Zurich University
of Applied Sciences

Life Sciences and
Facility Management

Institute of
Applied Simulation

Zurich University of Applied Sciences
Institute of Applied Simulation

Modeling Environmental and Nutritional Impacts of Vegan Agriculture

Master Thesis

Patricia Krayer

Master in Life Sciences
Applied Computational Life Sciences
Submission: 31.08.2021

Supervision

Dr. Nyfeler, Matthias
ZHAW Life Sciences und Facility Management, Schloss 1, CH-8820 Wädenswil

Dr. Müller, Adrian
Research Institute of Organic Agriculture (FiBL), Ackerstrasse 113, CH-5070 Frick

Impressum

Modeling Environmental and Nutritional Impacts of Vegan Agriculture

Master Thesis

Citation: Krayer, P. (2021). Modeling Environmental and Nutritional Impacts of Vegan Agriculture. Master Thesis. Wädenswil: Zurich University of Applied Sciences (ZHAW).

Keywords: Food System Modeling, Vegan Agriculture, Food System Analysis

"All models are wrong, but some are useful"
George Box[1], Statistician

[1] probably thinking about SOLm

Acknowledgments

Before adressing the actual topic of this thesis, I want to express a very special Thank You to both of my supervisors for their immense support. Adrian Müller helped me with his comprehensive knowledge and expertise in food system modeling to develop, pursue and question strategies for this work. He introduced me into the model SOLm and helped, whenever problems, uncertainties or mysterious bugs, occurred. Matthias Nyfeler helped me greatly with all my problems related to data analysis and preparation. Further, I want to thank Anita Frehner who gave me valuable advice and content for all aspects related to nutrition. It was a pleasure to work with them and I enjoyed diving into this interdisciplinary topic.

Abstract

A transformation of the food system is needed to stay within the planetary boundaries and to feed the world, at the same time. One promising approach to reduce food system-related environmental impacts is the reduction of livestock, since animal-based products are consistently associated with higher environmental impacts than plant-based products. However, in today's agriculture, plant- and animal-production systems are heavily interlinked and systemic consequences of strong livestock reductions, therefore, not clear. The interlinking especially holds true for organic agriculture, where manure is a valuable nutrient source. The goal of this thesis was therefore to analyze effects on nutrition and environment of a shift to a 100 % vegan world for different production systems in the year 2050. For the analysis, a modeling approach was chosen: SOLm, a mass and nutrient flow model, was adapted to enable different choices of crop rotation patterns, treatment systems for grasslands and to choose the vegan and organic shares of the food system. Six vegan scenarios with different model assumptions were implemented to explore potential outcomes of a vegan world. Three of these scenarios described a vegan-conventional world, the other three a vegan-organic world. The scenarios differed further in their total cropland area and the applied crop rotation patterns, which were based either on existing crop distributions, literature, or on results of linear optimization problems. The optimization problems were designed to minimize the necessary cropping area under the constraints of fulfilling nutritional requirements (in a vegan-conventional world) or nutritional and, additionally, agronomic requirements (in a vegan-organic world). For the analysis of environmental impacts, a selection of already implemented indicators was made. To assess the nutritional impacts of the food systems, data about macro- and micronutrient contents from the USDA SR28 database was collected, cleansed and integrated into SOLm. Furthermore, as indicator for food quality, the aggregate index AHEI-2010 was calculated for each scenario. Considering the same cropland area as in the reference scenario, the model resulted in insufficient amounts of calories, proteins and fat for all of the vegan-organic scenarios. Although a crop rotation design based on actual stockless systems led to a better performance than other crop rotations, fat supply was still found to be critical and far below the threshold. In contrast, both vegan-conventional scenarios with the same cropland achieved sufficient amounts of calories, proteins and fat. However, the supply of vitamin B12 and D was still far below the requirements. Further, calcium and selenium were found to be critical in those scenarios. Most vegan scenarios showed a better environmental performance than the reference scenarios, however, one vegan-conventional scenario resulted in a high increase in irrigation water use. The results indicate that the compatibility of vegan and organic agriculture is limited. To provide sufficient calories, proteins and fat to feed the world, the utmost share of organic agriculture was found to be 50 % with a vegan share of maximum 40 %.

The results suggest that a transition might help to respect planetary boundaries and provide sufficient macro- and micronutrients, at the same time. However, it was found to be nearly incompatible with organic agriculture due to the higher share of non-productive grassland areas and lower yields in such production systems.

Zusammenfassung

Eine Transformation des Ernährungssystem ist notwendig, wenn die Menschheit ernährt und gleichzeitig die planetarischen Ökosystemgrenzen eingehalten werden sollen. Ein vielversprechender Ansatz zur Verringerung der mit dem Ernährungssystem verbundenen Umweltauswirkungen ist die Reduzierung der Tierbestände, da tierische Produkte durchweg mit höheren Umweltauswirkungen verbunden sind als pflanzliche Produkte. In heutigen Agrarsystemen sind Pflanzen- und Tierproduktion jedoch stark miteinander verflochten, so dass die systemischen Folgen einer solchen Massnahme nicht klar sind. Diese Verflechtung gilt insbesondere für den biologischen Landbau, in dem Hofdünger eine wertvolle Nährstoffquelle darstellt. Ziel dieser Arbeit war es daher, die Auswirkungen auf Ernährung und Umwelt in einer 100-prozentig veganen Welt für verschiedene Produktionssysteme im Jahr 2050 zu analysieren. Für die Analyse wurde ein Modellierungsansatz gewählt: SOLm, ein Massen- und Nährstoffflussmodel, wurde angepasst, so dass verschiedene Fruchtfolgemuster, Behandlungsoptionen für Grassland und der vegane und ökologische Anteil des Lebensmittelsystems gewählt werden konnten. Sechs vegane Szenarien mit unterschiedlichen Modellannahmen wurden implementiert, um mögliche Ergebnisse einer solchen veganen Welt zu untersuchen, drei davon mit bio-veganen und drei mit vegan-konventionellen Produktionssystemen. Die Szenarien unterschieden sich außerdem in ihrer Gesamtanbaufläche und den angewandten Fruchtfolgemustern, die entweder auf bestehenden Anbauflächenverteilungen, der Literatur oder auf Ergebnissen linearer Optimierungsprobleme basierten. Die Optimierungsprobleme zielten darauf ab, die erforderliche Anbaufläche unter der Bedingung zu minimieren, dass die Ernährungsanforderungen (in einer vegan-konventionellen Welt) oder die Ernährungsanforderungen und, zusätzlich, agronomische Anforderunge (in einer bio-veganen Welt) erfüllt werden. Für die Analyse der Umweltauswirkungen wurde eine Auswahl von bereits implementierten Indikatoren getroffen. Um die Auswirkungen auf die Ernährung zu bewerten, wurden Daten über Makro- und Mikronährstoffgehalte aus der USDA SR28 Datenbank gesammelt, bereinigt und in SOLm integriert. Außerdem wurde als Indikator für die Lebensmittelqualität der Gesamtindex AHEI-2010 für jedes Szenario berechnet. Bei gleicher Anbaufläche wie im Referenzszenario ergaben sich für alle bio-veganen Szenarien eine unzureichende Menge an Kalorien, Proteinen und Fett. Obwohl ein Szenario mit einer Fruchtfolge, die auf tatsächlichen viehlosen Systemen basiert, zu einer besseren Leistung führte als andere Fruchtfolgen, war die Fettversorgung immer noch kritisch und weit unterhalb des Schwellenwerts. Im Gegensatz dazu erreichten beide vegan-konventionellen Szenarien mit der gleichen Anbaufläche ausreichende Mengen an Kalorien, Proteinen und Fett. Allerdings lag die Versorgung mit Vitamin B12 und D unter dem Bedarf. Auch Calzium und Selen erwiesen sich in diesen Szenarien als kritisch. Die meisten veganen Szenarien wiesen eine geringere Umweltbelastung auf als die Referenzszenarien, allerdings führte ein vegan-konventionelles Szenario zu einem hohen Anstieg des Bewässerungswasserverbrauchs. Die Ergebnisse zeigen, dass die Kompatibilität von veganer und biologischer Landwirtschaft begrenzt ist. Um genügend Kalorien, Proteine und Fett für die Ernährung der Welt bereitzustellen, darf der Anteil der biologischen Landwirtschaft maximal 50 Prozent betragen, wobei dann der Anteil der veganen Landwirtschaft maximal 40 Prozent betragen sollte. Die Ergebnisse legen nahe, dass eine Transformation zu einer veganen Welt dazu beitragen könnte, die planetarischen Grenzen zu respektieren und gleichzeitig ausreichend Makro- und Mikronährstoffe bereitzustellen. Sie deuten jedoch darauf hin, dass sie mit der biologischen Landwirtschaft nur begrenzt vereinbar ist, da der Anteil an unproduktiven Grünlandflächen höher ist und zudem die Erträge geringer ausfallen.

Contents

Glossary

Acronyms and Abbreviations

AAS	Amino acid score
AHEI-2010	Alternate Healthy Eating Index 2010
ALA	α-linolenic acid
BAU	Business as usual
BNF	Biological nitrogen fixation
CED	Cumulative Energy Demand
DAQ	Domestically available quantity
FAO	Food and Agriculture Organisation of the United States
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
GHG	Greenhouse gases
IPCC	The Intergovernmental Panel on Climate Change
LA	Linolenic acid
LCA	Life Cycle Assessment
N	Nitrogen
P	Phosphorous
PUFA	Polyunsaturated fatty acids
SOLm	Sustainability and Organic Livestock model
SR28	Standard Reference Database (28), USDA
USDA	United States Department of Agriculture

Chapter 1

Introduction

Food systems provide food and employment opportunities and are therefore at the core of human societies. However, agricultural production and other food system processes depend on many natural resources, such as land, water and energy. They are further associated with emissions, e.g. greenhouse gas emissions or ammonia, which put pressure on our natural systems. Agriculture contributes, for example, to about 70 % of the global freshwater use, and the entire global food system to about one quarter of the global greenhouse gas emissions (IAASTD 2009; Vermeulen et al. 2012). Further, due to the strong intensification of agriculture in past decades, based on increasing amounts of synthetic fertilizers, global nitrogen (N) and phosphorous (P) cycles have been heavily disrupted (Robertson and Vitousek 2009; Cordell and White 2014). As a consequence, agricultural production has been found to be a major driver behind the concerning fact that some of the planetary boundaries have already been crossed, and some are at the edge of being exceeded (see Figure 1.1) (Campbell et al. 2017).

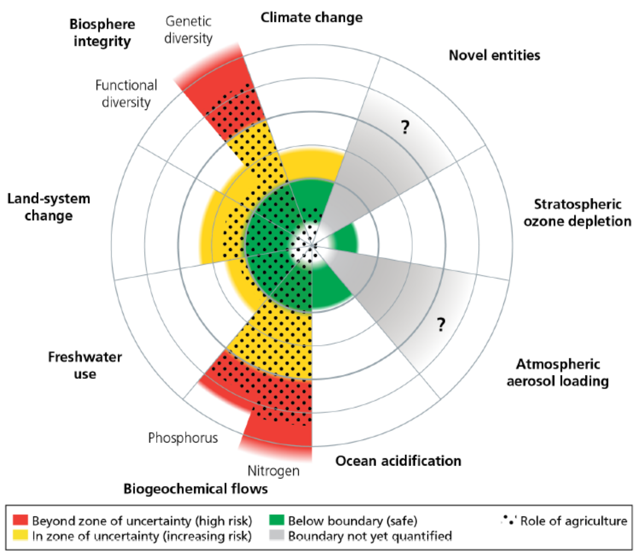


Figure 1.1: State of the planetary boundaries. Dotted areas indicate the contribution of agriculture. (Source: Campbell et al. (2017)

)

Consequently, there is an urgent need for action to drive the transformation towards a more sustainable food system, especially given the fact that the world population is estimated to increase to about 9 billion by 2050 (Alexandratos and Bruinsma 2012). Together with changing dietary habits, necessary production volumes are projected to increase by about 60 % (Kearney 2010). The overall challenge will therefore be to create a global food system that provides sufficient food to fulfill nutritional requirements of humans and does simultaneously keep humanity from transgressing the planetary boundaries.

One promising approach is to reduce the consumption of animal-based products. This strategy is based on widely accepted findings that the production of animal-based products is generally associated with higher environmental impacts than the production of crop-based products (Poore and Nemecek 2018; Springmann et al. 2018; Hallström et al. 2015). The high contribution of livestock to environmental impacts is caused by energy losses through feed conversion, enteric fermentation processes and manure management, which are associated with high nutrient losses and GHG emissions (Poore and Nemecek 2018).

However, the role of livestock in our current food system is not only to provide food for human nutrition: livestock manure is a valuable nutrient source in agriculture and, therefore, plays an important part in the global nutrient cycle. Reducing the amount of livestock would consequently lead to systemic changes in the food system.

1.1 Problem Statement

Since it is widely recognized that the production of animal-based products is associated with a higher environmental burden compared to plant-based products, one might want to conduct a thought experiment of a world without livestock keeping, thus, analyzing environmental impacts and the nutritional feasibility of a 100 % vegan world. Although, this is an extreme scenario, which is improbable to be realized any time soon, this thesis makes an attempt to explore possible outcomes of such a vegan world. Through this, an insight shall be gained about the potential and limitations of such a path towards a more sustainable food system.

So far, numerous studies analyzed impacts of a shift towards *vegan diets*, but not much research has been done on *vegan agricultural systems* (Poore and Nemecek 2018; Springmann et al. 2018; Erb et al. 2016; Zumwald 2017). The terms seem similar, however, the approaches are different: vegan diets refer to the sole consumption of food products, which are plant-based. Even though these products are vegan, their whole production chain does not necessarily have to be. The production of crops requires nutrients (e.g. N, P, K), which are often applied in the form of animal-based manure. In the global food system, animal manure is an important source of nutrients for crop production. An amount of 18.7 Tg to 30 Tg of N is estimated to flow from the animal- to the plant-production system, accounting for up to one third of the total N-surplus in the plant production system (Barbieri et al. 2021; Zumwald 2017). The global food system in its current form relies, therefore, on the utilization of animal-based inputs. In contrast, a vegan agricultural system can be defined as plant production system, totally independent from, i.e. without any nutrient flows connecting it to, the animal production system. In such a system, an important source of nutrients is missing and has to be replaced by alternatives. This can be achieved by: i) the use of crops with the ability of biological nitrogen fixation (BNF), or ii) the use of synthetic fertilizers. When examining the impacts of a 100 % vegan world, one has to refer to such a vegan agricultural system, instead of scaling up the impacts of vegan diets, therefore accounting for the role of livestock in the food system.

This thesis makes an attempt to analyze environmental and nutritional outcomes of a vegan agricultural system on a global scale. To do so, the following research questions were defined:

1. To what extent is it possible to feed the world with vegan agriculture in the year 2050?
2. How would a transition to vegan agriculture affect the environmental impacts related to the global food system in the year 2050?

3. How does the implementation of vegan agriculture affect the feasibility and environmental performance of organic agriculture – and vice versa?

The first research question addresses the feasibility of vegan food systems (in this thesis defined as capability of producing sufficient amounts of calories, proteins and fat) and their performance related to other nutrients. The second research question addresses the environmental impacts arising in vegan food systems.

The third research question addresses the fact, that organic agriculture shows a higher dependency on animal-based inputs compared to conventional agriculture. Organic agriculture is considered as a promising strategy to reduce food system-related environmental impacts (Mäder et al. 2002; Muller et al. 2017). However, due to the renunciation of synthetic fertilizers, manure is a priority source of nutrients in organic farming systems. The importance of livestock for organic agriculture has recently been pointed out by Barbieri et al. (2021). It is therefore not clear, if organic and vegan agriculture – two approaches with potential when considered by itself – are compatible. Consequently, one goal of this thesis is to analyze the dynamics arising in mixed, i.e. vegan and organic agricultural systems, and to find potential degrees of compatibility.

Different than previous modeling approaches assessing the impacts of a transition towards a vegan world, this thesis includes some aspects, which have not yet been covered jointly:

- a biophysical model is used to capture the entirety of the global food system,
- a large set of nutritional indicators is included to assess the nutritional quality,
- for organic farming systems, different crop rotation patterns are applied in order to do justice with the reality of organic farming requirements,
- the choice of different treatment options for grassland is enabled.

The overall aim of this thesis is to contribute to a better understanding about potential effects of different food systems and, therefore, helping to shape policy decisions about transformation paths towards more sustainable food systems.

1.2 Approach

This thesis makes an attempt to answer the above research questions by developing a model structure within the biophysical model SOLm (Sustainability and Organic Livestock model), which facilitates the assessment of nutritional and environmental impacts of potential manifestations of a global vegan agricultural system in the year 2050. In the scope of this thesis, six main scenarios were developed, representing different potential manifestations of a vegan world.

Each of these scenarios describes a different vegan agricultural system, by differing in either the total cropland use, the applied crop rotation design or the management method (organic or conventional). Three of the scenarios are dedicated to a global conventional agricultural system, while the others address an organic food system.

For the organic scenarios, two crop rotation designs on an aggregate level were developed, based on literature about organic and stockless farming systems. Further, an optimization problem was formulated and solved, with the objective to find an optimal crop rotation design to minimize the cropland area and to fulfill nutritional requirements and agronomic recommendations of organic agriculture. For two of the conventional scenarios, the shares of food crops were the same as in the reference of the year 2050. An optimization problem was further developed for a conventional scenario, minimizing the cropland area under the constraint to fulfill only nutritional requirements.

The scenarios were implemented by parametrizing the current structure of the model SOLm (V6) to facilitating the choice of the characteristics of the scenarios, i.e. different crop rotation designs, specified shares of vegan and organic agriculture and the choice of the treatment method for grassland. SOLm was designed to gain an understanding for environmental effects which arise due to policy changes in agriculture (Müller et al. 2020). SOLm depicts mass and nutrient flows of the global food system and links agricultural activities (cropping, livestock farming) with commodity production for feed, food and other purposes, and with related in- and outputs. The model contains a set of environmental indicators, which are calculated on a country-level basis for the whole food system.

For the assessment of environmental effects, a set of these environmental indicators was selected and the results of each scenario were compared to the corresponding results of two reference scenarios (scenario 2009 and scenario 2050). To analyze nutritional effects, data about nutrient contents of food commodities was integrated into SOLm. For this, data, from the USDA database SR28 (USDA 2016) about micro- and macronutrient contents in food items, was previously collected and prepared, by matching and aggregating to fit with the current structure of SOLm. Additionally, based on the newly acquired nutritional data, the Alternate Healthy Eating Index AHEI-2010 (Chiuve et al. 2012) was calculated for each scenario. The amino acid score (AAS), a rough indicator of protein quality, was integrated into the model, but has not been evaluated for the food systems.

To analyze interactions and the compatibility between vegan and organic agriculture (research question 3), environmental and nutritional outcomes were analyzed, based on the currently most adopted organic crop rotation schemes, with gradual shares of organic (0 %, 25 %, 50 %, 75 %, 100 %) and vegan (0 %, 20 %, 40 %, 60 %, 80 %, 100 %) agriculture.

To facilitate an interactive analysis of environmental and nutritional outcomes on different geographical levels (global, national), an R Shiny Dashboard was implemented, summarizing the main results of this thesis.

1.3 Thesis Structure

This thesis is structured in six chapters. After this chapter, the basic terms and concepts are outlined in chapter 2. This chapter starts with an introduction about the design principles of different agricultural production systems, which were considered in this thesis. Furthermore, section 2.2 gives an overview of studies addressing similar research questions. In chapter 3, SOLm is introduced and model adaptations and assumptions are presented. Furthermore, the analyzed scenarios, the process of nutritional data integration and the indicators are described. In chapter 4 and chapter 5, results of the model runs are presented and discussed, focusing on the nutritional feasibility and quality of the food systems (research question 1), the environmental impacts (research question 2) and the compatibility of vegan and organic agriculture (research question 3). A conclusion and outlook is given in chapter 6.

Chapter 2

Theoretical Foundations

In this chapter, the main concepts utilized in this thesis are described in section 2.1. Then, an approach is made to find first answers to the research questions by reviewing existing literature. For this, an overview of related studies, analyzing nutritional and environmental impacts of food systems reduced in livestock, or the compatibility of vegan and organic agriculture, is given in section 2.2.

2.1 Agricultural Concepts

This thesis makes an attempt to analyze impacts of a vegan world, which requires the implementation of vegan agriculture on a global scale. The first of the following sections (subsection 2.1.1) will set the definition of vegan agriculture and outline characteristics of and differences between this and other related agricultural systems. Furthermore, since the implementation of crop rotations is one of the core elements of this study, in section 2.1.2, an introduction is given into the concept and challenges of crop rotation designs in vegan and non-vegan farming systems.

2.1.1 Vegan Agriculture

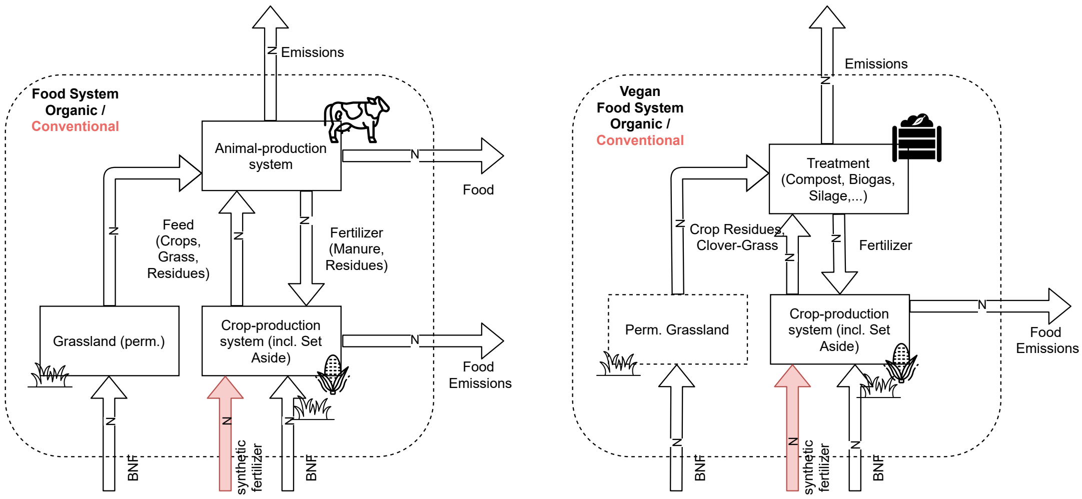
Although vegan agriculture was recently identified as an innovative approach with potential to transform the European food system, only little research has been done so far, and definitions are not consistent across literature (Schmutz and Foresi 2017; Engelhardt et al. 2020; Seymour and Utter 2021). Vegan Agriculture was first defined by Visak (2007) as "agriculture without animal production, such as meat, dairy or eggs and without the use of manure that results from animal production". On a more abstract level, in this thesis, the term **vegan agriculture** is used to describe plant production systems without interactions with the animal production system. In the following section, the differences between related farming systems, beginning from the on-farm perspective, will be described.

