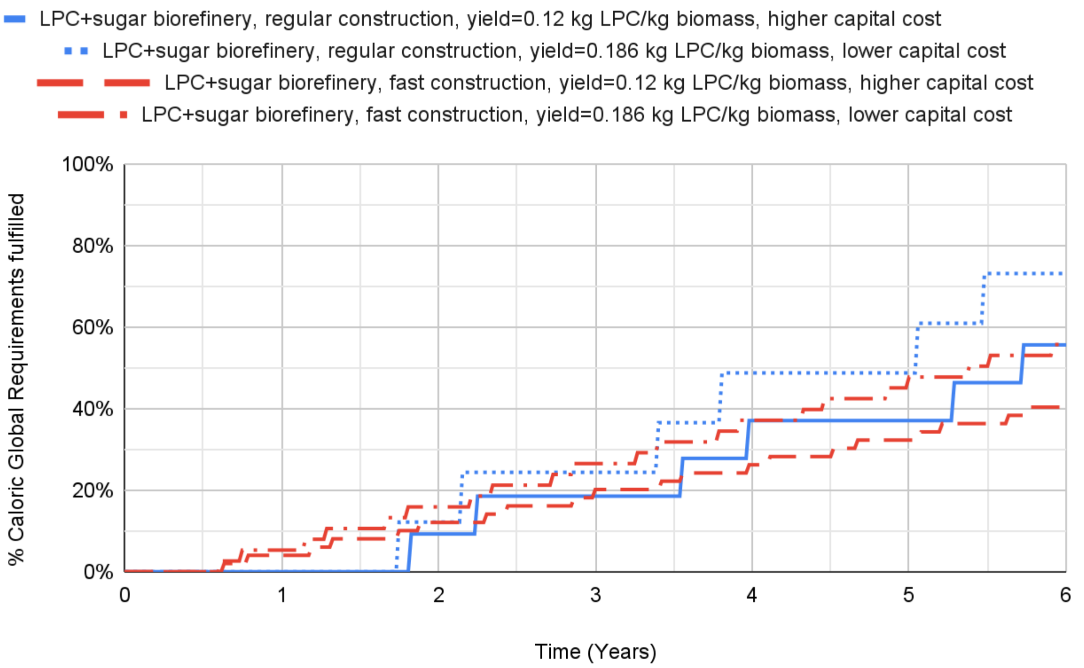

Figure S2. Expected ramp-up speed of LPC and lignocellulosic sugar production in terms of the global caloric requirements fulfilled over time for a combined LPC+sugar biorefinery design.

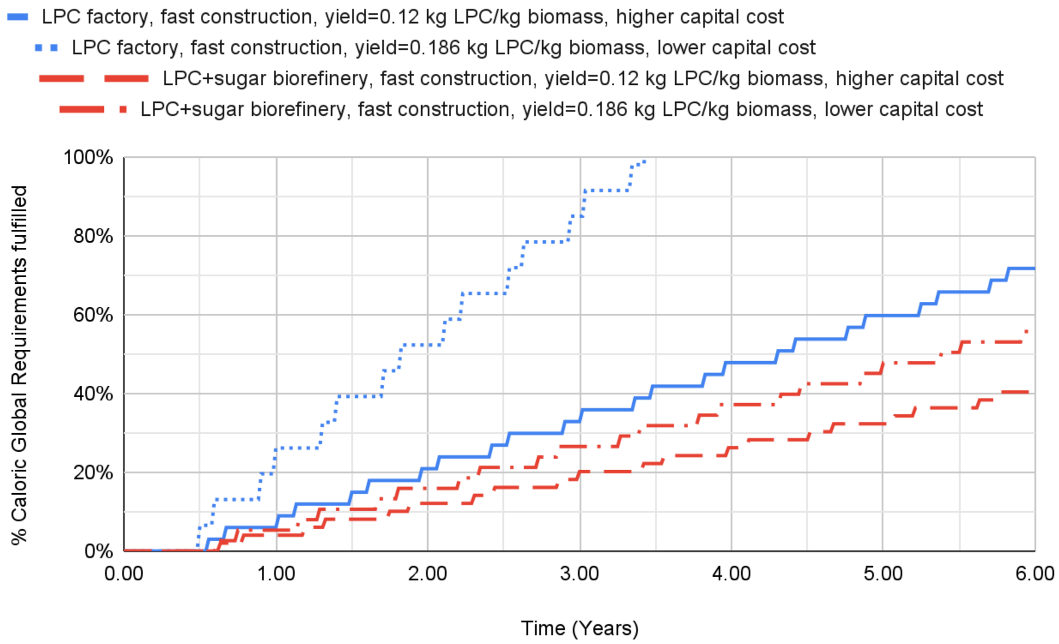

Figure S3. Expected ramp-up speed of LPC vs LPC and lignocellulosic sugar production in terms of the global caloric requirements fulfilled over time for fast construction speeds.