Vegan agriculture on farm-level

For vegan farms, the above definition specifically excludes:

- the production of livestock,
- the production of feed,
- the selling of feed or crop residues for feeding purposes,
- the use of animal-based inputs, such as manure.

In traditional agriculture, animal- and plant-production systems are usually interlinked through mass-, nutrient- and energy-flows (Figure 2.1). On the one hand, nutrient-rich outputs from the



(a) Traditional production system (b) Vegan production system

Figure 2.1: Comparison between nitrogen flows in stocked and vegan food production systems. Red flows describe nitrogen flows which are prohibited in organic agriculture. (Source: own figure).

animal-production system, such as manure or residues from food production, such as bone meal, are used in plant-production systems as inputs, mainly for fertilizing purposes. On the other hand, a part of the crop production (feed crops, grasslands or crop residues), is utilized for feeding purposes, and is therefore an input of the animal production system. Vegan Agriculture is therefore an approach to decouple the plant-based from animal-based agricultural production systems.

Since the definition of vegan agriculture does not make any restrictions on any agronomic practices, but only on the exclusion of animal-based inputs and outputs, it may be practiced on conventional or organically managed agricultural systems. **Organic agriculture** is considered as a promising approach to reduce food system-related environmental impacts (Mäder et al. 2002; Reganold and Wachter 2016; Muller et al. 2017). It describes a regulated management systems with the aim to preserve natural resources by promoting and enhancing biodiversity and soil biological activity (FiBL 2021). Organic agriculture primarily seeks to close nutrient cycles by the use of on-farm resources. Two main aspects, in which organic farming differs from **conventional farming**, are the restricted use of fertilizers and pesticides.

In contrast to conventional farming systems, organic producers refrain from synthetic nitrogen fertilizers and chemical-synthetic plant protection products, whose production is associated with a high energy consumption and through its application leads to adverse impacts on soil fertility (Tuomisto et al. 2012). Alternative nutrient sources are either leguminous plants (nitrogen fixing plants, e.g. clover) or the application of manure. Organic farms primarily seek to close nutrient cycles by the continuous use of on-farm resources. For these reasons, excreta from animal husbandry is often used for fertilization in organic agriculture. An additional important measure of organic farming systems is the implementation of spatial and temporal diversification through **crop rotations**. These help to maintain soil fertility and regulate pests and diseases (FiBL 2021). Temporary grasslands (legume-grass mixtures) play a vital role in crop rotations (in the following also called **set aside**). The ability of leguminous plants to fix nitrogen and to provide it to subsequent crops, makes these temporary grasslands important nitrogen sources in organic farming systems. The harvest of temporary (and permanent) grasslands is often used as fodder for ruminants.

According to the principles of organic agriculture, the keeping of livestock is no requirement, however, it is recommended to establish at least cooperations with animal-keeping farms. In contrast, the regulations of **biodynamical** management systems stipulate the keeping of livestock (FiBL

2021; Demeter 2021). Due to these design principles of organic agriculture, the interlinking between animal- and plant-production systems is naturally higher in organic than in conventional production systems. As a consequence, the implementation of vegan agriculture is inherently more challenging for organic than for conventional farming systems.

In this thesis, the term **vegan-organic** is used for agricultural farming systems, which are vegan and comply with requirements of organic principles. Analogously, **vegan-conventional** farming systems describe vegan systems under conventional management (without further agronomic restrictions).

Most farms which describe themselves as *vegan*, have a strong motivation due to animal-ethical or environmental considerations (Bonzheim 2014). Therefore, they are usually farming organically, thus, being vegan-organic. The existence of such vegan-organic farms gives proof that the implementation of vegan-organic agriculture on farm-level is possible. However, the distribution is modest: in North America, approximately 50 vegan-organic farms were reported by Seymour (2019). In Europe, 15 vegan-organic farms are certified according to the *biocylic vegan standard* (BNS), additionally, four are in transition and 15 farms are self-declared vegan-organic farms (vegan-farming.org 2021). The BNS-label has been accepted recently in the IFOAM family of global standards in 2017 (IFOAM 2021). The regulations of this standard cover more aspects than the above stated definition of vegan agriculture. Among the requirements of the biocyclic vegan standard, which, for the modeling approach in this thesis, will not be considered, are the strong emphasis on compost for fertilization purposes and the restriction of beneficial insects (BNS 2017). The reason is that I try to model the potential of vegan agriculture as a concept and thereby try to keep as many variables constant ('et ceteris paribus') to allow for a better understanding of the influence of specific factors. The influence of the implementation of these recommendations could be part of a future study.

Further terms, which are related to vegan farming systems are **stockless** and **stockfree**. The terms differ in their extent of interlinking with the animal production system. Stockless farming systems are defined as systems which have less than 0.2 Livestock Units (LU) per ha, and show limited interaction with livestock-keeping farms (Schmidt 2003). An interaction with the animal-based production system, e.g. through the utilization of manure for fertilization, or production and selling of hay or feed crops, is therefore not fully excluded in stockless systems. The term stockfree is used as a synonym for vegan systems, i.e. plant-production systems without any interaction with animal-production systems. The more positively connoted ending *-free* was deliberately chosen as an alternative to *-less* in stockless, since it indicates that something is missing (Schmutz and Foresi 2017). Furthermore, vegan-organic systems are sometimes referred to as **veganic** ((Schmutz and Foresi 2017). For this thesis, I will stick to the term vegan farming (instead of stockfree), since the meaning is defined by the wording itself and needs no further explanation (according to Schmutz and Foresi (2017)).

While vegan-organic farming is still a small niche, stockless-organic farming is widely spread: according to Schmidt 2003, about 25 % of organic arable farms in Germany were stockless at that time. Furthermore, 21 % of all organic arable farms are stockless and without considerable cooperation with livestock-holding units. A newer study from Maas et al. (2017) found with 34 % stockless organic arable farms a high increase since 2003 among organic farmers, which can partly be explained by a trend towards specialization.

Stockless-organic systems and vegan-organic systems differ mainly in the underlying motivation to renounce livestock farming: due to ethical reasons, vegan-organic farmers actively oppose against livestock keeping, while stockless-organic farmers explain their absence of livestock commonly by pragmatic reasons, such as a higher work intensity or the lack of livestock keeping before converting to organic agriculture (Bonzheim 2014; Schmidt 2003).

Although stockless-organic farms have less constraints in certain aspects, however, the challenges for stockless-organic and vegan-organic systems are often similar (Bonzheim 2014; Schmutz and Foresi 2017). In the thesis of Zumwald (2017), the main challenges of vegan-organic farms were summarized as:

- weed control, and
- maintaining a positive nutrient balance in the long run.

An important measure to counter these problems is the implementation of crop rotations, a concept which will be discussed in subsection 2.1.2.

Vegan agriculture on a global level

From a global macro-perspective, vegan, vegan-organic and vegan-conventional agriculture are specified by the characteristics, as described in Table 2.1.

In vegan-organic agricultural systems, the only primary origin of nitrogen is biologically fixed nitrogen from leguminous plants (grain legumes and legumes in set aside or permanent grassland). Within the system, there are sources such as recycled nitrogen from crop residues and food waste (or potentially excreta).

The utilization of crop commodities and residues or roughage from set aside for feeding purposes is prohibited. Further, a crop rotation according to specified principles has to be implemented in an organic system. In contrast, in vegan-conventional agriculture, nitrogen is also introduced into the food system through the application of synthetic fertilizers. Furthermore, crop rotations are not required in conventional systems.

Table 2.1: Agricultural systems, characteristics and nutrient sources. BNF: biological nitrogen fixation; SF: synthetic fertilizers; AN: animal-based fertilizer.

Agricultural System	N-source	Crop Rotation	Feed Utilization	Animal husbandry
Conventional	SF, AN, BNF	Not required	Allowed	Allowed
Organic	AN & BNF	Required	Allowed	Allowed
Vegan	SF &BNF	Not required	Not allowed	Not allowed
Vegan-conventional	SF &BNF	Not required	Not allowed	Not allowed
Vegan-organic	BNF	Required	Not allowed	Not allowed

2.1.2 Crop Rotations and Grassland

Crop rotations refer to the practice of cultivating crops in a defined sequence on the same land and have been used for thousands of years (Bullock 1992). Nowadays, it plays a crucial role for organic farming systems, in particular. The implementation of temporal and spatial diversification through the use of different subsequent crops over a range of several years helps in lowering the weed pressure, avoiding erosion and maintaining soil structure (Bullock 1992). Additionally, it helps to prevent pests and diseases, therefore, reducing the dependency on pesticides (Curl 1963).

For the share of specific crop groups in organic crop rotations, some basic rules are recommended (FiBL 2021; Böhler et al. 2007):

- share of grain legumes $\leq 35\,\%$,
- share of grains $\leq 50\,\%$,
- share of leguminous areas (grassland + grain legumes) $\geq 20\,\%$,

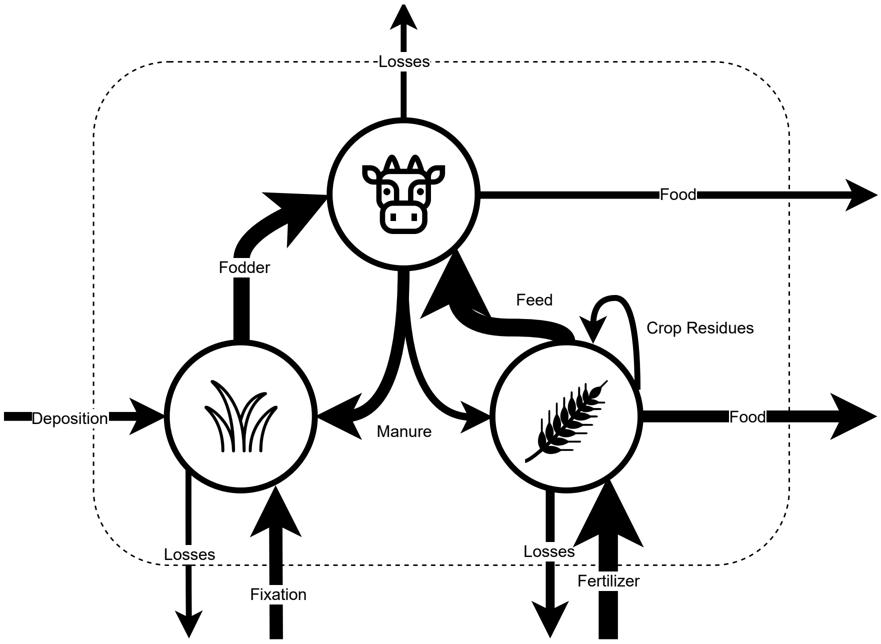


Figure 2.2: Nitrogen flows in agriculture. Size of arrows is indicative, but not directly proportional to N-flows, based on Barbieri et al. (2021). (Source: own figure)

- share of oil crops ≤ 35 %,
- share of grassland ≥ 10 %.

Since a considerable grassland share is a highly recommended in organic crop rotations, the following section will describe the role in non-vegan and vegan production systems.

The role of grassland & the role of livestock

Crop rotations usually contain a share of non-productive grassland, which contains leguminous plants. Next to their ability to fix nitrogen, grassland in the crop rotation helps to suppress weed and increase humus content in soil (Cui et al. 2019).

In non-vegan farming systems, the grassland production is generally utilized or sold as fodder and therefore contributes to the revenue. However, vegan (or stockless) farms often have no direct use of temporary grassland in their crop rotation, since they cannot (or do not want to) utilize or sell the harvest as fodder. This leads to economic losses in the short-term. Therefore, several studies have examined the optimal balance between fertility building and fertility exploiting crops in stockless-organic crop rotations, and, furthermore, if crop rotations without temporary grassland are feasible. Most studies found that a higher share of temporary grassland contributes to increased carbon and nitrogen contents in soil, compared to crop rotations without set aside (**sparkes_investigating_nodate**; Schmidt 1997; Schmidt et al. 1999). Furthermore, microbial activity and soil structure are enhanced through application of at least one year of grassland in a crop rotation (Schmidt 2003).

Current recommendations for stockless-organic farms therefore still include a considerable part of 10 % to 20 % of temporary grassland in the crop rotation (Böhler et al. 2007; Jäger 2013). With lower set aside shares, a negative N-surplus, decrease in humus contents, deterioration of soil structure and problems with specific weeds have to be expected (Schmidt 2003).

As stated before, grassland plays an important role in agricultural systems, due to its ability to fix nitrogen, but also to solve and take up other nutrients from the soil. They play therefore an essential role in the nutrient cycle of today's agricultural systems (see Figure 2.2). On the one hand, in non-vegan production systems, the use of grassland as fodder leads to a concentration of these nutrients in animal-based food products or in manure (Zumwald 2017). As manure, the nutrients can be transported and be made available for other crops. In today's agriculture, livestock is therefore a key element of the nitrogen nutrient cycle (see Figure 2.2). In vegan agricultural systems, it is more challenging to make the nutrients, contained in grassland, available for other crops at other locations. However, it is theoretically possible to utilize clover-grass from temporary grasslands as fertilizing biomass, either through direct use, or indirectly as treated biomass. Below, some treatment options are described.

Mulching refers to the process of leaving the legume-grass cut mixture on the field. This process is associated with high N-losses through leaching and volatilization and leads, furthermore, to high N-accumulations on a single field (Benke et al. 2017). The removal of the cut biomass to other fields is also referred to as **cut and carry** or **mobile green manure** and is a more flexible utilization method of grass-legume biomass. Even more flexibility (especially temporal) is given, when grassland cut is ensiled. **Composting** is a further treatment method for grassland cut. The production of high-quality compost is, however, a complex process and requires skilled personnel. Even though the use of compost has shown to be soil-enhancing, from a nutrient perspective, it is associated with higher N-losses than other treatment methods (Maheshwari 2014; Benke et al. 2017).

2.2 Related Work

The following sections describe results of previous studies related to the research questions of this thesis. In subsection 2.2.1, the state of research related to the nutritional feasibility of vegan agriculture is presented. subsection 2.2.2 outlines recent results about the environmental performance of plant-based dietary patterns. In the last section subsection 2.2.3, existing literature about the compatibility of vegan and organic agriculture is reviewed.

2.2.1 Nutritional Feasibility of a Vegan World

Since a vegan world implies a vegan diet, the first of the following sections will focus on results of studies addressing the question of how healthy a vegan diet is on an individual level. In the second section, the global perspective is taken, presenting studies about the feasibility of vegan diets from a systemic perspective.

Feasibility of vegan diets: Is a vegan diet healthy?

People following a vegan diet do not consume any products of animal origin. The underlying motivations to follow a strict diet are not homogeneous: they range from ethical, environmental and health concerns to religious beliefs (Janssen et al. 2016; Dyett et al. 2013; Kerschke-Risch 2015). The proportion of vegans in the world is still very small: different reports show shares between 0.1 % to 5 % in Switzerland, Germany, Austria and Israel (Swissveg 2020; Richter et al. 2016; Cohen 2015). These numbers indicate that it is possible to survive with a vegan lifestyle, but is it also healthy?

Studies with aggregate indices have found that vegan diets are associated with positive health effects: Clarys et al. (2014) found in their survey among 1475 participants that the aggregated index values of the Healthy Eating Index 2010 (HEI-2010) and the Mediterranean Diet Score (MDS) are higher than in vegetarian or omnivorous diets. They found a better fat intake profile, lower protein and higher dietary fiber intake compared to omnivorous diets. Further, a meta-analysis conducted by Dinu et al. (2017) found significant reduced risk of incidence from cancer for vegetarian and vegans. Both studies suggest that vegans have a lower Body Mass Index (BMI) and a lower energy intake than other diet types.

Health advantages were also confirmed by Dewell et al. (2008) and were explained by higher intake of protective nutrients and phytochemicals and by minimizing the intake of dietary factors associated with chronic diseases. Studies found that vegetarian and vegan diets are generally higher in fibre, magnesium, Fe(III), folic acid, vitamins C and E, n-6 polyunsaturated fatty acids (PUFA), carotenoids, flavonoids, phytochemicals and antioxidants (Dewell et al. 2008; Li 2011; Bakaloudi et al. 2020; Petti et al. 2017; Menzel et al. 2021).

However, the intake of other nutrients was found to be lower compared to omnivorous diets: especially fat, proteins, calcium, n-3 PUFA, iodine, potassium, selenium, Fe(II), zinc and the vitamins A, B2, B3, B12 and D (Li 2011; Menzel et al. 2021; Bakaloudi et al. 2020; Petti et al. 2017). From these nutrients, the intake levels of calcium and especially vitamin B12 were found to be below recommendations and also deficiencies of zinc and selenium were found to be probable (Bakaloudi et al. 2020). In the recent study by Menzel et al. (2021), it was shown that veganism might be related to a lower bone health due to the lower intake values of vitamin A, B2, the essential amino acid Lysine and n-3 PUFA. Due to the potentially inadequate supply of these nutrients, the German Nutrition Society does not recommend a vegan diet for pregnant or lactating women, infants, children or adolescents (Richter et al. 2016).

Furthermore, some studies have found a relationship between psychological conditions (eating disorders and depression) and veganism (Petti et al. 2017; Iguacel et al. 2021). However, the causality is not clear in this case: an adoption of a vegan diet might also be the result of these psychological disorders (e.g. as a means for weight control). No association was found between a vegan diet and stress or well-being (Iguacel et al. 2021).

An overview of potentially critical and uncritical nutrients in vegan diets is given in table 2.2, based mainly on Bakaloudi et al. (2020), a review summarising the outcomes of 48 studies about vegan nutrition.

In summary, it can be assumed that a vegan diet can be healthy, but at the same time deficiencies in several nutrients might appear if the diet is not adopted carefully. For the feasibility of vegan agriculture, this also indicates that some of above-mentioned micronutrients could be produced in insufficient amounts because they are mainly found in animal-based products.

Feasibility of vegan agriculture: can vegan agriculture feed the world?

An estimate of Zumwald (2017), based on FAOSTAT balance sheets, indicates that current food supply from plant production systems might not be sufficiently high to cover the demand of the global population, if specific dietary guidelines for healthy vegan nutrition were followed. The approximation compared the *current* production pattern with the requirements. This thesis will continue the analysis by addressing the potential of plant-based production which could be achieved, when all cropland was used for food, instead of feed, production.

Several modeling approaches were conducted in recent years to assess environmental impacts of different food systems. Most studies found lower cropland use for vegan products, which indicates that it could be possible to feed the world when the same cropland area is used as today.

Among these models are Life Cycle Assessments (LCAs), a common methodology to assess environmental impacts of products or diets. LCAs are typically product-based assessments and evaluate environmental effects by adding emissions caused and inputs utilized during the life cycle of a defined functional unit (e.g. a product entity). Different LCA studies found significantly lower

Table 2.2: Nutrient intake of vegans, compared to omnivorious diets. + indicates higher intake levels; **-** lower intake levels; **-*** critically low intake levels. Relative intake based on Bakaloudi et al. (2020), [a] Dewell et al. (2008), [b] Li (2011). Potential sources mainly based on EFSA (2019).

Nutrient	Potential Sources	Relative intake
Dietary fibers[b]	fruits, berries, fruit juices, vegetables, milk	+
Magnesium	nuts, whole grains, fish, vegetables, legumes	+
Iron	meat, fish, cereals, egg, green vegetables	+-
Folate		+
Vitamin B1	wheat germs, sunflower seeds, soybeans	+
Vitamin B6	fish, nuts, liver, avocado, poultry	+
Vitamin C	fruits and vegetables and their juices	+
Vitamin E	germ oils, nuts, soy, palm oil	+
n-6 PUFA[b]	vegetable seed oils	+
Carotenoids[a]	carrots, pumpkins, sweet potato	+
Flavonoids[a]	fruits, soy, vegetables, cacao	+
Fat	animal fats, plant oils	-
Proteins	meat, legumes, seeds	-
n-3 PUFA[b]	fish, eggs, algae, nuts, soy, linseed	-
Iodine	marine products, eggs, milk	-
Vitamin A	offal and meat, butter, dairy, eggs	-
Calcium	milk, green vegetables, legumes, nuts	-*
Selenium	fish, liver, sea food, legumes, cereals	-*
Zinc	legumes, whole grains, nuts, seeds	-*
Vitamin B2 (riboflavin)	milk, vegetables, fish, eggs	-*
Vitamin B3 (niacin)	meat products, cereals and milk	-*
Vitamin B12	Seafood, animal meats, eggs, liver	-*
Vitamin D	fish, mushrooms, meat, eggs	-*

cropland use associated with vegan diets compared to omnivorous diets (Poore and Nemecek 2018; Hallström et al. 2015; Baroni et al. 2007). For example, Poore and Nemecek (2018) found, reductions in arable land up to 49 %, when shifting to a vegan diet.

However, LCA studies have certain drawbacks: they usually model the impacts of selected food products, instead of modeling the impacts of the whole food system. As a consequence, in such product-based analyses, decisions over allocation methods have to be made (e.g. splitting the environmental impacts between milk and meat). In contrast, biophysical food system models try to catch the entirety of food-system related emissions and inputs. In a food-system perspective, the linkings between several products (e.g. an increase in by-products) are captured naturally through mass- and nutrient flows.

Erb et al. (2016) used a biophysical model to analyze impacts on deforestation related to different options, among them dietary patterns. It was found that vegan diets are the only diets allowing all other options without an expansion of cropland. However, this study mainly focused on calorie production, therefore, neglecting that other macro- and micronutrients are necessary to feed the world. For organic farming systems, furthermore, they did not consider the fact that crop rotation designs are generally different than in conventional systems (Barbieri et al. 2019).

Stehfest et al. (2009) estimated that a switch to plant-based diets would need up to 2.7 million ha of pasture and 100 000 ha less cropland.

The results of these studies suggest, that cropland use is reduced when vegan dietary patterns are adopted. From this perspective, one may conclude, that with the same amount of cropland as today, it should be possible to produce the same amount of nutrients – or more – with vegan diets. However, since no study has analyzed feasibility of global vegan agriculture with a biophysical model on a micronutrient level under consideration of crop rotations, this study makes an attempt to close this gap.

2.2.2 Environmental Performance of a Vegan World

In general, studies agree on the statement that dietary change is an important measure, and more effective than technological advances, to mitigate climate change and other environmental problems related to food systems (Garnett 2011; Poore and Nemecek 2018). Especially vegan nutrition is found to be associated with very low environmental impacts in comparison to omnivorous or even vegetarian diets.

Notarnicola et al. (2017) analyzed in their LCA study the environmental impacts of 17 selected food products, representating about 60 % of the European food consumption (food basket). The products were then categorized into several main food categories. The results showed that for all impact categories, animal products had the highest environmental impact per kilogram. The analysis showed further that the agricultural production phase generally has the highest environmental burden. However, LCA studies rely on assumptions about inputs and emissions on producer-level, and these vary heavily for different agricultural systems and regions. Poore and Nemecek (2018) developed an approach to take these variances into account: in their meta-analysis with data from 570 studies covering 38'700 farms in 119 countries, they analyzed environmental impacts of 40 products. Despite a high variability in the results of the different farming systems, they were able to confirm the patterns found by Notarnicola et al. (2017): it was shown that an exclusion of animal products in diets would lead to considerable reductions in environmental impacts. According to Poore and Nemecek (2018), even low-impact animal products exceed the impacts of plant-based substitute protein in the categories greenhouse gas (GHG) emissions, eutrophication and acidification. If animal-based proteins would be replaced by vegetable proteins, arable land use could be reduced by 19 %, GHG emissions by 49 %, eutrophication by 49 % and freshwater use (scarcity-corrected) by 19 %.

However, as stated above, LCA studies usually do not capture the entirety of food systems, as a biophysical model does. A food-system perspective is, however, necessary to capture the interlinking between the animal and plant production system, e.g. to assess impacts on the nitrogen cycle.

One approach to analyze the global food system with a biophysical model was made by Erb et al. (2016). They analyzed the global food system in 2050 with the model BioBaM, a model calculating differences between projected supply and demand, and based on this, deriving trade amounts of 14 product groups. They analyzed the effects of different dietary patterns (meat, vegetarian, vegan), different productivity levels and livestock feed compositions on land use (deforestation). Several options were identified where no deforestation would be necessary to feed the world. They found that only vegan and vegetarian diets would facilitate to stop cropland expansion at all, while for other dietary patterns, cropland would have to expand at least into productive grazing land. For organic agriculture, characterized by lower yields, only few options for zero-deforestation remain when current dietary patterns are maintained. A vegan-organic system would leave all options feasible without cropland expansion, whereas in a vegetarian-organic scenario, a cropland expansion of 11 % into grasslands would be necessary, at least.

The analysis of Erb et al. (2016) focuses on agricultural land use, whereas, this thesis attempts to capture a wider variety of environmental indicators. Springmann et al. (2018) analysed environmental impacts of current and projected food systems on five environmental indicators: GHG emissions, cropland use, freshwater use and nitrogen and phosphorous application. They analyzed the potential of different mitigation measures (reductions of food loss and waste, technological and management-related improvements and dietary changes). It was found that without the implementation of any measures, GHG emissions of the food system will increase by 87 %, cropland use by 67 %, phosphorous and nitrogen application by 54 %, and 51 %, respectively. They found that animal-related GHG emissions account for 72 % to 78 % of the agricultural emissions. Furthermore, dietary change towards a more plant-based diet would reduce the environmental impact of the food system by 56 %, (GHG emissions) and 6 % to 22 % (other environmental impacts). For their analysis, they developed a model, based on the database and calibrated with the International Food Policy Research Institute's International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) (Robinson 2015). In contrast to SOLm, the model starts from the final consumption demand of food and other products (e.g. biofuels) and derives related production of primary commodities and related inputs and emissions (e.g. feed).

SOLm was utilized by Schader et al. (2015a) to assess the environmental global impacts of a global food system with reduced animal numbers: specifically, a restriction was implemented that no feed should be cultivated on arable cropland (no food-competing feed stuffs). It was found that, compared to the baseline of the current food system, the GHG emissions could be reduced by 18 %, the land use for acre crops by 26 %, and the energy use by more than one third. They showed that, despite the necessary reduction of 70 % in animal-based proteins, energy availability and protein supply would still be sufficiently high to cover the needs of humanity.

In contrast to other studies, this thesis includes agronomic restrictions which arise in organic agricultural systems, due to the necessity of crop rotation implementation.

2.2.3 Are Vegan and Organic Agriculture Compatible?

Muller et al. (2017) extended and applied the food system model SOLm to investigate potential strategies to feed the world sustainably in the year 2050. The analysis resulted in the finding that a conversion into organic agriculture needs to be accompanied by further measures, such as food waste reduction or a reduction of food-competing feed components. For example, a 100 % conversion to organic agriculture with 50 % food wastage reduction and 100 % reduction of food-competing feed components could achieve the necessary amounts of calories and proteins without additional cropland areas. The results of this study suggest that a reduction of livestock (at least if fed with food-competing feed components) increases the viability of organic agriculture.

Another approach to model impacts of organic food systems was conducted by Barbieri et al. (2021). In their study, a focus was placed on limitations due to nitrogen availability in organic farming systems. They modeled potential food production of a conversion to 100 % organic farming with the Global Organic Agriculture Nutrient Model (GOANIM). GOANIM is a global, spatially explicit, biophysical linear optimization model. The production in each grid cell was optimized independently, depending on available N-resources. It was found that a 100 % conversion to organic agriculture without other measures would lead to a reduction of 57 % in energy production. They concluded that a partial conversion to 60 % organic agriculture was feasible, however, only with an existing livestock sector.

The studies indicate that binary solutions (organic, conventional or vegan, non-vegan) might not be the ultimate solution. Instead, combinations of measures with high leverage potential, in the best case mutually reinforcing, should be searched. Therefore, one of the goals of this thesis is to analyze the dynamics between the proposed solutions (organic and reduced livestock), by addressing research question three.

Chapter 3

Methods

The aim of this work was: i) to develop a model structure to allow the assessment of environmental and nutritional impacts of a global vegan food system and, ii) to explore outcomes of specific manifestations of a vegan world.

The first part (section 3.1) of this chapter focuses on the adaptations that have been implemented in SOLm to enable several choices:

I) share of vegan agriculture,

II) share of organic agriculture,

III) crop rotation design for organic and conventional areas,

IV) treatment methods of grassland and crop residues.

The section start with a short desription of the general structure of the model SOLm in subsection 3.1.1. The model adaptions facilitating a choice of the vegan and organic share of the food system (I and II), as well as the crop rotation (III) are described in subsection 3.1.2. The model assumptions of the crop rotations and treatment methods of grassland and crop residues (IV) are documented in subsection 3.1.3 and subsection 3.1.4, respectively.

The definitions of specific manifestations (scenarios) of a vegan world, which were used for the analysis, are given in section 3.2. The process of the integration of nutritional data, which was necessary to allow an assessment of the nutritional quality, is described in section 3.3. Furthermore, the selected environmental and nutritional indicators are introduced in section 3.4 and a short description of the evaluation process is part of section 3.5.

The entire workflow is depicted in Figure 3.1. First, external nutritional data was collected and cleansed in R (R Core Team 2020), using the tidyverse packages dplyr and ggplot2 (Wickham et al. 2019; Wickham et al. 2018; Wickham 2016). Agronomic data, based on literature research was integrated directly (without processing) in SOLm. The model structure was adapted by adding new modules or adapting existing modules. An evaluation of the results was done in R, utilizing the shiny and shinydashboard packages (Chang et al. 2021; Chang and Ribeiro 2018). The R library gdxxrw (Dirkse et al. 2020) is an API, which facilitates data exchange between R and GAMS. However, it was not utilized, after errors in data formats of imported data had been detected.

3.1 Model

This thesis utilized the model SOLmV6 (Muller et al. 2017) to assess potential impacts of a vegan world. The general structure of SOLm is described below in subsection 3.1.1. The adaptations,

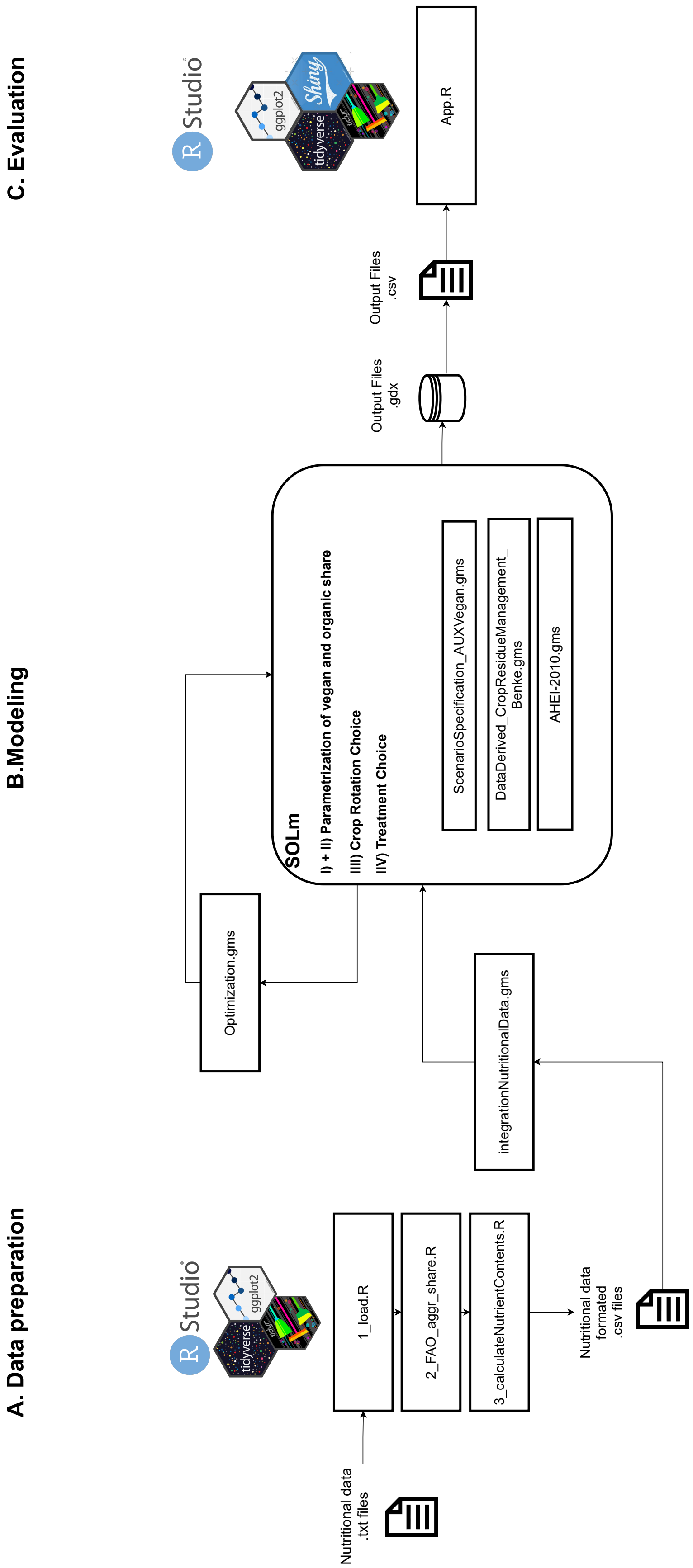


Figure 3.1: Data workflow connecting the three main steps (A: data preparation; B: Modeling, C: Evaluation) and utilized programming languages and packages for each step. Boxes indicate developed codes for the analysis. (Source: own figure)

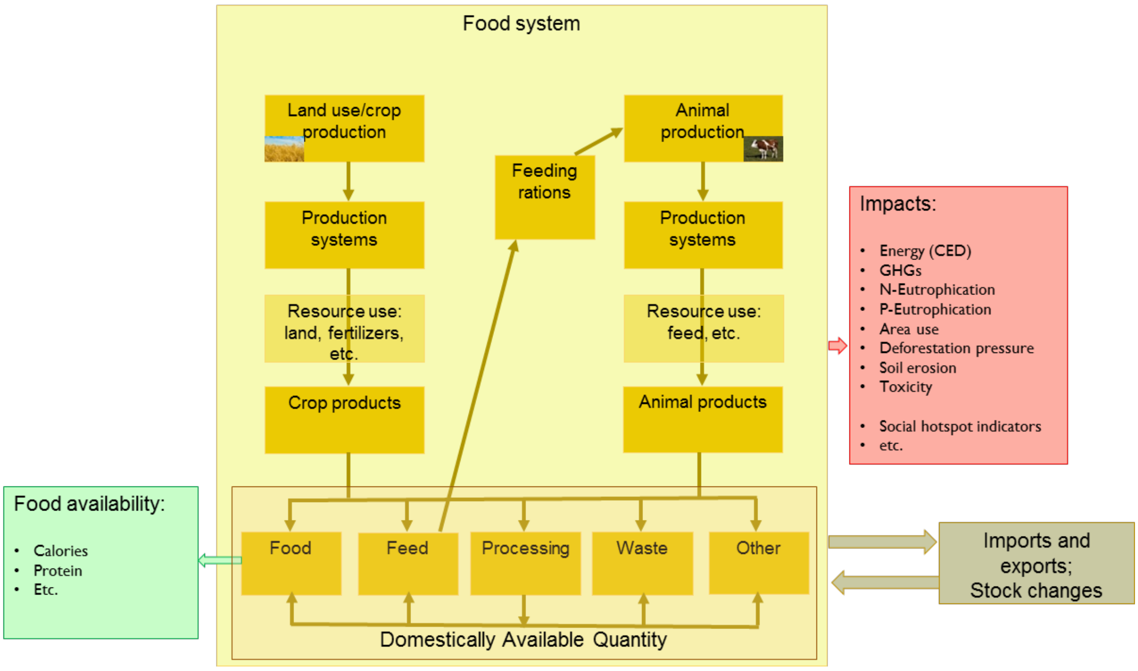


Figure 3.2: General calculation workflow of SOLm. (Source: Müller et al. (2020))

which were made in the model structure to allow the choice of different parameters, such as the share of vegan or organic agriculture, the crop rotation design or grassland treatment methods, are then outlined in subsection 3.1.2, subsection 3.1.3 and subsection 3.1.4.

3.1.1 SOLm: General Structure

SOLm is a nutrient- and mass-flow based model, depicting the global food system with its activities and related outputs, resource inputs and emissions. SOLm is written in GAMS (General Algebraic Modeling Language), a programming language developed for optimization problems (GAMS 2021). It allows therefore the integration of optimization modules. SOLm has been developed in the scope of an FAO project from 2011 to 2013 with the aim to evaluate the environmental impacts of different food system scenarios. For this thesis, the sixth version was used (Müller et al. 2020). The model calculations are based on national data from the FAOSTAT database (FAOSTAT 2021a) and link production, consumption and trade of all crops, commodities and countries used in the database (Müller et al. 2020).

SOLm is a static model: dynamic processes are represented by average values over several years. For example, crop rotations are represented by shares of individual crops in the total area. The geographical units (regions) of SOLm are countries, however, these can be aggregated or sub-regions can be defined, if data is available on these.

The model structure is depicted in Figure 3.2. The calculations start with specified amounts of plant production **activities** (e.g. 100 ha of wheat, 100 ha of rye, ...) for each region. Each of these activities is, on the one hand, related to specified resource input requirements (e.g. water use per ha, N per ha), on the other hand, the activities are associated with outputs, such as emissions, but also a defined amounts of main products, by-products and crop residues. Main and by-products of activities are captured by **commodities**, which are linked to specific characteristics (e.g. nutrient contents). The resulting commodity production of each commodity is then divided according to corresponding utilization shares to food, feed, waste, recycling or others. For each country and commodity, the domestically available quantity (DAQ) is calculated by adding imports and de-

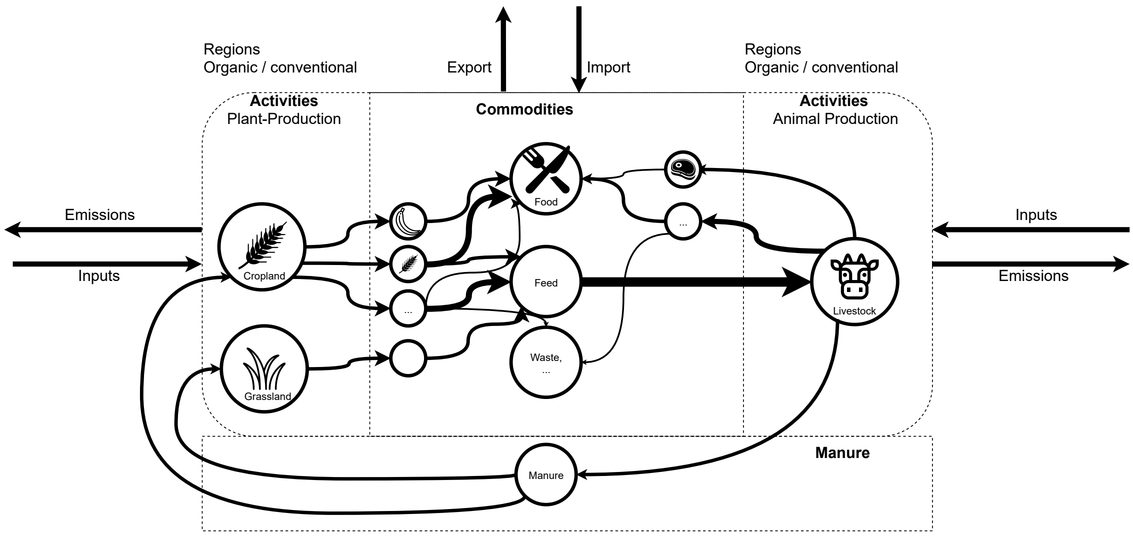


Figure 3.3: Simplified structure of SOLm, indicating mass and nutrient flows between plant- and animal production 'activities' and related 'commodities'. (Source: own figure)

ducting exports. Based on the cumulative amount of available feed, livestock numbers are derived, considering a specified allocation between different animals and animal types. Animal production is, similarly as in plant production, captured by activities with related inputs (e.g. feed, water) and outputs. Again, outputs of the animal system are, for example, manure, or food and feed commodities. Based on these calculations, environmental impacts and the DAQ of food and nutrients can be determined for each region. A more detailed explanation can be found in the documentation of SOLm (Müller et al. 2020).

The plant and the animal production systems in SOLm are linked by the nutrient and mass flows of feed (from plant production activities) and manure (from animal production activities) (see Figure 3.3).

3.1.2 Model Adaptations I - Parametrization of Vegan and Organic Agriculture

The goal of this part was to introduce parameters and adapt the model structure accordingly, so that the vegan and organic share of the food system could be specified and that a traditional, non-vegan agricultural system could be gradually transformed into a vegan-organic or vegan-conventional food system (see Figure 3.5). The organic share was specified with the parameter o, the vegan share with the parameter v. By the choice of the parameters o and v, a food system was divided into four parts: a vegan-conventional part, a vegan-organic part, a non-vegan-conventional part and a non-vegan-organic part. The adaptations are described below.

Organic share (o)

The parameter o specified the share of areas under organic management, as indicated by Equation 3.1 and Equation 3.2. The areas of each crop i and region r were divided accordingly into conventional and organically managed areas. For example, if the area for wheat production in the reference scenario had an area of 1000 ha and assuming an organic share $o = 0.4$, then, the organically managed area of wheat production would be 400 ha in the scenario.

$$Area_{i,r,org,Scenario} = o_r * Area_{i,r,Reference} \tag{3.1}$$

$$Area_{i,r,conv,Scenario} = (1 - o_r) * Area_{i,r,Reference} \tag{3.2}$$

Other model assumptions related to organic agriculture (e.g. input requirements, outputs) were almost the same as described in Muller et al. (2017). Two changes were made:

- The share of legume crops was not fixed at 20 % but defined by the crop rotation design (see subsection 3.1.3).
- The yield gap was calculated in two ways. The first method assumed an average yield reduction of 25 % (same as in Muller et al. (2017)), the second method accounted only for the yield gap related to plant protection (assuming no effect related to N-deficiency). The second yield gap calculation is based on DeLuca (2021) and will be referred to as *corrected* yield gap.

Vegan share v

The parameter v specified the *vegan share* of the food system. The vegan share defined that for $v = 0$, the system remained unchanged in comparison to the reference scenario. For $v = 1$, the food system was fully vegan, i.e. no livestock was held and no animal-based products produced. The following description gives an overview over the main changes, further explanations can be found in the code of SOLm (`https://github.com/KrayerPatricia/masterthesis.git`).

Area allocation

The cropland of each activity (crops and temporary grasslands) was divided into several parts, as shown in figure Figure 3.4. After dividing the areas into an organic and a conventional area for each crop, as stated above, the area was reduced for each crop according to its feed utilization to determine the total area for feeding purposes. At this point, a new parameter for the utilization share of feed areas (u) was introduced. This parameter determines how much of the feed area of the reference scenario is utilized as cropland in the scenario. For $u = 1$, the same total cropland area is used in the scenario as in the reference, for $u = 0$, the cropland of the scenario corresponds only to the part of cropland in the reference scenario which is utilized for food production. The cropland of the scenario is the divided, according to the vegan share v into a vegan and a non-vegan part. Four areas emerged from this procedure:

- Vegan-organic areas: organic crop rotation patterns were applied, only considering food crops.
- Vegan-conventional areas: conventional crop rotations were applied, only considering food crops.
- *Non-vegan*-organic areas: organic crop rotation patterns were applied, all crops considered.
- *Non-vegan*-conventional areas: conventional crop rotation patterns were applied, all crops considered.

The areas of permanent crops and permanent grasslands remained unchanged in all scenarios in comparison to the reference scenario.