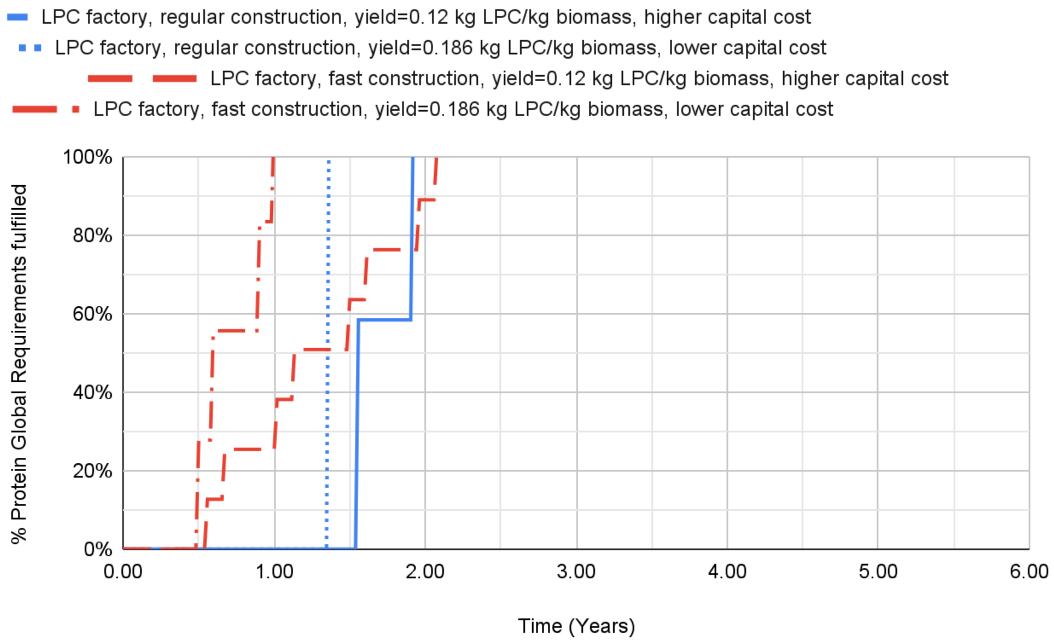

Figure S4. Expected ramp-up speed of LPC production in terms of the global protein requirements fulfilled over time for an LPC-only factory.

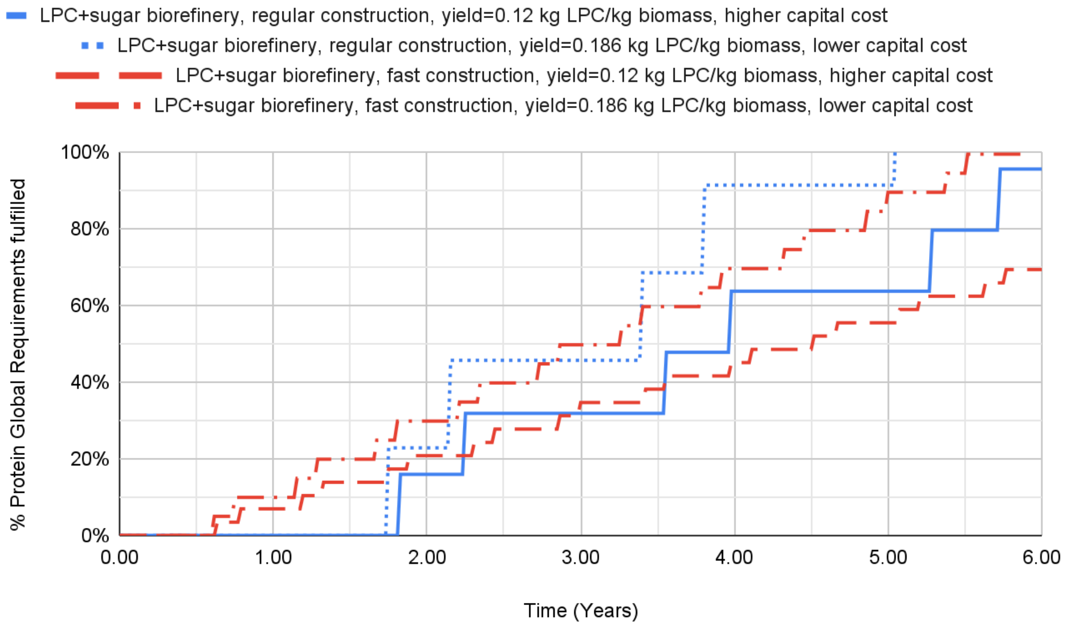

Figure S5. Expected ramp-up speed of LPC and lignocellulosic sugar production in terms of the global protein requirements fulfilled over time for a combined LPC+sugar biorefinery design.