In each of the four parts, a crop rotation design (according to the design in subsection 3.1.3) was applied and based on this, an allocation of individual crops was conducted. Areas in all regions r of the crop rotation categories C (cereals, legumes, oil crops, root crops, vegetables, fruits, set aside) were specified according to the chosen crop rotation design (see Equation 3.3 and Equation 3.4), which defined shares for these categories.

$$Area_{C,r} = share_{C,r} * Area_{total,r} \tag{3.3}$$

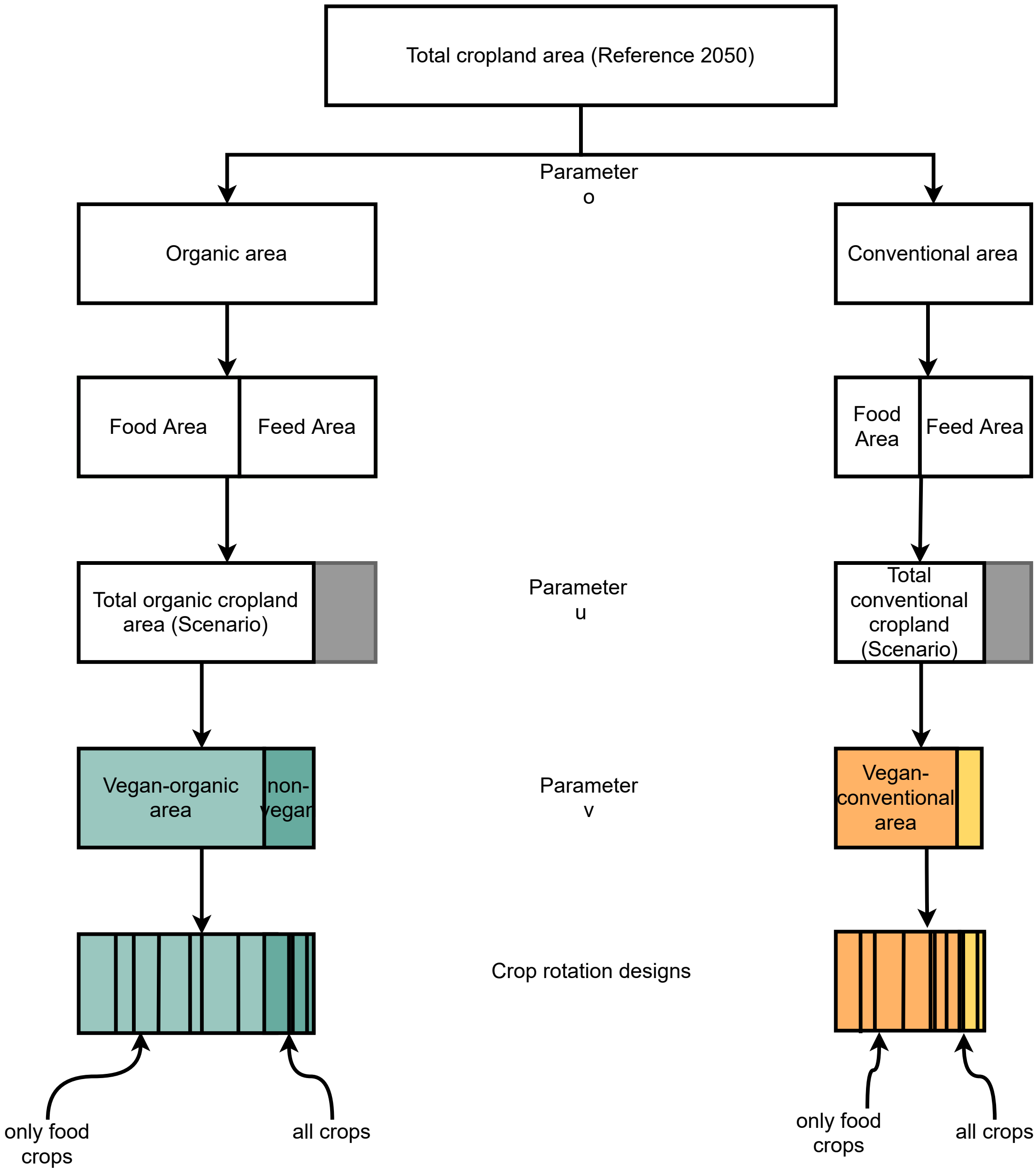


Figure 3.4: Schematic process of area allocation with parameters o, v, u and the crop rotation designs. (Source: own figure)

For each individual crop i and region r, the final area was determined by using the same ratio within a crop rotation category as in the reference scenario. In the vegan area, only potential food crops were allocated (i.e. food utilization share > 0), while in the non-vegan area, also pure feed crops (e.g. triticale and green maize) were allowed.

$$Area_{i,r,Scenario,v,r} = Area_{C,r,Scenario,v} * \frac{Area_{i,Baseline,Total,r}}{Area_{C,Baseline,Total,r}} \tag{3.4}$$

Utilization shares

Further, the vegan and the non-vegan system differ in their nutrient flows (see Figure 3.5). In a mixed system ($0 < v < 1$), the feed flow (nutrient flow from cropland to livestock) was scaled with v. To achieve this rescaling, the feed utilization share of all crop-based commodities was reduced by a factor $(1 - v)$. The corresponding share was then added to the food utilization (excluding commodities without food utilization, such as green maize). For example, assuming a vegan share of $v = 0.4$ and a feed and food utilization of 70 % and 30 % of maize grains in the reference scenario, respectively. Then, in the scenario, the feed utilization rate was reduced to $(= 0.7 * (1 - 0.4))$ and the food utilization share increased accordingly. For temporary grasslands with a food utilization share of 0, the fodder amount was scaled with v, the remaining part was then used as biomass for fertilization (grassland to treatment).

3.1.3 Model Adaptations II - Crop Rotation Patterns

A generic crop rotation pattern template was implemented in the programming code to allow the choice of different crop rotation designs for the allocation of crops, as described above. The actual crop rotation designs, which were utilized for this thesis, can be found in Table 3.1. Since SOLm is a static model, crop rotations are implemented via shares within the total cropping area. To allow enough flexibility to choose crops that fit to climatological and ecological characteristics of different countries and world regions, the crop rotations (respectively the shares of the total area) have only been specified on an aggregate level for eight crop groups: *grains 1*, *grains 2*, *legumes*, *root crops*, *oil crops*, *vegetables*, *fruits* and *set aside*. The category *grains 1* contains the main cereal crops: wheat, rice and maize, whereas *cereals 2* contains all other cereal crops. The group *fruits* contains only berries, since most other fruits are permanent crops and therefore not part of the crop rotation. The category *set aside* contains temporary grasslands (clover-grass mixtures) and fodder ley activities. The activities in each crop group are listed in Appendix C.

For this thesis, some designs were developed for different conventional and organic scenarios. Since little literature has been found on vegan-organic farming systems and their crop rotations, different approaches were made to develop the designs. For organic areas, two crop rotation designs (*Organic*, *Stockless*) were derived, based on existing literature. A further crop rotation for organic agriculture was developed based on an optimization problem (*optimized (org.)*).

For conventional areas, the default allocation of activities (crop rotation *BAU*) is based on the distribution of crops in the reference scenario. A further crop rotation design has been developed based on an optimization problem *(Optimized (conv.))*.

For all vegan areas of the scenarios (vegan-conventional and vegan-organic), the crop rotation design was applied by only considering food crops. For the non-vegan areas, all crops were considered.

Crop rotation pattern "Organic"

The first crop rotation design is an approximation to current crop rotation patterns in organic farming systems and is based on Barbieri et al. (2017). They analyzed and summarized crop rotations described in 77 publications, including 238 crop rotations of organic and conventional

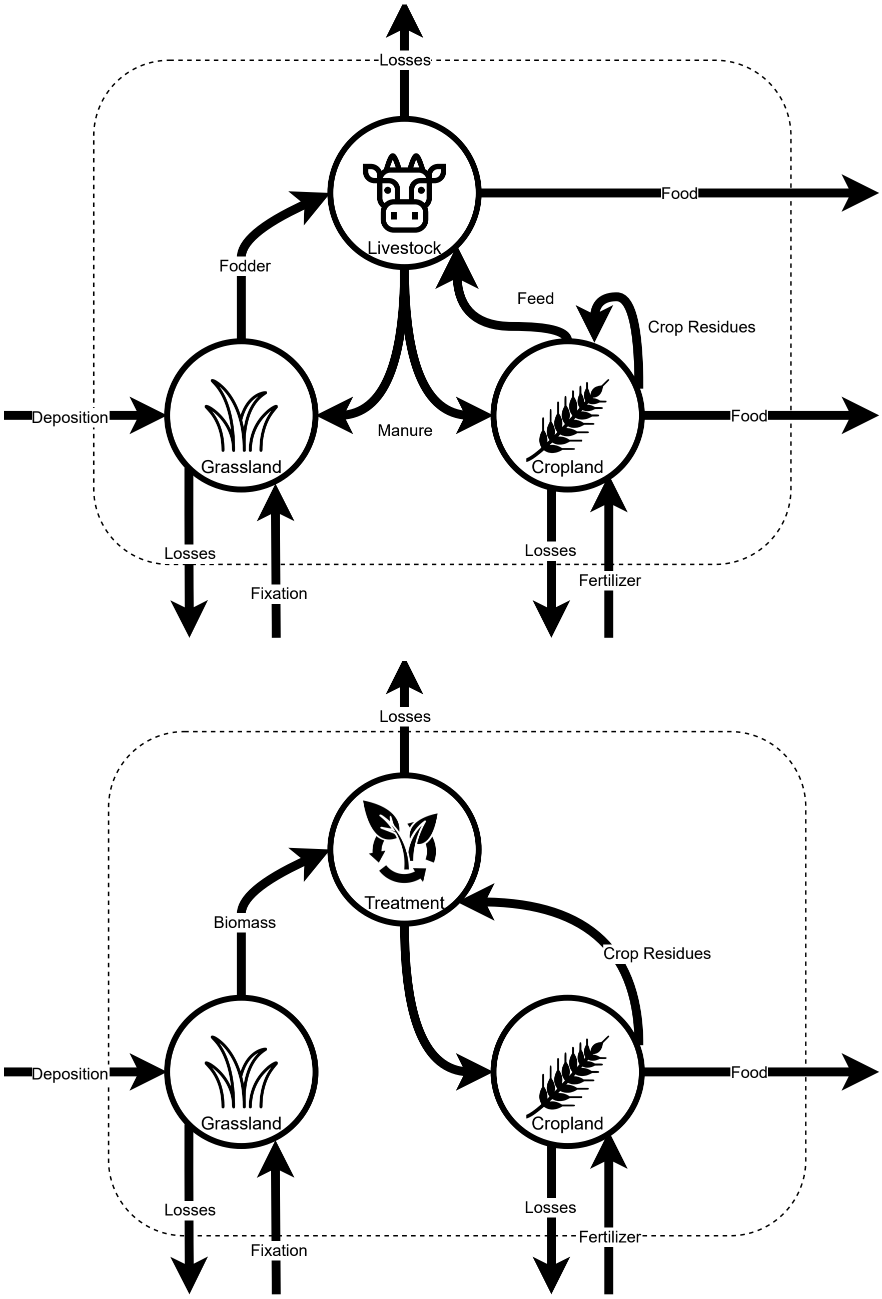


Figure 3.5: Comparison of nitrogen flows in non-vegan (top) and fully vegan (bottom) agricultural systems. (Source: own figures)

Table 3.1: Shares of a given crop rotation category in the total area. WE: Western Europe, NA: Northern America. * indicates that the share is calculated country-specific for countries in 'other' regions, based on Equation 3.5.

Crop Rotation Cat.	Organic			Stockless	Optimized (org)	Optimized (conv.)
	WE	NA	Others			
Cereals 1	0.22	0.4	*	0.26/*	0.05	0.1
Cereals 2	0.21	0.12	*	0.25/*	0	0
Grain Legumes	0.14	0.21	0.13	0.14	0.35	0
Oil crops	0.01	0.03	0.02	0.01	0.2	0.35
Root crops	0.09	0.01	*	0.11/*	0.01	0
Vegetables	0.07	0.02	0.03	0.045	0.16	0.55
Fruits	0.01	0.04	0.02	0.005	0	0
Set Aside	0.25	0.17	0.36	0.19	0.23	0
Total starchy crops			0.48	0.62		

cropping systems. The study categorized the crops into categories and analyzed the diversity and crop rotation length for organic and conventional agriculture. Based on the supplementary material of this study, the average crop rotation design, i.e. the share of the crop rotation categories, was calculated for three main world regions. Thus, it was assumed that these crop rotation patterns would be suitable from an agronomic point of view for the respective region. Some minor adaptations were made to the data. First, some entries were adapted, based on information of the underlying studies. Second, the share of the category *industrial* was added to the group *fruits*, and the share of the category *pulses/cereals* was split between *cereals2* and *legumes*. Further, a redistribution was conducted for the shares of cereals and root crops to ensure that the relative importance of these groups in producing starch-based calories is respected for each country. For this, the following approach was applied to all countries in the region *other countries*: The total share of *all starchy crops*, consisting of the categories *starchy root crops* and *cereals* (1 and 2), was set equal to 49 %, as indicated by the results of Barbieri et al. (2017). However, the share of the *cereals* (1 and 2) and *root crops* within the total area of all *starchy crops* was calculated to be the same as today for each country. Equation 3.5 shows the the calculation of the share of the category *cereals* 1. For the groups *cereals 2* and *root crops*, the procedure was conducted accordingly. With this approach, each country still uses the same type of starchy crops for the production of starch-based calories.

$$Area_{Cereals1,r,Scenario} = Area_{StarchyCrops,r,Scenario} * \frac{Area_{Cereals1,r,Reference}}{Area_{StarchyCrops,r,Reference}} \tag{3.5}$$

Crop rotation pattern "Stockless"

The second crop rotation design is based on a study about stockless-organic farming systems in Germany. Schmidt (2003) analyzed performance and crop rotations of twelve stockless-organic farms. The average crop rotation structure was calculated based on the presented crop rotations. Crops were classified into the defined crop rotation groups, and the average share within the total crop rotation was calculated .

The procedure of the country-specific redistribution of shares of cereals and root crops, as described above and represented by Equation 3.5, was repeated for this crop rotation design.

Crop rotation pattern "BAU"

For the conventional areas, the *business as usual*-pattern (BAU) has been applied in two scenarios. The areas of the crops occupy the same proportions as in the baseline. For the allocation of crops in vegan areas, a vegan crop rotation design was calculated, only considering food crops (feed utilization share < 1). As stated above, for the crop share in the vegan areas, only food crops (that means, crops which are not only used for feed, such as green maize or triticale) were allowed to be allocated (set F). The business as usual crop rotation design calculated the share of the food crops, as shown in Equation 3.6. For the allocation in non-vegan areas, the calculation of the crop rotation share of crops included all crops. For crop i in region r, the area share was calculated as follows in Equation 3.7:

$$Area_{i,r,Scenario} = \frac{Area_{i,r,Baseline}}{\sum_{c \in F} Area_{Baseline}} * \sum_{c \in F} Area_{Scenario} \tag{3.6}$$

$$Area_{i,r,Scenario} = \frac{Area_{i,r,Baseline}}{\sum_{c} Area_{Baseline}} * \sum_{c} Area_{Scenario} \tag{3.7}$$

Crop rotation patterns "Optimized (Conventional / Organic)"

Existing crop rotation patterns are driven by current consumption patterns or economic incentives (e.g. subsidies), and do not necessarily reflect an optimal solution regarding the nutritional quality of the produced food. Therefore, an attempt was made to develop a crop rotation pattern with the goal of optimizing nutritional values of the production. This was achieved by formulating two linear optimization problems, one for conventional and one for organic agriculture, respectively. In both, the objective function was the cropping area (global or country-wise), which was to be minimized. While for the first optimization problem, only nutritional constraints were considered (*goal: feed the world*), also agronomic constraints based on requirements of organic agriculture were taken into account for the second optimization problem (*goal: feed the world, sustainably*).

Optimization problem 1: optimized-conventional

$$\min_{x} \quad f(x) = x_1 + x_2 + ... + x_n \tag{3.8a}$$

$$\text{subject to} \quad A_1 \cdot x \leq b, \tag{3.8b}$$

Optimization problem 2: optimized-organic

$$\min_{x} \quad f(x) = x_1 + x_2 + ... + x_n \tag{3.9a}$$

$$\text{subject to} \quad A_1 \cdot x \leq b, \tag{3.9b}$$

$$A_2 \cdot x \leq 0. \tag{3.9c}$$

The decision vector x contains the areas, dedicated to the crop rotation categories: *cereals 1*, *cereals 2*, *grain legumes*, *starchy root crops*, *oil crops*, *vegetables*, *fruits*, *set aside*. The sum of these areas corresponds to the total cropping area of temporary crops.

Equation 3.8b and Equation 3.9b refer to identical nutritional constraints, which have to be fulfilled for both optimization problems. The nutritional constraints are based on lower threshold values for the intake of specific macro- and micronutrients per capita and day, as indicated in Table 3.6, based on intake recommendations of EFSA (2019). The solution should be able to produce enough macro- and micronutrients to feed the world. The negative entries in A_1 show for each crop rotation group, how much of each nutrient is produced on 1 ha on average. To calculate these values in the existing SOLm-structure, the nutrient density d (the amount of nutrients produced on 1 ha) was calculated for all individual SOLm crops i and defined nutrient content c, first. The calculation is based on an average value across all countries r, considering the nutrient contents of the primary commodities of the specific crop activity, the extraction rate e and and the corresponding yield y.

$$d_{c,i} = \frac{1}{n_{countries}} \sum_{r} y_{i,r} * Content_{c,PrimComm} * e_{PrimComm,r} \tag{3.10}$$

In a next step, the average nutrient density was calculated for all crop rotation categories CAT Equation 3.11.

$$d_{c,CAT} = \frac{1}{n_{i \in CAT}} \sum_{i \in CAT} d_{c,i} \tag{3.11}$$

The vector b in Equation 3.8b and Equation 3.9b contains the target values for all nutrients (amount which has to be produced in one year to feed the global or national population). Since crop rotations do only describe area distributions of temporary crops, the amount of macro- and micronutrients, which are produced by permanent crops in the baseline scenario, were deducted from the target amount. An upper threshold has been introduced for the intake of carbohydrates, which should ensure that the energy intake based on carbohydrates does not exceed 60 % of the total energy intake, the upper recommendation limit set by EFSA (2019).

The second optimization problem (Equation 3.9a to Equation 3.9c) included agronomic constraints, based on organic farming requirements or recommendations. These are shown in Table 3.2. The matrix A_2 (see 3.12) corresponds to the agronomic constraints 1 to 5 and is shown below. For agronomic constraint 6, the net average nitrogen withdrawal has been calculated for the crop rotation categories per hectare.

Table 3.2: Agronomic constraints used for the optimization problem

No.	Requirement / recommendation	Value
1	Max. share of grains	50 %
2	Max. share of grain legumes	35 %
3	Max. share of sunflowers & canola	35 %
4	Min. share of set aside	10 %
5	Min. share of set aside & grain legumes	20 %
6	Positive N-balance	$N_{fixed} - N_{output} > 0$

$$A_2 = \begin{pmatrix} 0.5 & 0.5 & -0.5 & -0.5 & -0.5 & -0.5 & -0.5 & -0.5 \\ -0.35 & -0.35 & -0.35 & 0.65 & -0.35 & -0.35 & -0.35 & -0.35 \\ -0.35 & -0.35 & 0.65 & -0.35 & -0.35 & -0.35 & -0.35 & -0.35 \\ 0.1 & 0.1 & 0.1 & 0.15 & 0.1 & 0.1 & 0.1 & -0.9 \\ 0.2 & 0.2 & -0.8 & 0.2 & 0.2 & 0.2 & 0.2 & -0.8 \end{pmatrix} \tag{3.12}$$

The optimization problem was applied on a global level and on a country level, considering current population numbers and yields. The results of the optimization problems for the global shares of the crop groups are shown in Table 3.1. The results for the absolute values for crop rotation group areas (global) can be found in (Appendix E). The results for the country-wise optimization problem were not implemented in SOLm.

The linear optimization problem was solved in GAMS Studio (GAMS 2021), by adding a new module to the SOLm structure, to make use of existing sets and parameter values of all crops.

3.1.4 Model Adaptations III: Treatment Options for Grassland

Due to the design principles of organic agriculture, all organic crop rotation patterns include a proportion of temporary grassland, which has no direct use in vegan agricultural systems (since there is no feed production necessary). Therefore, potential options for the handling of clover-grass and crop residues were determined which facilitate the later use as biomass fertilizer. The following options were implemented or data was added in SOLm: *Composting*, *biogas*, *silage*, *cut and carry*. Depending on the treatment process, a different share of the nitrogen in the crop material is lost due to volatilization, leaching and denitrification. The nitrogen losses due to management or after application are based on Benke et al. (2017) and shown in Table 3.3.

Table 3.3: Treatment systems in SOLm. N-transfer rate 1 considers N-losses during storing and application, N-transfer rates 2 considers losses after application (leaching, volatilization).

Treatment System	N-tansfer rate 1	N-transfer rate 2	Share in model runs
Composting	0.5	0.3	0.3
Cut and Carry	1	0.6	0.3
Silage	0.93	0.6	0.3
Biogas	0.92	0.76	0.05

Based on the nitrogen transfer rates, the losses during management (before application of the biomass fertilizer) were determined ($rateN_{loss} = 1 - rateN_{transfer}$), and, based on these, the amount of nitrous oxide (N_2O) emissions. Furthermore, direct and indirect nitrogen losses after application were calculated, based on the calculated total amount of N-losses after application. Here, we assumed that the shares between the amounts of N_{direct}, $N_{leaching}$ and $N_{volatilization}$ stayed the same as in the reference.

3.2 Scenario Definitions

To assess the potential outcomes of a vegan world, various scenarios have been developed that stand for different manifestations of vegan agriculture. Scenarios 1 to 3 describe a 100 % vegan world with conventional agriculture, where synthetic fertilizers and pesticides are not restricted. Also, no restrictions are made to the crop rotation scheme. Similarly, scenarios 4 to 6 cover fully vegan agricultural scenarios under organic management (see Figure 3.6).

All scenarios differ in one or multiple of the following parameters: **share of areas under organic management (o)**, **share of vegan agriculture (v)**, the **utilization share of feed areas (u)**, which were originally dedicated to feed production. Further, the **fertilization methods** and the applied **crop rotation scheme**. The parameters of all scenarios are shown in Table 3.4 and the context of the scenarios described in further detail below.

3.2.1 Scenarios 0a & 0b: Reference Scenarios

In SOLm, two reference scenarios are implemented and have been used for previous studies (Muller et al. 2017; Schader et al. 2015b). The *baseline* is based on current FAOSTAT data, averaged over the years 2009 to 2013, while the *reference scenario 2050* is based on hypothetical projections for the year 2050, as delivered by the FAO. Therefore, all model assumptions which are not specified below are being kept the same as in the reference for the year 2050, according to the principle *'et ceteris paribus'*.

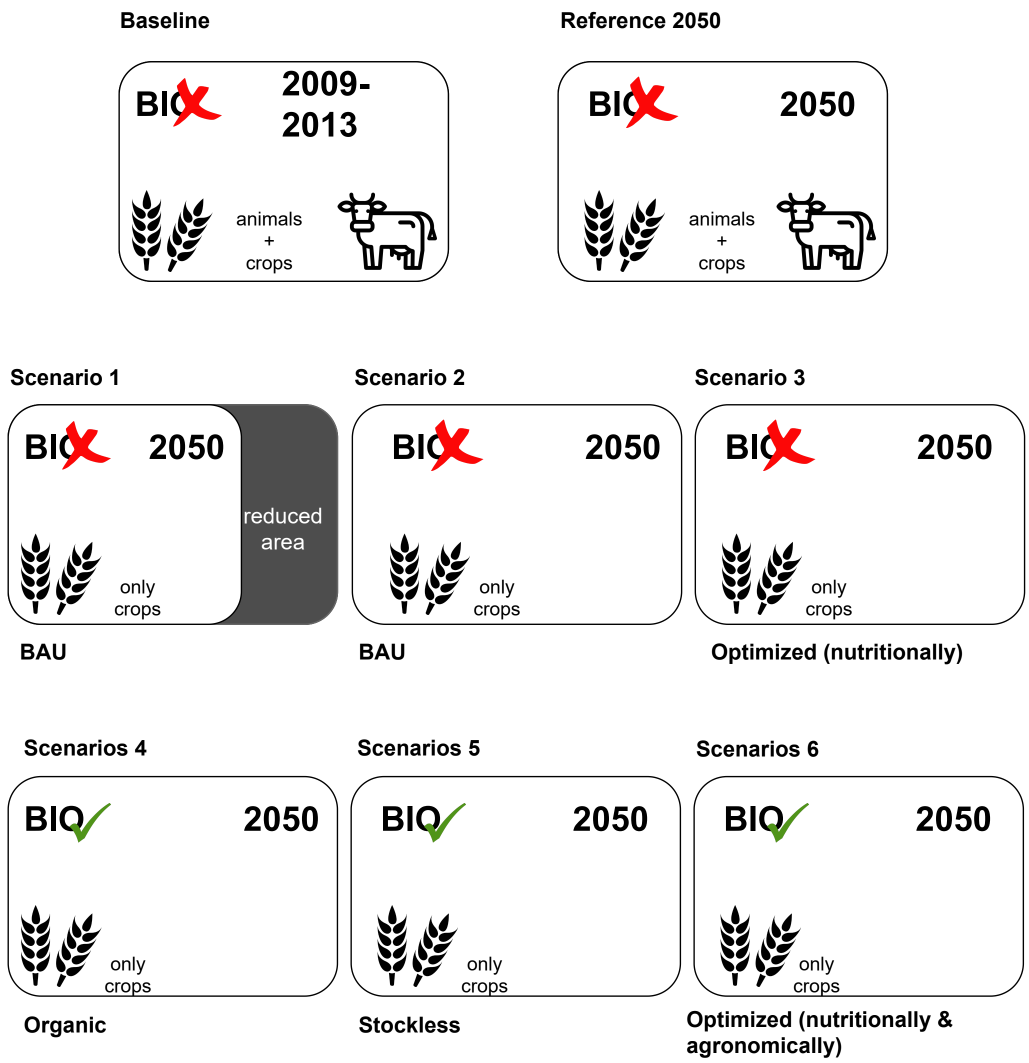


Figure 3.6: Overview over scenarios 1 to 6 and the reference scenarios. (Source: own figure)

3.2.2 Scenarios 1 to 3: Vegan-conventional Scenarios

The first three scenarios describe fully vegan food systems ($v = 1$) under conventional management ($o = 0$). These scenarios should answer the question if a vegan agricultural system under conventional management is able to feed the world and allow to assess environmental impacts of such systems. The scenarios are described below and illustrated in Figure 3.6.

- Scenario 1 (Vegan-Conv1): Scenario 1 describes a similar but vegan world to the reference scenario of the year 2050, however, without areas dedicated to feed production. These areas are deducted from the cropland area and are therefore free for other uses (e.g. conservation, reforestation, ...). This scenario delivers answers to the question, if it would be possible to just 'cut the current animal system out' without changing much of the rest. On the remaining cropland areas, only crops for human consumption are cultivated, and the permanent meadows remain unchanged, their utilization as feed is disallowed. The share of individual crop areas in the total cropland area the same share as in the reference 2050, however, only considering food crops (crop rotation design 'BAU').

Table 3.4: Overview over chosen parameters and crop rotation designs for scenarios 1 to 6 and of the reference scenarios.

Scenario	Name	o	v	u	Fertilization	Crop Rotation Pattern
0a	Baseline_{2050}	0	0	-	BAU	BAU
0b	Baseline_{2009}	0	0	-	BAU	BAU
1	Vegan-Conv1	0	1	0	BAU	BAU
2	Vegan-Conv2	0	1	1	BAU	BAU
3	Vegan-Conv3	0	1	1	BAU	Optimized (Conv.)
4	Vegan-Org1	1	1	1	BNF	Organic
5	Vegan-Org2	1	1	1	BNF	Stockless
6	Vegan-Org3	1	1	1	BNF	Optimized (Org.)

- Scenario 2 (Vegan-Conv2): Scenario 2 is again similar to the reference scenario 2050. In contrast to scenario 1, the total cropland area (including former feed areas) is utilized for food production, i.e. the cropland area is not reduced. Again, however, only food crops are grown, therefore, no feed is produced and nothing is utilized as feed at all (also no crop residues or fodder from permanent meadows). Furthermore, the distribution of crops on the cropland is again similar to the distribution of crops grown for food in the reference scenario 2050 (crop rotation 'BAU'). This scenario helps to answer the question how food amount and quality of a vegan world would look like if the production patterns remained similar to today.

- Scenario 3 (Vegan-Conv3): In scenario 3, the total cropland is used for food production. However, in contrast to scenario 2, an optimized crop rotation design is applied ('optimized (conv.)'). This scenario explores the nutritional and environmental potential that lie in a redistribution of crops, only based on nutritional requirements of humans.

3.2.3 Scenarios 4 to 6: Vegan-organic Scenarios

Scenarios 4 to 6 describe vegan food systems ($v = 1$) under organic management ($o = 1$). In all of these scenarios, the total cropping area of the reference 2050 is used and organically managed. Therefore, among other restrictions, no synthetic fertilizers are allowed and the yield is adapted. Two yield gap options were explored for all scenarios: i) an average yield gap reduction of 25 % determined by Seufert et al. (2012) and, ii) a reduction which assumes that nitrogen supply is sufficiently high (therefore only accounting for plant protection-related reduction of yield). In vegan systems, all nitrogen which is used as fertilizer in the system originates from BNF. Since organic farming systems utilize crop rotations for fertilization and other purposes, crop rotation patterns have been applied that do not reflect the business-as-usual distribution in the reference scenario 2050. Scenario 4, 5 and 6 differ in the applied crop rotation scheme, as specified below. Since not much information is available about vegan crop rotations (see subsection 3.1.3), these different crop rotation schemes have been used as approximations for potential vegan-organic farming systems. The crop rotation schemes are described in detail in Table 3.1.

- Scenario 4 (Vegan-Org1): This scenario applies a crop rotation scheme (organic) based on a study conducted by Barbieri et al. (2017). The average crop rotation schemes were used as basis for this scenario. This scenario gives indications, if a vegan world could be organically managed, if the production patterns were similar to today in organic agriculture.

- Scenario 5 (Vegan-Org2): Scenario 5 applies a crop rotation scheme (stockless), based on a study by Schmidt (2003). This scenario answers the question if a vegan world can be managed organically, if the production pattern found in of stockless farming systems in Western Europe were applied.

- Scenario 6 (Vegan-Org3): In scenario 6, the applied crop rotation scheme (optimized org.) is based on the result of an optimization problem, considering nutritional constraints and requirements of organic farming systems. Similar to scenario 3, the target was to minimize the cropping area and to fulfill nutritional requirements, i.e. feed the global population at the same time. The scenario provides information about potential feasibility and environmental performance improvements, considering a change in production pattern, based on an optimization.

3.2.4 Option Spaces

In order to gain a better insight into the dynamics between vegan and organic agriculture (research question 3), sub-scenarios with graduated proportions of the vegan share v (0%, 20%, 40%, 60%, 80%, 100%) and the organic share o (0%, 25%, 50%, 75%, 100%) were run. The crop rotation scheme was kept constant (crop rotation 'Organic') and the full cropland area was utilized ($u = 1$). Both yield gap options were applied for all options.

3.3 Integration of Nutritional Data

SOLm food commodities are based on the definitions in the FAOSTAT database and are linked to information about calorie, protein and fat content. However, for the assessment in this thesis, it was necessary to expand the set of available nutritional indicators with micro-nutritional content information. To include micronutrient content values in the model, data had to be collected for relevant commodities (on an individual and aggregated level) used in SOLm. The Standard Reference Legacy 28 (SR28) of the United States Department of Agriculture (USDA) is a comprehensive database on nutritional food quality, containing values for 150 different nutrients and about 8'800 food items (USDA 2016). The SR28 database is relational and built up of 12 entity categories, each in form of text-files (USDA 2015) (see Figure 3.7). Thus, it was possible to connect the nutritional values of food items with further information. The Standard Reference Legacies are final versions and are therefore not updated. Since not all needed food items in SOLm were found in the SR28 database, an additional database from the USDA ('Full Download') was used to find nutrient values for specific items (USDA 2021). Whenever possible, the use of the latter database was avoided, since data might be updated and does therefore not allow to compare results when experiments, based on this data source, are repeated.

The data was integrated into the model SOLm by conducting the steps 1 - 6, as described below. For the calculations in step 2 to 5, R and the R-packages of the tidyverse-ecosystem were used (R Core Team 2020; Wickham et al. 2019). For the data integration in step 6, an external module (`includeNutrients.gms`) was written in GAMS and included into the current model structure of SOLm.

3.3.1 Step 1: Food Matching

The nutritional data from the SR28 database contains values for food items, which do usually not match the food items utilized in SOLm. Therefore, the USDA-food items were matched manually with the relevant individual FAOSTAT-food items. For this, a list, connecting 661 food ids of the SR28 database with 427 food ids of the FAOSTAT database was generated. All matches have been tagged with a quality level (*low*, *middle*, *high*). The resulting file (`.csv`) matching the ids of the USDA-database to the ids of the FAOSTAT-database can be found on Github (`https://github.com/KrayerPatricia/masterthesis`).

The food matching was conducted according to the standard procedures for food matching (Arsenault et al. 2015; Stadlmayr et al. 2012). According to these, the following rules were applied:

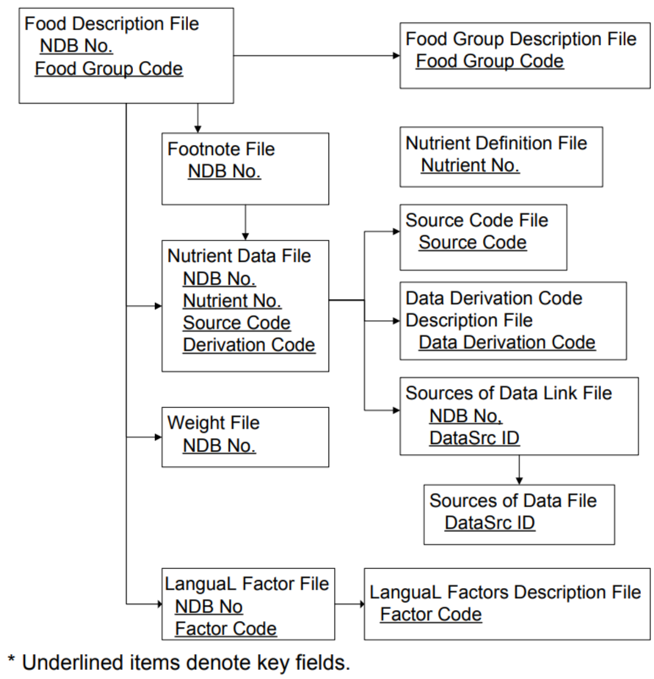


Figure 3.7: Relational structure of the database USDA SR28. (Source: USDA (2015))

- If several food items of a database match to one specific food item of the target database, then an averaged value of at least three items should be taken. This rule was implemented as follows: if no generic item was found in the USDA-database (e.g. *"Apples, raw"*), then at least three items were linked to the respective item of the FAO-database (e.g. *"Apple, green"*; *"Apple, yellow"*; *"Apple, red"*) and the average nutrient value was calculated.
- The processing state was considered (e.g. *"raw"*,*"fried"*, *"cooked"*). This rule was implemented as follows: in case of food items, which are mainly eaten in a processed manner (e.g. lentils), only food items with the respective processing characteristics from the USDA-database were considered. In case of ambiguous eating habits (e.g. vegetables, which can be eaten raw or processed), raw items from the USDA-database were preferred, since the nutrient amounts in the raw items reflect the full potential of available nutrients.
- The water- or calorie-content should be considered.This rule was implemented as follows: assuming that water- and calorie-content are related, the nutrient values of the USDA-database were corrected only by a factor, given by the ratio of the calorie contents of the linked food items $f = \frac{kcal_{\text{FAO}}}{kcal_{\text{USDA}}}$.
- If no matching item was available, then items with supposedly similar properties (plant family, leaf or root, colours) were linked.

3.3.2 Step 2: Nutritional Values of Individual Food Items

Each content value c of a nutrient n was corrected with a factor determined by the ratio of given calorie contents of the USDA and FAO database (see equation 3.13). The nutrient contents (per 100 g fresh matter) of an individual food item i in SOLm was then calculated as average value of the content of all linked food items of the USDA database (j). A weighting vector w has been added, which would facilitate different weightings of the linked items for future studies.

$$c_{\text{i, n, FAO}} = \sum_j w_j * c_{\text{j,n, USDA}} * \frac{c_{\text{i, kcal, FAO}}}{c_{\text{j, kcal, USDA}}} \tag{3.13}$$

3.3.3 Step 3: Nutritional Values of Aggregated Food Items

Since SOLm utilizes values of aggregated food items for specific calculations, the nutrient contents of aggregate commodities (e.g. apples and products) were calculated. These aggregations were done for each country separately, based on the share of individual food items in the total amount of the related food group (e.g. 90 % apples, 10 % apple juice in Switzerland). For this, the DAQ of single and group commodities were calculated, based on supply utilization account data (FAOSTAT 2021b).

For a commodity group C, containing single commodities s, the nutrient content c per 100 g of a specific nutrient n in a region r was calculated as shown in equation 3.14.

$$c_{n,C,r} = \sum_{s \in C} w_{s,r} * c_{n,s} \tag{3.14}$$

where w is a weight,

$$w_{s,r} = \frac{\mathrm{DAQ}_{s,r}}{\mathrm{DAQ}_{C,r}} \tag{3.15}$$

and the DAQ was calculated as follows:

$$\mathrm{DAQ}_{s,r} = \mathrm{production}_{s,r} - \mathrm{export}_{s,r} + \mathrm{import}_{s,r} \tag{3.16}$$

3.3.4 Step 4: Calculation of Amino Acid Score (AAS)

For all individual and aggregated food items, the amino acid score (AAS), a rough estimate of protein quality, was calculated, based on contents of essential amino acids and their related reference values (see equation 3.17 and Table 3.5).

$$AAS_{food}(\%) = \min_{AA} \frac{(\mathrm{mg}_{AA} \text{ per } \mathrm{g}_{Protein})_{food}}{(\mathrm{mg}_{AA} \text{ per } \mathrm{g}_{Protein})_{reference}} * 100 \tag{3.17}$$

Table 3.5: Reference values of indispensable amino acids, based on FAO (2011)

No.	Amino Acid	mg per g reference protein
1	Cystine + Methionine	33
2	Histidine	21
3	Isoleucine	55
4	Leucine	96
5	Lysine	69
6	Phenylalanine + Tryptophan + Tyrosine	94

3.3.5 Step 5: Handling of Missing Values

Although the USDA SR28 database provides data on nutritional values of over 5000 food items, a considerable amount of nutrient values has not yet been determined and is therefore missing.

Ignoring these data (or setting them to zero) would lead to a distorted outcome of nutritional indicators. An analysis of the missing data pattern was conducted and different imputation methods (Mean Imputation, Hot Deck Imputation, Regression Imputation) were applied. For the final integration, the method *Mean Imputation* was used, whereby the means were calculated for each food group, separately. A selection of visualizations for the analysis of missing values and different imputation methods can be found in Appendix D.

3.3.6 Step 6: Integration into SOLm

For the integration of the final nutrient content data, the set of nutrients in SOLm was extended, and a module was written in GAMS (`includeNutrients.gms`) and included into SOLm (`$include includeNutrients.gms`), making use of all existing sets and elements within the model.

3.4 Selection of Indicators

To assess the environmental impacts, a set of environmental indicators has been selected. Similarly, a set of nutritional indicators has been chosen to evaluate the nutritional production potential.

3.4.1 Environmental Indicators

SOLm contains an extensive amount of country-specific data on in- and outputs related to a variety of activities and also has an implemented set of environmental indicators which were used in previous studies (Schader et al. 2015a; Muller et al. 2017). From these indicators, a selection was made for this thesis, which is shortly described below. Further explanations can be found in Muller et al. (2017).

Land Use

All areas dedicated to agricultural purposes are being measured and categorized into temporary cropping areas (with or without temporary grassland), permanent cropping areas, temporary grassland and permanent grassland. Further land use categories, such as forest areas, were not considered.

Greenhouse Gas Emissions (GHG)

Greenhouse gas (GHG) emissions are captured for agricultural activities (animal and plant-production), as well as for deforestation.

Nitrogen Surplus

The nitrogen surplus measures for each activity the difference between nitrogen inputs and outputs in a system. In plant production systems, inputs are found in mineral and organic fertilizers, biological nitrogen fixation, crop residues, seeds. Outputs are contained in harvest and released through emissions (e.g. through fertilization). In animal production systems, the nitrogen inputs are feed and the outputs are emissions and food. Following Muller et al. (2017), the nitrogen surplus per hectare is reported, since it is seen as an indicator for the viability of organic farming systems.

Cumulative Energy Demand (CED)

The CED is an indicator of the utilized amount of non-renewable energy, based on LCA data. Due to a lack of better knowledge, it is assumed that all processes utilized the same amount of energy in 2050 as they do now. Although trade is considered in the model, energy use for transportation is not included due to lack of data.

Water Use

The water use indicator measures the amount of irrigation water. The values in SOLm are based on AQUASTAT data (Alexandratos and Bruinsma 2012) about irrigation requirements for different crops and commodities. Different production systems (organic / conventional) are assumed to be similar in their irrigation water requirements.

3.4.2 Nutritional Indicators

So far, SOLm contained health-related data about calorie, protein and fat contents of food commodities. For this thesis, further nutrients were integrated into the model (for the procedure, see section 3.3) to extend the range of available indicators. If values about the adequate intake (AI), average requirements (AR), the population reference intake (PRI) or the reference intake (RI), which indicate amounts which have to be consumed to stay healthy, were available, the relative surplus was calculated. The treshold values were based on EFSA (2019).

Main nutrients: calories, proteins and fat

Calories, proteins and fat were chosen as primary indicators of the feasibility of a food system. A system will be referred to as *feasible*, if it supplies the minimal requirements, according to Table 3.6.

Further nutrients

Further nutrients were chosen as indicators for the food quality in the food system. A focus was placed on nutrients which might be critical in vegan systems. The full list of nutritional indicators is shown in Table 3.6.

Protein quality: amino acid score (AAS)

To capture the protein quality of the output of the food system, the indispensable AAS was measured for the entire food system output. It measures the lowest value of limiting amino acid contents per gram protein, divided by corresponding reference values. The AAS is a rather simplistic indicator for protein quality, since it does not capture the digestibility of specific amino acids and proteins. However, due to lack of data for digestibility correction factors, this approach has been chosen to allow approximate comparisons between the potential protein quality of food systems. The AAS was calculated and integrated into SOLm, but in the end not evaluated due to low data quality (high share of missing values for amino acids which led to unreasonable results).

Overall diet quality: AHEI-2010

To evaluate the diet quality of specific food systems in a more holistic approach, the aggregate index Alternate Healthy Eating Index AHEI-2010 (Chiuve et al. 2012) has further been calculated for each country and as global average. The AHEI-2010 is based on known correlations between food types and chronic disease risk for diseases like diabetes, heart failure or specific types of cancer. The total AHEI of a diet is the sum of scores in 11 categories: whole grain intake (g), PUFA (% of energy intake), trans-fatty acids (% of energy intake), fish consumption (g), sodium (g), nuts and leguminous vegetables (portions), fruits (portions), sugar beverages (portions), red meat (portions), alcoholic beverages (portions) (see Equation 3.18). For each category, an optimal and a worst consumption amount threshold was defined by Chiuve et al. (2012), which are scored with 10 and 0 points, respectively. Amounts in between are interpolated linearly. The detailed method is described in more detail in Chiuve et al. (2012). For the calculation of the AHEI-2010 of the entire food system output, a new module was written in GAMS (`calculateAHEI.gms`) and included into SOLm.

$$\mathrm{AHEI}_r = \sum_{category} score_{category,r} \tag{3.18}$$

Table 3.6: Nutritional Indicators: $\text{Treshold}_{\text{low}}$ indicates a recommended intake or minimal intake (Unit per capita and day). $\text{Treshold}_{\text{high}}$ indicates upper limits of the recommended intake range. AI: adequate intake; AR: average requirements; PRI: population reference intakes; RI: reference intake. Values based on EFSA (2019).

No.	Indicator	Measure	Unit	$\text{Treshold}_{\text{low}}$	$\text{Treshold}_{\text{high}}$
1	Energy	AR	kcal	2’400	-
2	Proteins	PRI	g	66.4	132.8
4	Fat	RI	g	53.3	93.3
5	18:3 n-3 c,c,c (ALA)	AI	g	2.7	-
6	18:2 n-6 c,c (g) (LA)	AI	g	10.56	-
7	Calcium, Ca	PRI	mg	950	-
8	Carbohydrate, by difference	RI	g	270	360
9	Fatty acids, total saturated	-	g	-	-
11	Iron, Fe	PRI	mg	11	-
12	Niacin	PRI	mg	16.5	-
13	Potassium, K	AI	mg	3500	-
14	Riboflavin	AR	mg	1.3	-
15	Selenium, Se	AI	ug	70	-
16	Vitamin A	PRI	ug RE	700	-
18	Vitamin B-12	AI	ug	4	-
19	Vitamin C, total ascorbic acid	PRI	mg	102.5	-
20	Vitamin D (D2 + D3)	AI	ug	15	-
21	Zinc, Zn	PRI	mg	8.45	14.6
22	AAS	-	%	-	-
23	AHEI-2010	-	dmnl	-	-

3.5 Evaluation of Results

To allow a dynamic visualization of all results, an R Shiny Dashboard has been developed, using R and the shinydashboard package (R Core Team 2020; Chang and Ribeiro 2018).

Chapter 4

Results

In this chapter, selected results of all model runs are presented, the structure follows the order of the research questions. In section 4.1, the first research question is addressed, focusing on the nutritional quality and therefore the feasibility of vegan food systems. Specifically, in subsection 4.1.1, the feasibility is analyzed by comparing the nutritional outputs of the vegan scenarios to recommended or required intake values. The results of the ecological impacts (research question 2) of vegan scenarios are described in section 4.2. The results considering the dynamics between organic and vegan agriculture are part of section 4.3.

4.1 Feasibility of Vegan Food Systems

The model calculations showed that the replacement of all animal-based nutrients is challenging and that not all of the scenarios were able to produce the required amounts (see Figure 4.1 and Figure 4.2). Two vegan scenarios produced sufficient amounts of energy, proteins and fat. However, none of the scenarios, including the baseline and the reference of the year 2050, produced sufficient amounts of all the considered nutrients to feed the world. In subsection 4.1.1, nutrient availability for the main nutrients calories, proteins and fat, are described. If not other indicated, results are based on the assumption of an average yield gap. In subsection 4.1.2 and subsection 4.1.3, the results of the global availability are presented for other considered nutrients. These results are also summarised in Table 3.6. The following sections summarise the impacts on nutrient availability of production systems, yield gap and the crop rotation design. The subsection 4.1.7 contains results for the diet quality assessment with the aggregate indicator AHEI-2010.

4.1.1 Calorie, Fat and Protein Availability

It was found that – based on the model assumptions – it is possible to produce sufficient amounts of calories, fat and proteins with a vegan agriculture to feed the world. However, only two vegan scenarios, both vegan-conventional, reached the necessary amounts of all three macronutrients (see Figure 4.3). A sufficient amount of calories was produced in three vegan scenarios (Vegan-Conv2: 54.3 %; Vegan-Conv3: 7.5 % and Vegan-Org2: 7.7 %), whereas another one of the scenarios was only slightly below the threshold (Vegan-Conv1, −0.6 %).

Protein availability was only sufficient in the scenarios Vegan-Conv2 and Vegan-Conv3 (Vegan-Conv2: 37.1 %; Vegan-Conv3: 25 %). With all the other systems the target threshold could not be reached (−23.7 % to −2.4 %).