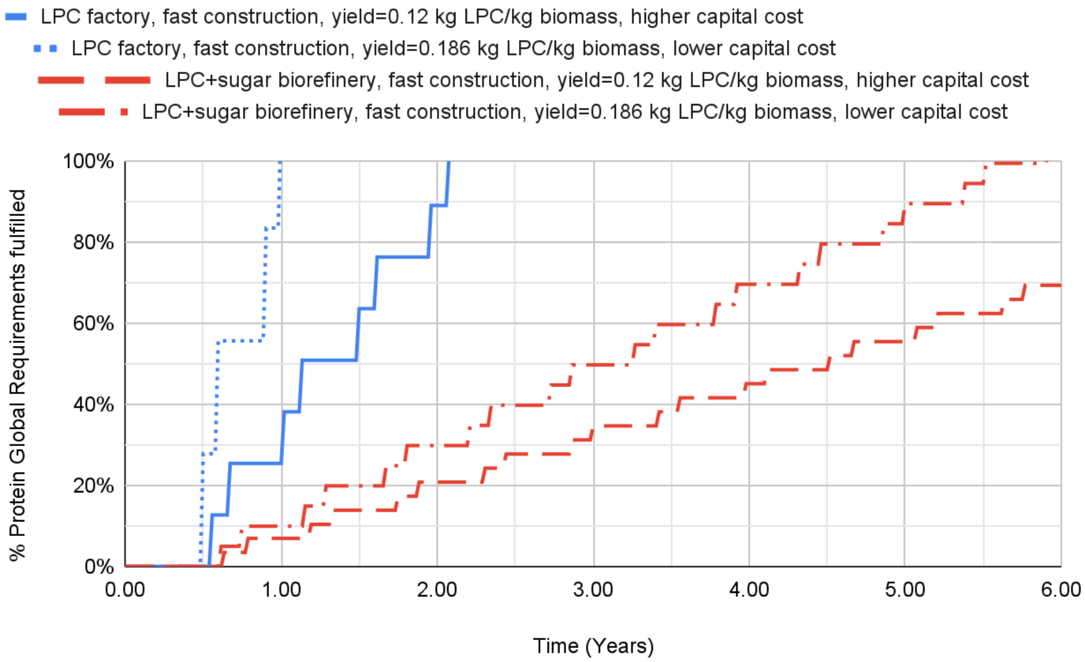

Figure S6. Expected ramp-up speed of LPC vs LPC and lignocellulosic sugar production in terms of the global protein requirements fulfilled over time for fast construction speeds.

Comparison of food crop cultivation to LPC forage crops

In the main analysis, we focused on current pasture land as the primary resource base for LPC+sugar production. This appendix examines whether cropland could alternatively be used for clover cultivation and LPC production during an abrupt sunlight reduction scenario. We compared the caloric yields of red clover (using the same cultivar and methodology from the main crop modeling analysis) against the best-performing staple crop from among six options (maize, wheat, soybean, rice, potato, and rapeseed) for each grid cell of global cropland. This comparison uses existing crop modeling results (Blouin et al., 2025) for the worst year of the extreme 150 Tg nuclear winter scenario.

We identified grid cells where: (1) all six staple crops failed to meet a productivity threshold of 500 kg/ha wheat equivalent (1.67 million kcal/ha), rendering them "unproductive" (Blouin et al., 2025), and (2) red clover for LPC and sugar production would yield more calories than the best available staple crop. We consider these two conditions to be necessary because food systems would likely strongly prefer familiar staple crops that remain productive, even when clover offers higher caloric yields. Staple crops require less processing and align with established food preferences and supply chains. Clover-based LPC is therefore only a compelling alternative in regions where conventional staple crop production has failed. Only 2% of the global cropland area met both criteria. This finding supports our decision to focus LPC+sugar production on pasture land rather than cropland. However, there may be potential for leguminous cover crops (when the main crop is not growing) for LPC and sugar, or intercropping (growing at the same time), especially with the nitrogen fixation benefit.

Figure S7. Analysis of croplands where LPC would likely beat the yields of staple crops, for Year 3 of a 150 Tg scenario.