The contribution of animal-based products to fat supply has been found to be considerable in the reference scenarios (see Figure 4.1). In vegan systems, consequently, fat supply is mostly critical. The model calculations suggest that fat production was far below the required amount in two of the vegan-organic scenarios (Vegan-Org1: −46.2 % and Vegan-Org2: −42.5 %), as is shown in

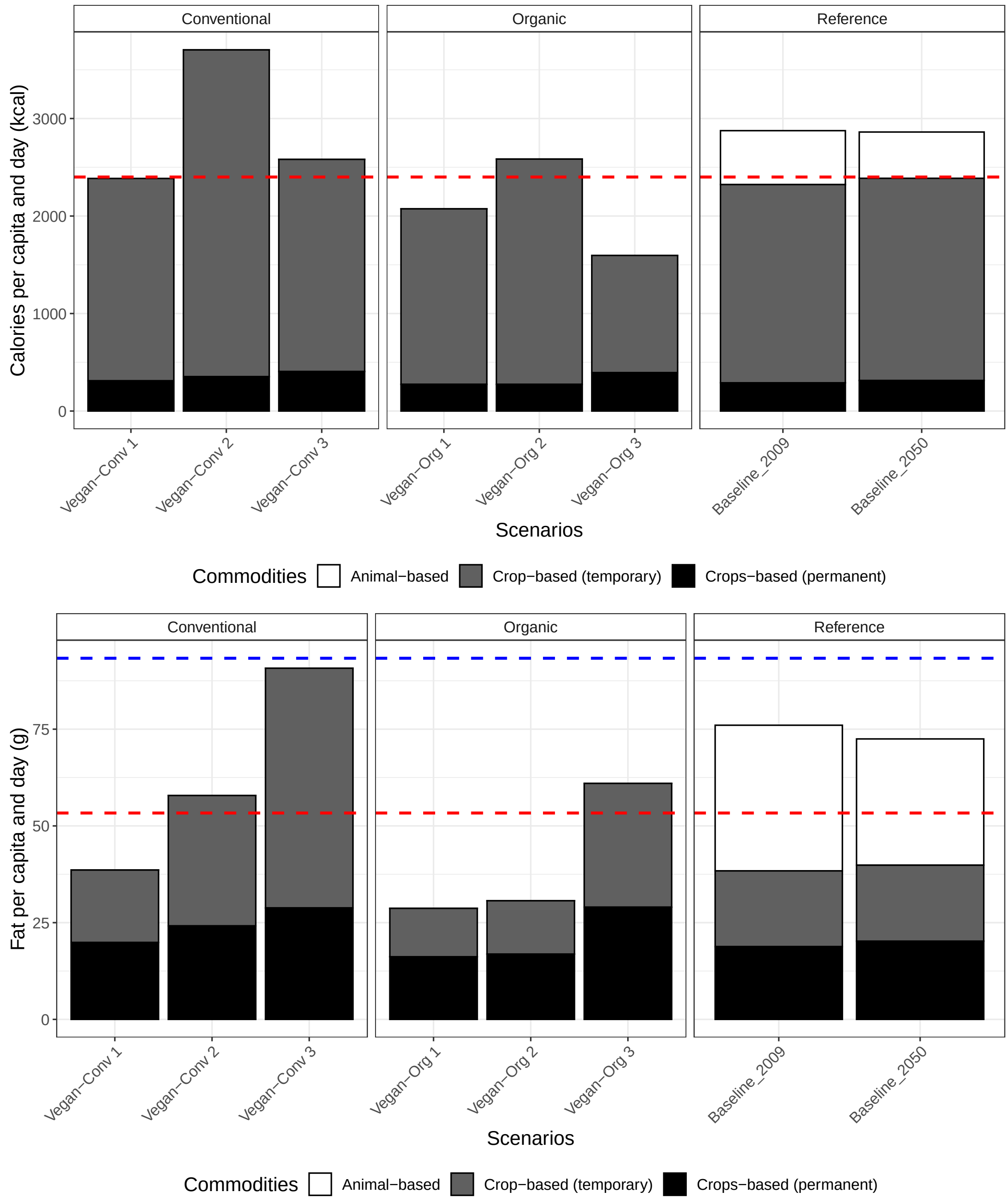


Figure 4.1: Results of model runs with main scenarios. Global availability per capita and day of calories (top) and fat (bottom). Red line indicates $\text{Treshold}_{\text{low}}$, blue line $\text{Treshold}_{\text{high}}$.

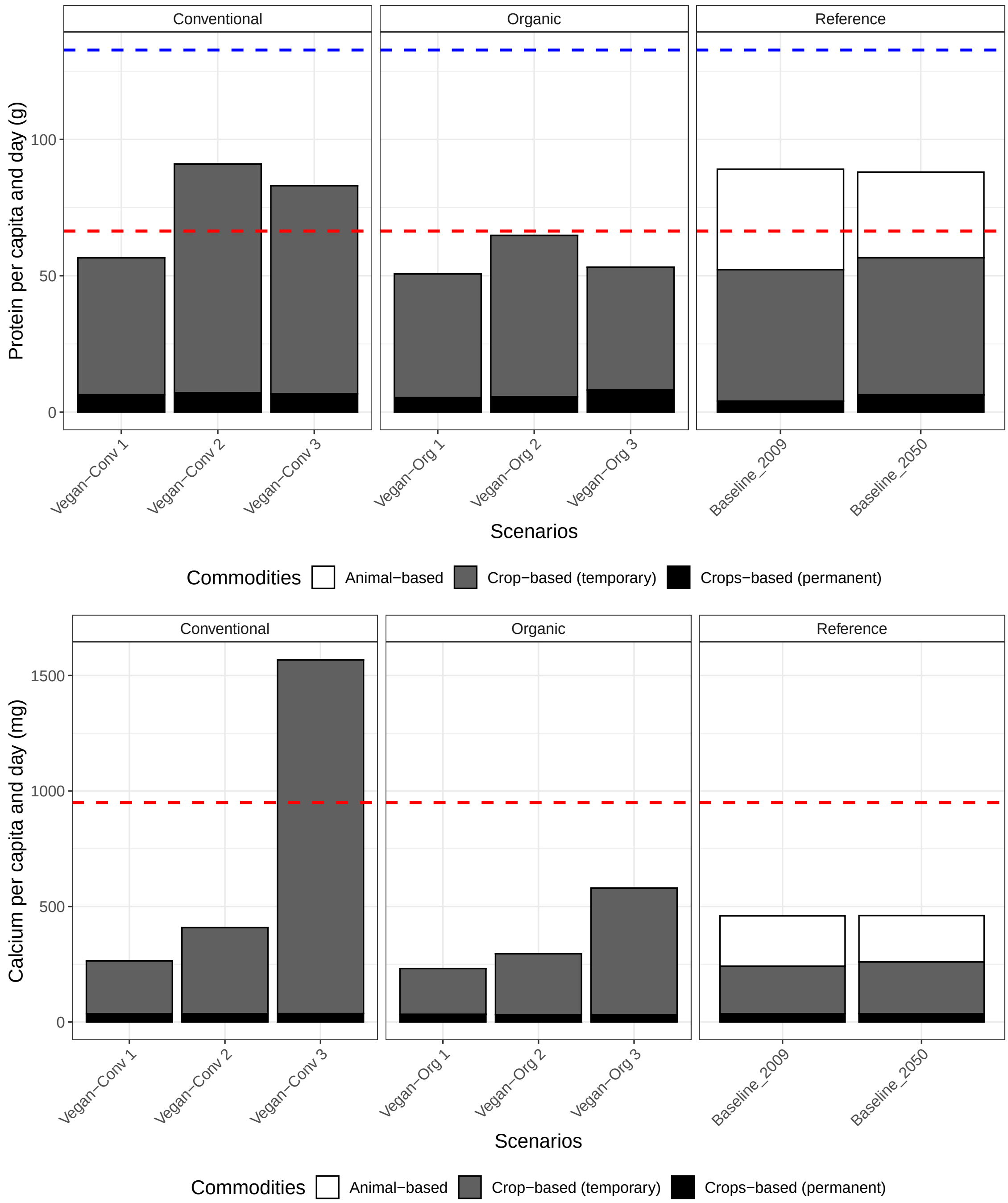


Figure 4.2: Results of model runs with main scenarios. Global availability per capita and day of proteins (top) and calcium (bottom). Red line indicates Treshold$_{\text{low}}$, blue line Treshold$_{\text{high}}$.

Figure 4.3. Only the third vegan-organic scenario exceeded the target amount of fat (Vegan-Org3: 14.3 %), however, protein and calorie production were insufficient in that case. In the vegan-conventional system 2 (Vegan-Conv2), the fat availability was found to be sufficiently high (8.5 % over threshold). The third vegan-conventional system (with an optimized crop rotation design) exceeded the required amount by 70.2 %.

4.1.2 Further Nutrients: Critical Availability

For all remaining macro- and micronutrients, the relative surplus (%) of the modeled availability in relation to the recommended intake is shown in Figure 4.4. The analysis showed that the supply of vitamin D and B12 in all vegan scenarios was strongly below the threshold; the same holds true for the reference scenarios, however less pronounced. The deficiency of vitamin B12 compared to the threshold is between −98.9 % and −99.6 % in the vegan scenarios, indicating that supplementation might be necessary.

Further, it was found that the supplied calcium amount is critically low in almost all vegan and non-vegan reference scenarios. The negative balance ranges from −39 % to −75.6 %. One exception is the vegan-conventional scenario 3, in which a considerable excess was produced (65 %).

Overall, the vegan-conventional scenarios 2 and 3, could supply most of the micronutrients, whereas the vegan-organic scenarios showed a higher percentage of undersupplied micronutrients. Especially the vegan-organic scenarios 1 and 3 could not supply most of the micronutrients. Critical in most vegan scenarios were the micronutrients selenium, riboflavin, niacin and ALA.

4.1.3 Further nutrients: uncritical availability

Dietary fibers, carbohydrates, zinc, vitamin C, potassium, iron and LA could be supplied above the threshold by most of the vegan scenarios. Whereof, dietary fibers, iron and LA were produced in excess in all of the vegan and non-vegan scenarios.

4.1.4 Influence of Production System

The nutrient availability in vegan-organic farming systems seems to be more critical than in conventional systems: None of the vegan-organic scenarios produced enough calories, fat and proteins to feed the world. The production of micronutrients was also found to be generally more critical than in conventional scenarios.

4.1.5 Influence of Crop Rotation Design

The results show that the crop rotation designs have a considerable effect on the nutritional output of a system. The crop rotation design *Stockless* for vegan-organic systems showed better results for all nutrients than the crop rotation design *Organic*. The crop rotation design *Organic* produced insufficient amounts of calories, proteins and fat (−13.6 %, −23.7 % and −46.5 %, respectively). In contrast, the protein production of the scenario with the *Stockless* crop rotation design was only −2.4 % below the intake recommendations. The implementation of the *optimized* crop rotation design for the vegan-organic scenario led to insufficient amounts for calories and proteins (−20 % and −35 %), however, better results compared to the other organic scenarios for the critical nutrients fat and calcium were achieved.

The optimized crop rotation design in the conventional scenario (Vegan-conv3) overally achieved the highest summed excess of all nutrients: the availability of all nutrients, except selenium, vitamin B12 and D, was above the required amounts.

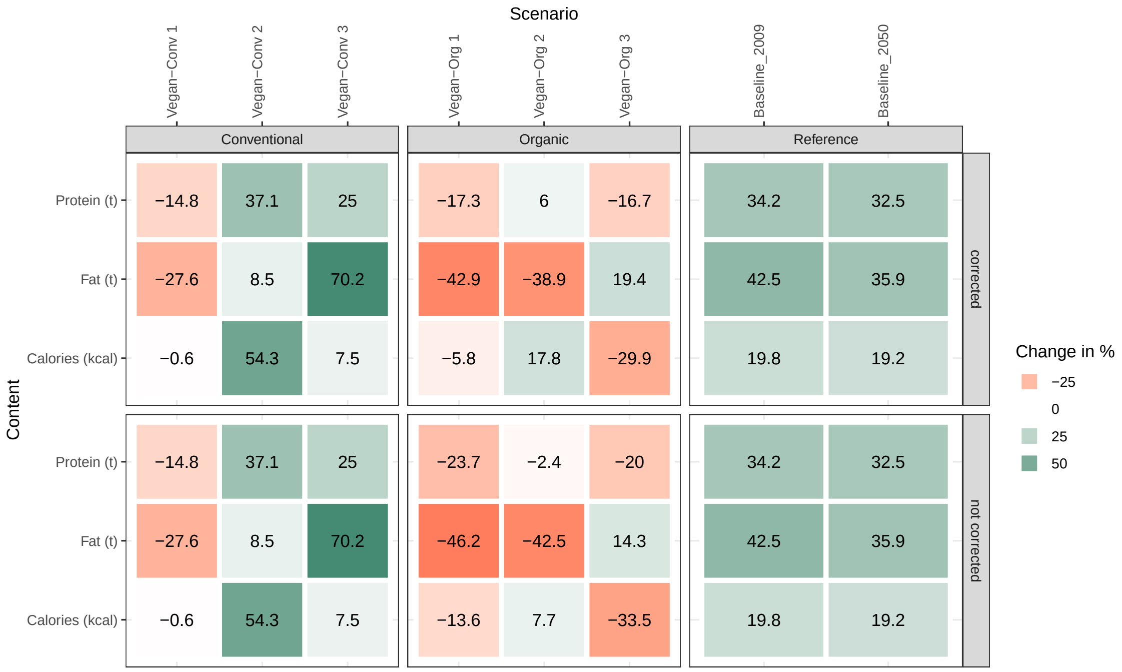


Figure 4.3: Energy, protein and fat availability, surplus (%) relative to intake recommendations for average yield gaps (below) and corrected yield gap (top).

Figure 4.4: Nutrient availability, surplus (%) relative to intake recommendations.

4.1.6 Influence of Yield Gap-Correction

Comparing the results of both yield gap approaches (of which the corrected version assumes a perfect nitrogen availability), only minor differences were detected for the vegan-organic scenarios. Although the assumption of perfect nitrogen availability led to higher yields and therefore a higher nutrient production was achieved, fat supply remains mostly critical, therefore none of the vegan-organic scenarios achieved a sufficient supply of calories, proteins and fat to feed the world (see Figure 4.3).

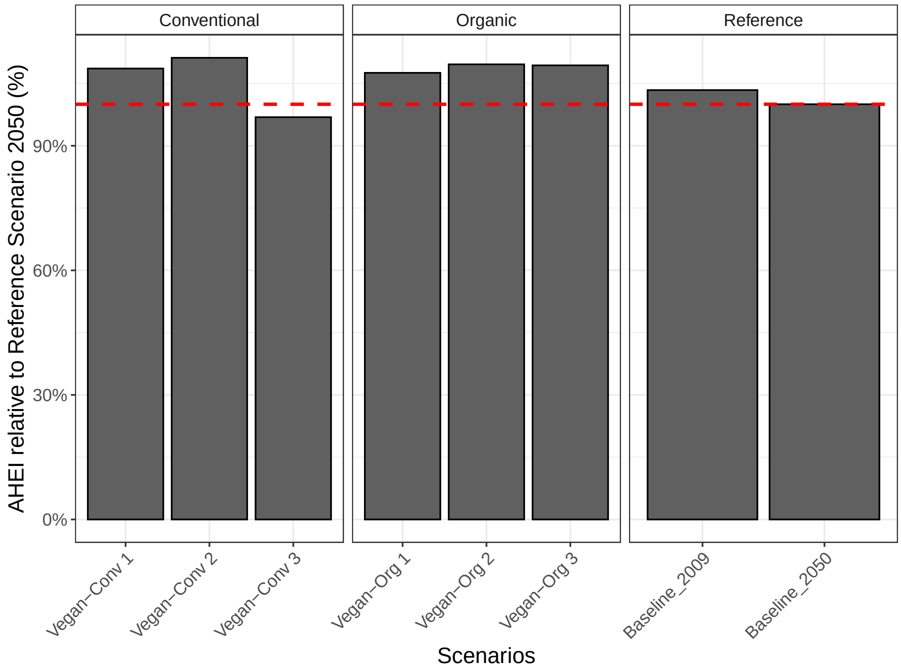


Figure 4.5: AHEI-2010 indicator (global mean), 100 % equals the AHEI of the reference scenario 2050 (indicated by red line).

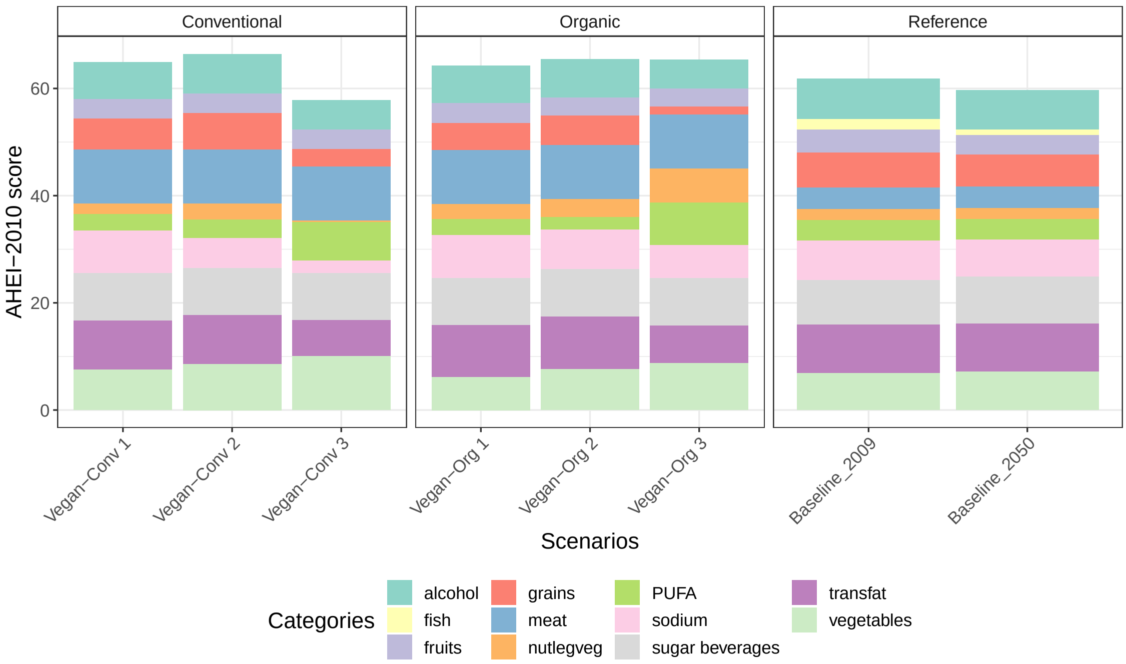


Figure 4.6: Global average AHEI-2010 score by category.

4.1.7 AHEI-2010

Considering the aggregated AHEI-2010 index, most vegan scenarios showed higher overall scores (global mean of all countries) compared to the reference scenarios. The AHEI-2010 individual scores were calculated for each country based on the available quantity of specific food items (e.g. amount of fish) or nutrients (e.g. amount of polyunsaturated fatty acids) per capita and day. The availability and the intake were therefore assumed to be equal. Under this assumption, the reference scenarios of the base years 2009 to 2013 and the year 2050 reached an average global score of 61.8 and 59.8, respectively (Figure 4.5). Only the vegan-conventional scenario with an optimized crop rotation, achieved a slightly lower score than the reference in the year 2050 (−3.1 %). The other vegan-conventional scenarios (both with the standard crop rotation BAU) exceeded the reference score of the year 2050 by 9 % and 11 %, respectively. The vegan-organic scenarios exceeded the reference score of 59.8 points by 8 % to 10 %.

If the total AHEI score is split into the global average scores of the different categories, it becomes clear that the reduced meat intake of the vegan scenarios contributed mainly to the increase (Figure 4.6). In the optimized scenarios, an increase in the categories *vegetables* and $PUFA$ was found. However, the larger amount of oil production is also related to higher consumption of transfats, which is adversely rated. The relatively lower score of the vegan-conventional scenario with optimized crop rotation seems to be mainly influenced by a low intake of nuts and leguminous vegetables, as well as a higher sodium intake.

4.2 Environmental Impacts of Vegan Agricultural Systems

The model runs for the vegan scenarios resulted in generally lower environmental impacts compared to the two non-vegan scenarios (baseline and reference 2050). The changes of the impact in relation to the reference 2050 is shown below for selected indicators.

Land Use

The agricultural land occupation modeled for the different scenarios is shown in Figure 4.7. The permanent areas (cropland and grassland) remained unchanged, thus, the land use mainly differs between the scenarios in the allocation of the temporary cropland and grassland.
The total temporary agricultural area (cropland and grassland) was reduced by 39 %, according to the model assumptions, in the Scenario Vegan-Conv1. In the other scenarios, the total temporary agricultural area was utilized as cropland, therefore, resulting in no reduction of temporary cropland areas. Assuming that the permanent grassland could be released for other utilization purposes, the reduction in agricultural areas lays between −77.6 % to −66.4 % for the scenario Vegan-Conv1 and all others, respectively.

Cumulative Energy Demand (CED)

An overview of the changes of several environmental indicators in relation to the impacts of the reference scenario 2050 is given in Figure 4.9. The results show that the CED, is generally lower in vegan systems than in the reference 2050 (reduction of up to 32 %). However, in the vegan-conventional system with the nutritionally optimized crop rotation, energy demand only decreased slightly by −3.8 %. This scenario has a very high share of vegetables in the crop rotation (55 % of the total area), a crop group with high nitrogen requirements, which is reflected in the high increase in the amount of N from energy-intensive fertilizer compared to the reference 2050 (67.2 %).

GHG emissions

The results for the GHG emissions are depicted in Figure 4.8. Since GHG emissions are related to the CED, it is consistent that the vegan-conventional scenario with nutritionally optimized crop rotation (Vegan-Conv3) also shows the lowest potential to mitigate climate change. The crop-related

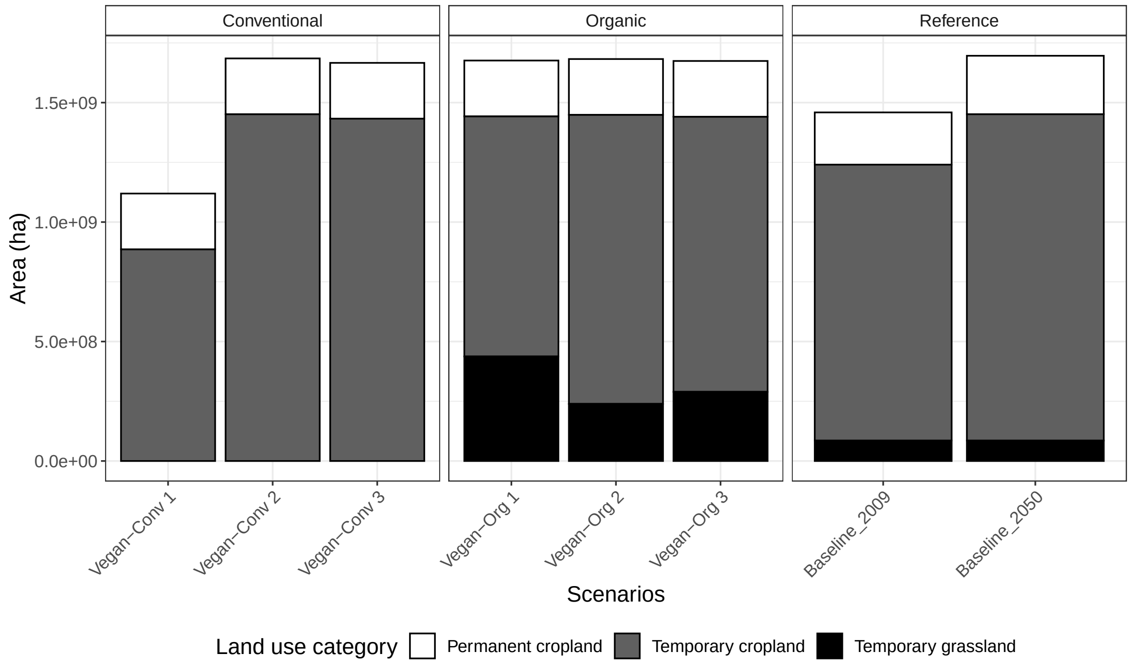


Figure 4.7: Land use categories for scenarios 1-6 and reference scenarios (without permanent grassland).

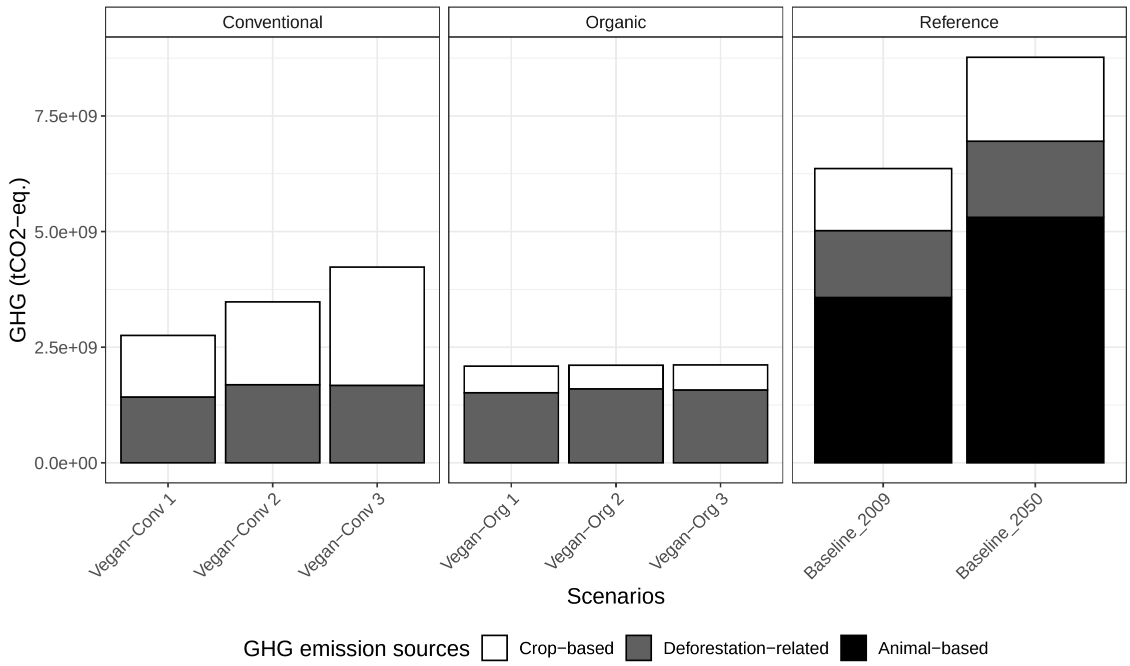


Figure 4.8: GHG emissions (tCO2e) for scenarios 1-6 and reference scenarios.

GHG emissions of this scenario are 40.9 % higher than the reference 2050, if deforestation-related GHG emissions are not included, or 22.3 %, if they are. However, the total GHG emissions (including animal-based emissions) in this scenario are still 51.7 % lower than in the reference 2050.

The other vegan-conventional scenarios show reductions in crop-related GHG emissions of −20.4 %

(Vegan-Conv1) and a slight increase of 0.5 % (Vegan-Conv2). Considering the total amount of GHG emissions (including animal production), a reduction of −68.3 % and −60.3 %, respectively, was determined. The organic scenarios show generally higher reductions in crop-related GHG emissions (ranging from −68.6 % to −71.7 %) and total GHG emissions related to the agricultural system (76.2 % to 75.9 %).

Nitrogen surplus

The results for the N-balance per hectare are shown in Figure 4.10. Without nutrient recycling measures (value chain waste, end-user waste, human faeces, permanent grassland), the N-balance is negative for all vegan scenarios, i.e. the input through synthetic fertilizers and leguminous plants does not sufficiently cover the N-removal through crops. For organic systems, an option was explored by introducing recycling measures (with 75 % of human faeces, 50 % recycling of value chain waste, 50 % recycling of end-user waste, 25 % of permanent grassland utilized as fertilizer). It shows a reduction potential for the N-deficiency by about one quarter. The results suggest that even with strong recycling measures vegan-organic scenarios are not able to reach a positive nitrogen balance.

Water Use

The changes in irrigation water use are shown in Figure 4.9. The irrigation water use (water stress adjusted) is below the amounts of the reference scenario 2050 for all vegan scenarios, except scenario Vegan-Conv3. This scenario shows a high dependency on irrigation water, with an increase of 55.5 % compared to the reference 2050. For the other scenarios, the relative reductions in irrigation water use are between 5 % to 26.1 %.

4.3 Interactions between Organic and Vegan Agriculture

To assess the compatibility of organic and vegan agriculture, the model was run with gradually increasing parameter values of organic (0 %, 25 %, 50 %, 75 % and 100 %) and vegan (0 %, 20 %, 40 %, 60 % 80 % and 100 %) shares for the food system. For each of these combinations (options), the same crop rotation patterns were applied for the corresponding organic areas (crop rotation design *Organic*) and the conventional areas (*BAU*), based on the crop rotations which are most similar to current patterns for organic and conventional agriculture. In the following subsection 4.3.1, the potential options to feed the world (considering energy, proteins and fat) are explored. In subsection 4.3.2, the influence of vegan and organic farming on the nitrogen balance are summarised. The subsection 4.3.3 describes environmental effects related to changes in the organic or vegan share of the food system.

4.3.1 Nutritional Feasibility

The following subsections show the results for the dynamics between vegan and organic agriculture for the main nutritional indicators calories, proteins and fat. In summary, the feasible options to fulfill all requirements are the following:

- Organic share = 0 %: all vegan shares possible
- Organic share = 25 %: vegan share ≤ 80 %
- Organic share = 50 %: vegan shares ≤ 40 %

Energy production

The results for the calorie surplus production for different shares of vegan and organic agriculture are shown in Figure 4.11. The results indicate that:

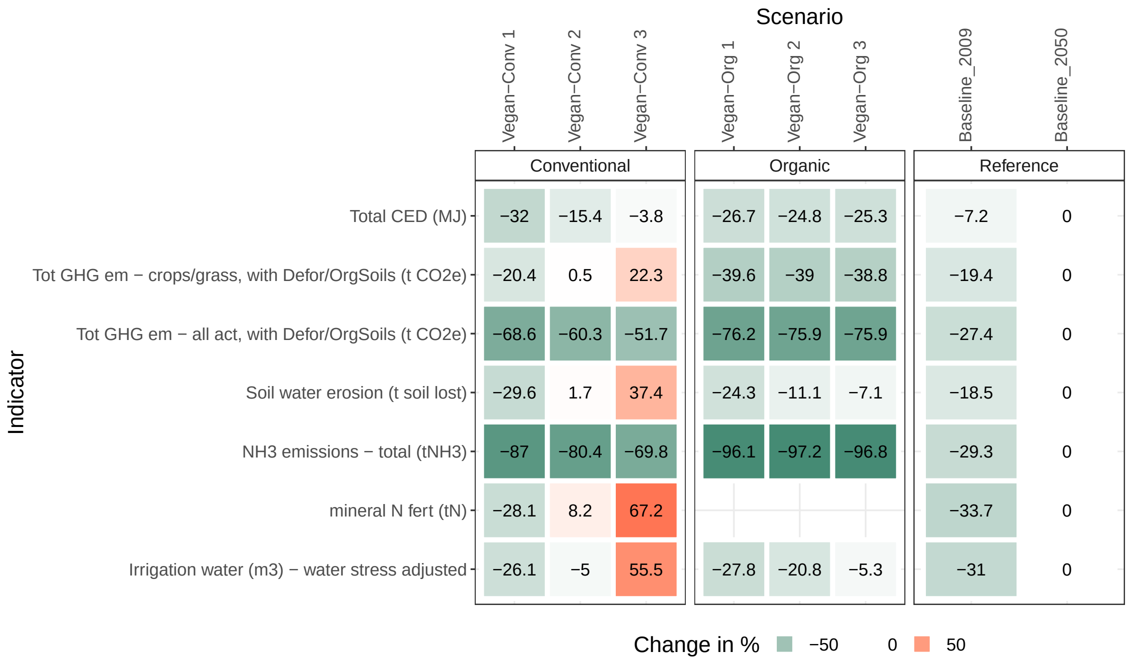


Figure 4.9: Change in Environmental Indicators relative to reference scenario 2050.

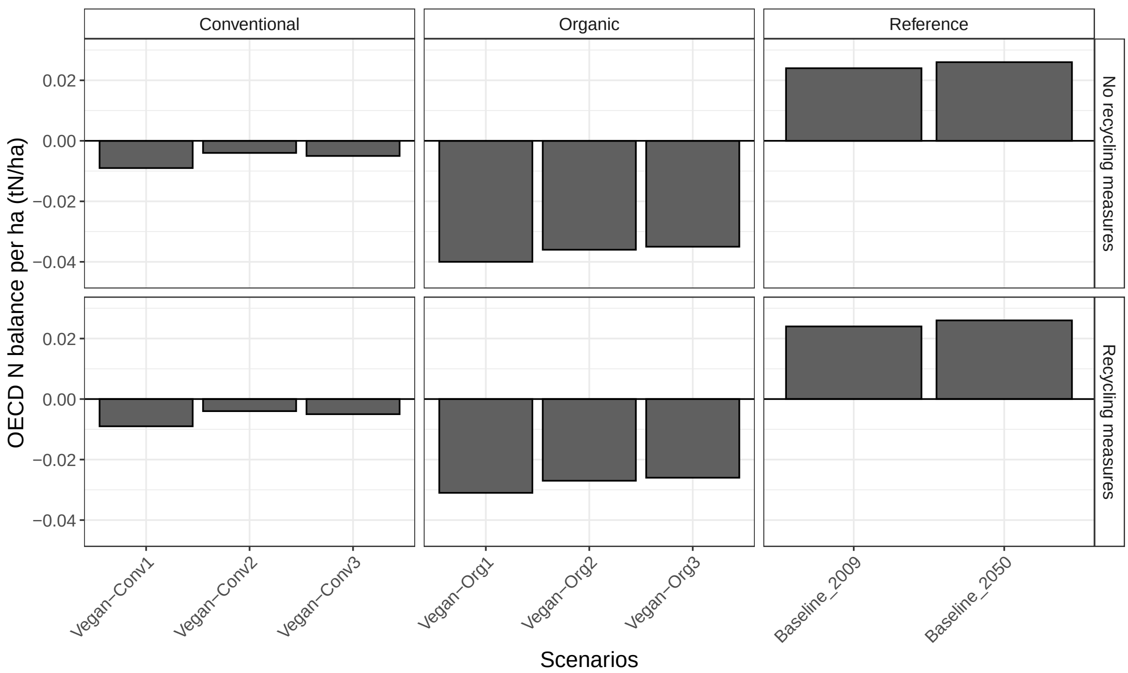


Figure 4.10: Global OECD nitrogen balance per ha for scenarios 1-6 and reference scenarios. Top: without recycling of human faeces, value chain waste, end-user waste. Bottom: organic scenarios with 75% of human faeces, 50% recycling of value chain waste, 50% recycling of end-user waste, 25% of permanent grassland utilized as fertilizer.

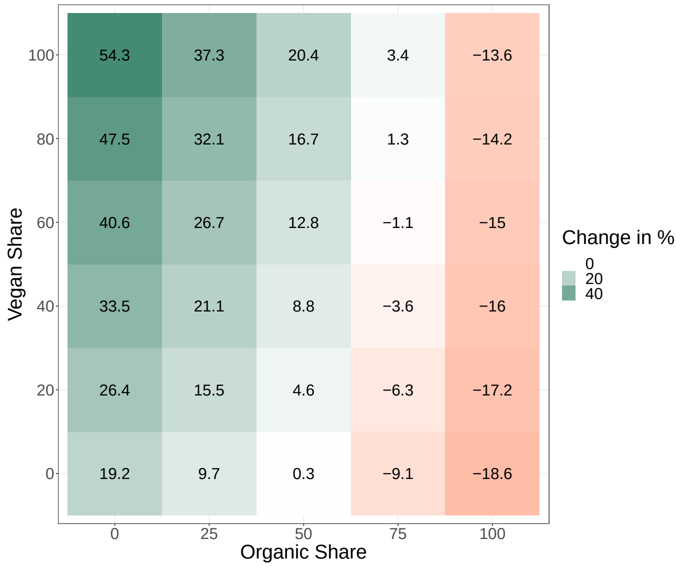


Figure 4.11: Surplus (%) of calorie production relative to intake recommendations

1. the higher the share of vegan agriculture, the higher the energy production.

2. the higher the share of organic agriculture, the lower the energy production.

These dynamics seem reasonable since organic farming systems require increased shares of areas for non-productive temporary grasslands and are characterised by lower yields. The increase of energy-related productivity for higher shares of vegan agriculture seems to be related to the fact that no produced calories are lost due to feeding.

The results for energy production indicate that the all vegan shares are possible for organic shares $\leq 50\,\%$. For an organic share of $75\,\%$, the vegan share of the food system would have to be above $80\,\%$.

Protein production

The results of the protein production are shown in Figure 4.12. In contrast to the energy production, the dynamics change:

1. For organic shares $\leq 25\,\%$: an increase in the vegan share increases the protein production.

2. For organic shares $> 25\,\%$: an increase in the vegan share decreases the protein production.

3. An increase of organic shares decreases the protein production.

These findings seem to be related to the fact that in conventional systems, where a certain amount of food-competing crops is utilized as feed, a higher vegan share avoids, again, the less effective protein production via the animal system. For higher organic shares, where larger areas of non-producing set aside are required, an increase of vegan agriculture also implies that these areas are effectively not used for food production.

All options for the vegan share of the food system are possible for an organic share $\leq 50\,\%$. For an organic share of $75\,\%$, the vegan share has to be zero (representing a system, as it is today).

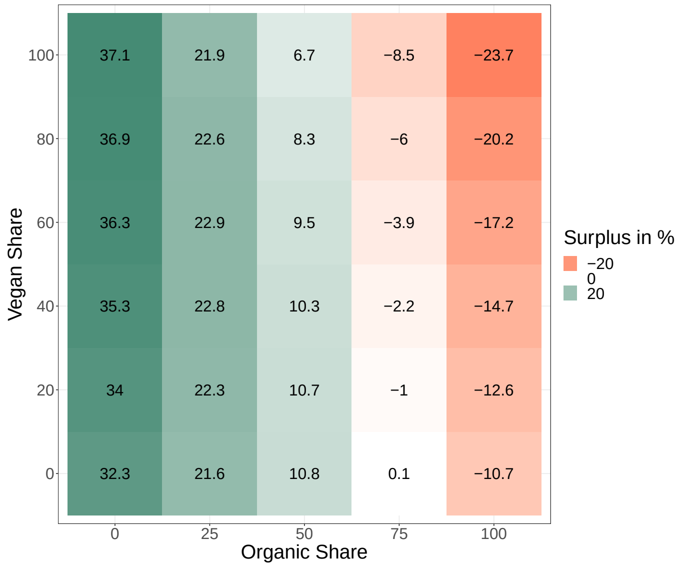


Figure 4.12: Surplus (%) of protein production relative to intake recommendations

Fat production

The results for the fat production surplus are shown in Figure 4.13. Here, the influence of vegan and organic farming on the system is as follows:

1. An increase of the vegan share reduces the fat production.
2. An increase of the organic share reduces the fat production.
3. For higher organic agriculture shares, the reduction in fat production related to vegan agriculture is more drastic.

Considering the fat production, several feasible options have been identified. For an organic share of 25 %, the vegan share should be ≤ 80 %. For an organic shares of 50 % and 75 %, the vegan share should be ≤ 40 % or ≤ 20 %, respectively, to produce sufficient fat to fulfill the global requirements.

4.3.2 Feasibility due to N-availability

The results for the N-balance per hectare are shown in Figure 4.14. An increase in vegan- and organic-share decreases the N-surplus; the net balance of zero is reached at a maximum of 75 % organic share and approximately 80 % vegan share. Assuming that a nitrogen deficiency of less than $-20\,\mathrm{kg\,ha^{-1}}$ is not sustainable in the long-term, the space of feasible options, as indicated above, does not change.

4.3.3 Further Environmental Effects

For irrigation water use and CED (see Appendix B), an increase in one of options (vegan or organic share) results in a reduction of the environmental impact compared to the reference scenario 2050. However, the GHG emissions show a different pattern (see Figure 4.15):

- An increase of the vegan share reduces the GHG emissions of the food system.
- For vegan shares ≤ 60 %: an increase of organic agriculture leads to an *increase* of GHG emissions.
- For vegan shares ≥ 80 %: an increase of organic agriculture leads to a *decrease* of GHG emissions.

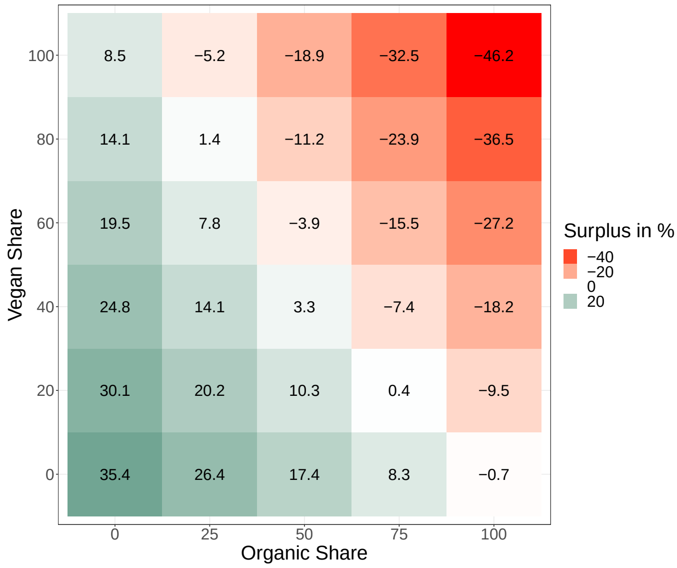


Figure 4.13: Surplus (%) of fat production relative to intake recommendations

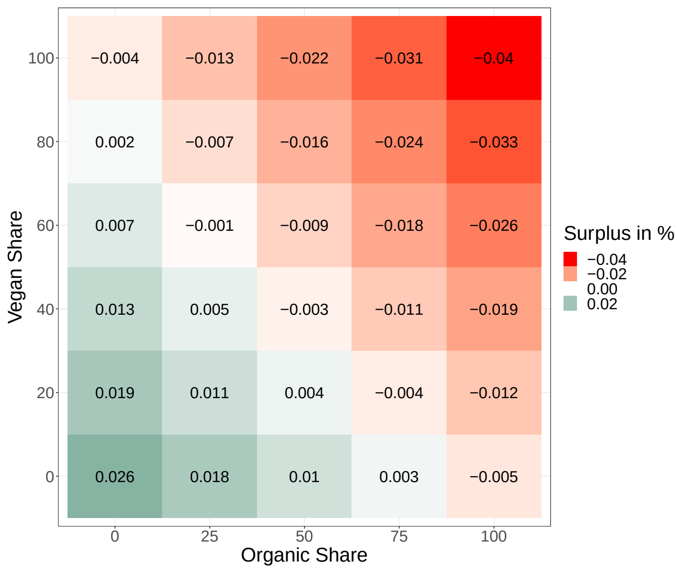


Figure 4.14: Global OECD nitrogen balance per hectare for varying organic and vegan shares.

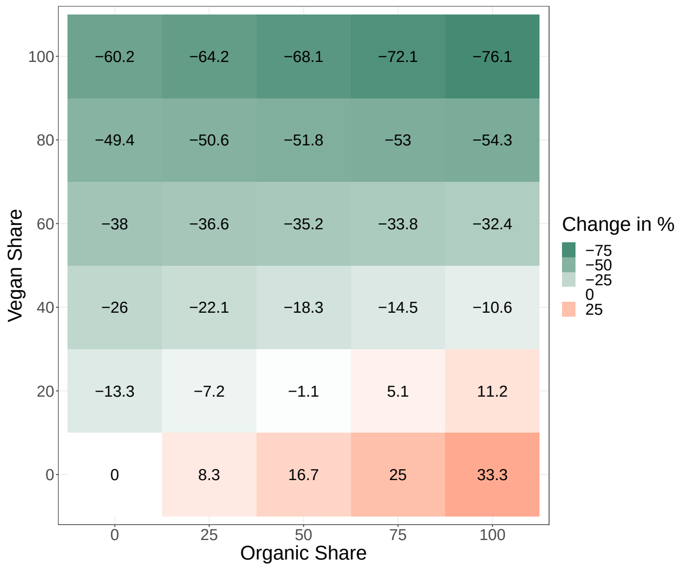


Figure 4.15: Change in GHG emissions relative to reference scenario 2050.

Chapter 5

Discussion

The aim of this thesis was to evolve the model structure of SOLm to facilitate the analysis of global environmental and nutritional impacts of fully or partly vegan food systems. In the scope of this thesis, the model was then applied to several potential manifestations of a vegan world with different production systems (organic or conventional), land utilization (full or reduced) and crop rotation patterns.

The results showed that the implementation of a 100 % vegan world would, on the one hand, generally lead to lower environmental impacts. On the other hand, nutritional deficiencies resulted in all of the vegan scenarios, but primarily the vegan-organic scenarios were of concern. However, the food availability in the baseline and the reference scenario 2050 were below the intake recommendations for some of the nutritional indicators, as well. Two of the vegan-conventional scenarios managed to produce sufficient amounts of calories, proteins and fat and were therefore classified as 'feasible' (see Table 5.1).

In the following, I will discuss the overall determined nutritional impacts of vegan food systems in section 5.1. In section 5.2 and section 5.3, a focus is placed on the performance of organic production systems and the healthiness of vegan food systems, respectively. section 5.4 addresses environmental sustainability of the determined feasible vegan food systems. Lastly, section 5.5 covers limitations of the approach, which was chosen for this thesis.

5.1 Is Vegan Agriculture a Feasible Option?

Some nutrient availabilities were found to be insufficient in most vegan *and* non-vegan reference scenarios: vitamin B12, vitamin D and calcium. Vitamin D and B12 seem to be the most challenging nutrients in a vegan world. However, supplementation is possible for both, e.g. through food fortification. The low supply of vitamin B12 and D in the vegan scenarios was unsurprising.

Vitamin D is mainly found in animal-based products, such as fish and eggs. A deficiency in vitamin D is associated with impaired bone mineralisation (EFSA 2019). Vitamin D is an exception among vitamins, as it can be synthesized in the skin in sunlight contact. It is not yet clear, how much of the actual requirements are covered by synthesized vitamin D, and how much has to be consumed by food (EFSA 2019). BLV (2017) state that only 10 % to 20 % of the required vitamin D are actually consumed with food. Therefore, it seems plausible that even the reference scenarios show availabilities far below the requirements.

Vitamin B12 is found in meat and dairy products. A deficiency is associated with anemia and neurological dysfunction (EFSA 2019). The supply by fermented food, such as tempeh, or algae remains controversial: so far, no reliable amounts could be detected in plant-based products (Craig

Table 5.1: Overview over nutritional performance of vegan scenarios 1-6. Vitamin B12 and D are not considered.

	V-Conv1	V-Conv2	V-Conv3	V-Org1	V-Org2	V-Org3
Main nutrients	-	feasible	feasible	-	-	-
Critical other nutrients	> 2	Calcium	Selenium	> 2	> 2	>2

et al. 2009). Therefore, for both vitamins (B12 and D), the American Dietetic Association recommends vegans the intake of fortified foods or supplements to meet their needs (Craig et al. 2009). In contrast, the low resulting vitamin B12 availability of $1.4\,\mu g\,d^{-1}$ capita^{-1} in the reference scenarios was surprising. However, globally, according to Stabler and Allen (2004), many populations ingest less than $1\,\mu g\,d^{-1}$ capita^{-1} of Vitamin B12. Thus, the result from the reference scenarios is below the intake recommendations of EFSA (2019) of $4\,\mu g\,d^{-1}$ capita^{-1}, but still plausible. According to EFSA (2019), a daily intake of $1.5\,\mu g\,d^{-1}$ capita^{-1} to $2\,\mu g\,d^{-1}$ capita^{-1} has been found to be the absolute minimum requirement for the maintenance of physiological functions, indicating that a part of the global population might suffer from vitamin B12-related conditions.

Calcium production was found to be critically low in most vegan scenarios (up to $-72.2\,\%$) and both non-vegan scenarios (both $\approx -52\,\%$). Insufficient calcium supply increases risk of osteoporosis and bone fracture (EFSA 2019). For the reference scenarios, the values are consistent with Arsenault et al. (2015), who had analyzed the current food availability in Senegal, Cameroon and Bangladesh and found calcium availability to be between $-69\,\%$ to $-55\,\%$ below the required supply. According to Kumssa et al. (2015), more than 1.1 billion people are at the risk of calcium deficiency. The global mean dietary supply of calcium was found to be $684 \pm 211\,mg\,d^{-1}$ capita^{-1}, which is below the intake recommendations of $950\,mg\,d^{-1}$ capita^{-1}. In our reference scenarios, the calculated calcium availability was $460\,mg\,d^{-1}$ capita^{-1}, therefore slightly below the uncertainty range.

The *vegan-conventional* scenario with optimized crop rotation achieved a considerable excess of calcium (65 %). This shows, which potential lies in the choice of a well-designed crop rotation. Although the optimized crop rotation in the conventional scenario seems extreme with its high share of vegetables (55 %) and oil crops (35 %) and only 10 % of cereals, it achieved all required nutrient amounts, except selenium ($-12.8\,\%$). A deficiency in selenium is associated with degenerative diseases, such as the Kashin-Beck disease (EFSA 2019). It remains open, what the resulting food basket would actually consist of, and if the food intake amount would be within a reasonable range for consumption.

The vegan-conventional scenario with the business-as-usual distribution of crops, also showed a high performance considering the nutritional quality: apart from the vitamins B12 and D, the supply covered all needs, except for calcium. This suggests that a conventional system on existing cropland areas could probably meet *all* nutritional demands by applying a weighted combination of the crop rotations BAU and *Optimized (Conv)*, as indicated in Equation 5.1, where w refers to a weighting factor and C to the respective crop rotation group.

$$share_C = w_{BAU} * share_{C,BAU} + w_{opt} * share_{C,opt} \tag{5.1}$$

The application of such a refined crop distribution could even lead to excess production which would allow a reduction in agricultural area. The results of the vegan-conventional scenario with reduced areas (Vegan-Conv1) showed that a reduction in land areas by approximately $-40\,\%$ *without* changing the distribution pattern, i.e. by applying the crop rotation design BAU, would barely cover the calorie demand, and lead to insufficient supply of nearly all other nutrients.

The results found for the Vegan-Conv2 scenario are consistent with Erb et al. (2016). They found that in scenarios with FAO-yields and 100 % vegan nutrition, cropland would not have to be expanded, i.e. the energy availability would be sufficiently high to feed the world. This matches with the results of this thesis, showing that a conversion into vegan diets without changing production patterns, would lead to an energy excess of 54 %. However, our results further showed that calcium supply might be short in such a scenario.

In summary, the results indicate that a vegan world with conventional agriculture could potentially cover all nutrient requirements – provided, that vitamin B12 and D are supplemented.

5.2 Is a Vegan-Organic World Feasible?

In contrast to conventional systems, the results showed that all of the implemented *vegan-organic* scenarios would not produce sufficient amounts of calories, proteins and fat, as well as other nutrient indicators. This is partly due to the lower yields in organic agriculture compared to conventional agriculture, but also a consequence of the required temporary grassland in organic crop rotations.

As described in subsection 2.1.2, grassland plays an important role in organic agriculture, contributing to an improvement of soil structure, suppression of plant diseases, an increase of humus content, weed suppression and N-accumulation in biomass. However, from a nutritional perspective, the area is *non-productive*, since it does not contribute directly to food production. The model results of the different crop rotation patterns showed the worst performance for the crop rotation pattern *Organic*, which is closest to the current crop rotation patterns in organic agriculture, since calorie, protein and fat requirements could not be reached.

The crop rotation design *Stockless* showed better results: the calorie supply was found to be sufficient. The protein supply is, however, only sufficient, if a positive N-balance is assumed (yield gap corrected). A sufficient fat supply was only achieved in the optimized crop rotation (which failed to meet the other nutritional requirements). The insufficient performance of the optimized crop rotation is partly surprising, since the optimization problem was designed to fulfill all nutritional requirements. However, the optimization problem was based on average yields of all countries for individual crops, and, furthermore, the average nutrient production per hectare per crop rotation group. This averaged values are very rough estimates, which do not meet the real conditions in individual countries. Thus, if these could be improved, better results might be achieved.

In summary, the results suggest that it would be challenging to have a fully vegan and organic world where all nutritional needs are met, if no further measures (such as food waste reduction) are applied and cropland is not extended. The comparison with corrected yield gaps shows that a reduction in N-deficiency and the related yield gap would not change the overall feasibility. One possibility to increase the nutritional performance of the vegan-organic food system would be to develop better crop rotation designs, e.g. by developing a refined optimization problem or by using existing real-word case studies of vegan-organic farms as templates.

The challenge of feeding the world with organic agriculture has also been discussed by Muller et al. (2017) and Barbieri et al. (2021). In the first study, SOLm was applied to analyze the feasibility of an organic world. They concluded that in a 100 % organic world, with a reduction in food waste and food-competing feed reduction of 0 % and 100 %, respectively, the required cropland area could be even reduced by 8 %. This scenario is not vegan, but reduced in animals (due to the *feed no food*-restriction). In contrast, the results of this thesis suggest that in a similar world (100 % organic, no food waste reduction, no food-competing feed stuffs and, additionally, no livestock), would lead to a nutritional gap with an energy deficiency of −13.8 %, therefore an increase in cropland area would be expected. Part of this discrepancy can be explained by the high shares of temporary grasslands, which were implemented in the organic scenarios of this thesis and by the calorie output of the still existing animal production system (fed with grasslands) in Muller et al. (2017).

The results of this thesis for vegan-organic farming systems, stand in contrast to the results of Erb et al. (2016). They found that it would be possible to convert to a vegan diet with organic agriculture without expanding current cropland areas. In contrast the results of this thesis suggest that energy production in an organic world with current production patterns (Vegan-Org1) would lead to an undersupply of calories of −13.8 %, assuming an average yield gap, or an undersupply of −5.8 %, assuming a reduced yield gap in the case of perfect N-availability. This discrepancy can be explained, again, by the existence of a considerable grassland share in organic crop rotations, which were considered in this thesis. This analysis showed, however, that even if energy requirements were met in a vegan-organic world, protein and especially fat supply, would still be challenging.

In contrast, the findings of this thesis are supported by Barbieri et al. (2021). Their model of the current food system suggest that a conversion to 100 % organic agriculture would decrease global food availability by −38 % in a scenario with an optimised livestock sector. In a scenario without livestock, food production would be even lower. They concluded that a shift to vegan diets is incompatible with organic agriculture. Their approach was to optimize production spatially explicit so that the calorie and protein supply are met. Since it is a more refined optimization approach than the one conducted in this thesis, this might indicate that no better crop rotation design exists which produces the necessary amounts of nutrients in a fully vegan and organic world.

The results of partly vegan and organic options showed that, considering only the nutritional requirements of calories, proteins and fat, the feasible options for vegan agriculture are restricted by the share of organic agriculture (Figure 5.1). Barbieri et al. (2021) stated that a maximum 60 % conversion to organic agriculture is possible. This result matches with the model results of this thesis, showing that a 50 % conversion to organic farming is still possible, however, a 75 % is not. The findings of this thesis suggest that a 60 % conversion to organic agriculture would require a conversion to vegan agriculture of maximum 40 % in order to meet the nutritional demands of calories, proteins and fat.

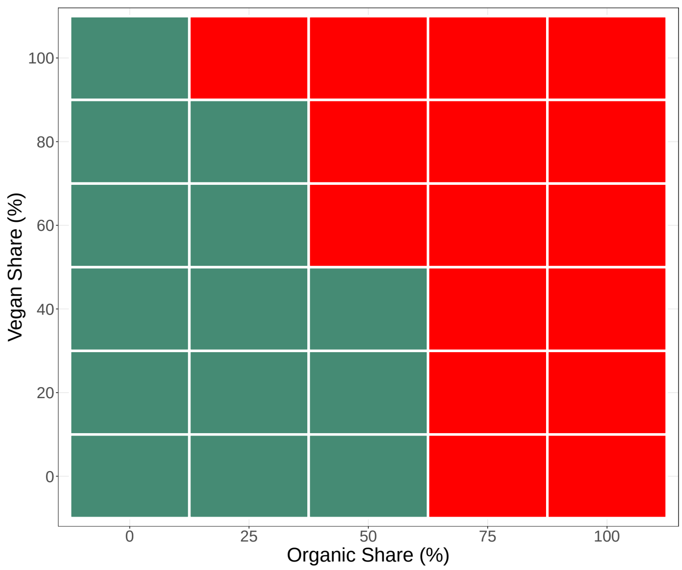


Figure 5.1: Potential options to fulfill calorie, protein and fat requirements. Green: feasible options. Red: unfeasible options.

The findings of this thesis support the assumption that ruminants play an important role in organic food systems, as was also concluded by Zanten et al. (2018) and White and Hall (2017) for two reasons: i) due to their ability to convert grassland into human-edible nutrients, especially in organic agriculture, where grassland in the crop rotation is indispensable, and ii) due to their capability for making nutrients available as fertilizer. The utilization of grassland as mobile manure with the selected treatments did not compensate for having ruminants in the system, since the N-balance decreased with increasing vegan share.

5.3 Is Vegan Agriculture a Healthy Option?

Although not all of the nutritional requirements were met in the vegan scenarios, the results of the assessment of the overall diet quality with the aggregate index AHEI-2010, indicate that the nutritional quality might be higher in vegan than in non-vegan scenarios. The global average AHEI-2010 score was 59.8 and 61.8 for the baseline and the reference scenario 2050, respectively. The results seem reasonable, although a bit higher than the scores reached in the assessment of Chiuve et al. (2012), where the average AHEI score was 47.6 ± 10.8 for women and 52.4 ± 11.5 for men.

The results showing better AHEI-2010 scores for the vegan than for non-vegan food systems are in line with Clarys et al. (2014), who found better scores for vegans with the Healthy Eating Index (HEI) and the Mediterranean Diet Score (MDS). However, it might be possible that in a vegan world, these indicators would evolve and explicitly include further factors and nutrients which are critical in vegan diets (e.g. vitamin B12).

It has to be noted, that for this calculation, it was assumed that the intake and the availability are congruent. The AHEI-2010 of the global food system is a rough approximation of the overall food quality and not directly related to the individuals diet. The comparison of nutrient availability in vegan food systems and actual nutrient intake in vegan diets shows similarities, but also differences: This thesis showed, for example, that critical nutrient availabilities in vegan-conventional food systems occur for vitamin B12, D, calcium and selenium. These nutrients are also those that were found to be below the intake recommendations in vegan diet assessments (Bakaloudi et al. 2020). In contrast, the results suggest that the availability of other critical nutrients in vegan diets (zinc, vitamin B2 and B3) is given in vegan food system.

5.4 Is Vegan Agriculture more Ecologically Sustainable?

The results showed that the analyzed vegan scenarios, in general, have a lower environmental burden related to GHG emissions, CED and irrigation water use than the non-vegan reference scenarios.

These results are consistent with those of other studies, who found that a shift to plant-based diets would reduce environmental impacts (Springmann et al. 2018; Poore and Nemecek 2018). However, since not all of the scenarios were found to be feasible from a nutritional perspective, the following part will discuss the environmental impact of the applicable scenarios with potential to feed the world.

The two potentially feasible scenarios of a 100 % vegan world (Vegan-Conv2 and Vegan-Conv3), show both considerable reductions in GHG emissions compared to the reference 2050. The modeled GHG emissions of the baseline scenario are 6.46 Gt CO_2ey^{-1}, therefore higher than values from Smith et al. (2014), who estimated that agriculture contributes to 5 - 5.8 Gt CO_2ey^{-1}. To remain within the 2 °C target of climate change, Wollenberg et al. (2016) estimated that a reduction to 4 - 4.8 Gt CO_2ey^{-1} would be needed. With both of the potentially feasible vegan-conventional scenarios, this goal would be reached. Further, it should be noted permanent grasslands remained unutilized in the vegan scenarios, therefore an additional reduction in GHG-emissions could be potentially achieved by carbon sequestration (reforestation).

If the system is converted to a 100 % vegan-conventional system and current production patterns remained, irrigation water use could be reduced by 5 %. This result is in line with Springmann et al. (2018), who found that dietary change towards a more plant-based diet would reduce the irrigation water use by 5 %. If the nutritionally optimized crop rotation pattern was adopted, however, irrigation water use would increase by 55.5 % compared to the reference 2050. This result demonstrates that effects of a food system conversion can be highly dependent on the actual implementation (crop choice). When a threshold for the planetary boundary is set, as proposed by Springmann et al. (2018), to a maximum of $3190\,\mathrm{km}^3\,\mathrm{a}^{-1}$, then the vegan-conventional scenario with optimized crop rotation exceeds the limit with a water-stress adjusted irrigation water use of $4380\,\mathrm{km}^3\,\mathrm{a}^{-1}$.

Table 5.2: Summary of the results for nutritional feasibility and environmental performance related to thresholds for planetary boundaries.

	V-Conv1	V-Conv2	V-Conv3	V-Org1	V-Org2	V-Org3
Main nutrients	-	feasible	feasible	-	-	-
Critical other nutrients	> 2	Calcium	Selenium	> 2	> 2	>2
Planetary boundary water		ok	nok			
Planetary boundary GHG		ok	ok			

Under current production patterns, a conversion into a 100 % vegan-organic world was found to be infeasible, since none of the main nutritional indicators was produced in sufficient amounts to cover the needs of humanity in 2050. If nutritional feasibility with respect to calories, proteins and fat *and* the planetary boundaries for water and GHG emissions are to be respected, then the results suggest that only three options remain: a conversion into a 80 % or 100 % vegan system with 0 % organic agriculture or a 80 % vegan system with 25 % organic agriculture (Figure 5.2). The results for organic agriculture imply that a high share is associated with high GHG emissions. It should be noted that these findings are based on the assumption, that a high share of organic agriculture needs large areas of grassland. In this model, the grassland output is fed to ruminants, if no further constraints (as in vegan systems) are set. Therefore, in the model calculations, the livestock numbers and related GHG emissions increase, when a high organic share meets a low vegan share. Especially in large countries with low livestock numbers in the reference, such as india, this leads to high increases in animal-related GHG emissions. Although it might be a logical consequence to use grassland as fodder (in a non-vegan world), this coupling might become false, if the animal product supply exceeds demand.

5.5 Limitations

The model utilized for this thesis is, as every model, based on a multitude of assumptions, which try to reflect reality as close as possible. It was out of the scope of this thesis to analyze the effects of all uncertainties of these assumptions in detail. An approach was made by looking at the concept of *vegan agriculture* from multiple viewpoints through different crop rotation designs. However, the crop rotation designs selected were – of course – not conclusive. Furthermore, they do barely take regional differences into account. To depict such, further data about national or regional crop rotation design in different production systems would be necessary. Better results for vegan-organic farming systems could potentially be achieved by applying the results of the county-based optimization problem (considering regional differences in yields). This thesis did also not consider the temporal aspects of crop rotations, i.e. interactions between crops in the succession and related effects on yields.

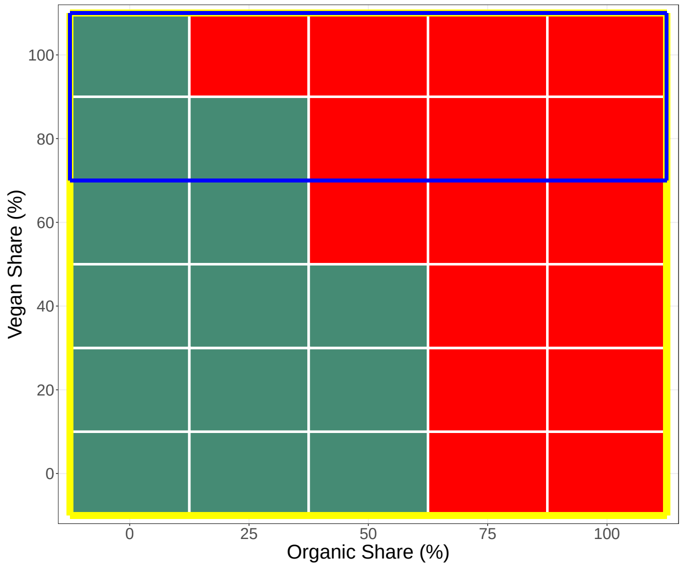


Figure 5.2: Potential options to fulfill calorie, protein and fat requirements. Green: feasible options. Red: unfeasible options. Yellow border: within planetary boundary water. Blue border: within planetary boundary GHG emissions.

It was out of the scope of this thesis to conduct an extensive sensitivity analysis related to the following uncertainties.

- **Nutritional data I**: missing data of nutrient contents was replaced by food group means. This approach does not take into account the high variability of nutrient contents within food groups and might be skewed by outliers. Other imputation approaches should be utilized and results compared systematically.
- **Nutritional data II**: the nutritional data of food items was are averaged over a range of matching food items in the SR28 database. This approach does not reflect the potential that would lie in the use of specific food varieties with different characteristics. Furthermore, nutrient losses through processing were only if food items are commonly eaten cooked.
- **Agronomic model assumption**: The shares of specific treatment options for grass and crop residues were assumed. Due to high variances in the N-losses of these options, changes in treatment option shares could lead to considerable changes in N-loss and -recovery. It is recommended to vary the treatment shares randomly (Monte-Carlo approach) to find ranges of uncertainty.

Further, the model is purely biophysical, based on mass- and nutrient flows and related emissions and input use. Changes in the system which arise through changes in demand are deliberately not predicted in any way. However, it must be considered, that such changes in demand are possible and could change the assumptions (e.g. deforestation pressure) and therefore the outcomes, e.g. GHG emissions.

Chapter 6

Conclusion and Outlook

In the following section 6.1, the main findings of this thesis are being summarised. In section 6.2, an outlook for future research is provided.

6.1 Conclusion

This thesis analyzed nutritional and environmental impacts of vegan agriculture by applying a biophysical model. The results substantiate the dilemma of producing sufficient food and reducing environmental impacts of the global food system at the same time. Vegan agriculture was found to show great potential to decrease the food system-related environmental impacts. However, nutritional impacts of most of the analyzed scenarios did not meet the nutritional requirements to feed the world. Only two of the fully vegan scenarios covered the necessary supply of calories, proteins and fat. It has to be noted that these two (conventional) scenarios are the scenarios showing generally the worst results for environmental indicators (although in many categories still better than the reference 2050). In the following, the main findings of this thesis are being summarised.

1) a 100% vegan world is feasible - but only with supplements

The findings suggest that a conversion to 100 % vegan agriculture might be feasible, but challenging, from a nutritional perspective. Just reducing the cropland area by the area utilized for feed in the reference scenario 2050 would result in a nutrient production which approximately covers calorie requirements, but falls short of proteins and fat. Two of the vegan-conventional scenarios produced sufficient amounts of calories, proteins and fat to meet the global demand in 2050 and can therefore be considered as feasible options for vegan agriculture. However, also in these scenarios, the vitamins B12 and D would have to be supplemented, as their intake values are far below the recommendations. Further, calcium was found to be critical in vegan and non-vegan systems. One of the feasible scenarios did produce sufficient amounts of calcium, however, fell short of selenium. The other feasible scenario was found to produce enough selenium, but not calcium. It can be assumed that a better crop rotation design can be found through a combination of the presented crop rotation designs which fulfills all macro- and micronutrient requirements. It has to be noted that the supply of vitamin B12, D and calcium was also below the threshold in the reference scenarios, indicating that supplementation might be necessary in our current food system, as well.

2) a 100% vegan world is feasible - but only in a conventional system

The situation was found to be more challenging for organic systems. None of the three 100 % organic scenarios produced calories, proteins and fat in sufficient amounts. Overall, the crop rotation design *Organic*, based on current organic production patterns, showed the lowest nutritional performance by not reaching any of the target amounts for calories, proteins and fat. The application of the crop rotation design *Stockless*, based on crop rotation designs of stockless farming systems, showed a better performance by supplying the necessary energy amounts and, furthermore, protein, if an optimal nitrogen supply was assumed. However, fat availability was still considerably below the requirements. In contrast, the *optimized* crop rotation design for organic agriculture resulted in an excess supply for fat, however, protein and calorie production was found to be insufficient in this scenario. Since the definition of the optimisation problem was made on a very aggregate level, a more refined approach could help to find a better crop rotation design for organic agriculture to cover the needed supply of macro- and micronutrients. The findings of this thesis suggest that, based on current crop rotation designs in organic agriculture, a conversion to a 100% vegan world is only possible in a conventional (non-organic world). With an organic share of 25% or 50%, a maximum transition of 80% or 40% to vegan agriculture would be possible to meet calorie, protein and fat requirements. The application of a reduced yield gap (assuming an optimal N-availability) improved yields and food production, however, did not change the overall picture. This also indicates that the potential arising through optimised treatment of grassland is limited.

Results indicate that a further limitation on the viability in a vegan-organic world arise through the limited N-supply. An increase in vegan and organic shares decreases the N-surplus and might lead to undersupply. In this thesis, the effect of such an undersupply on yields has not been modeled, but may aggravate nutrient shortage, additionally.

3) a 100% vegan world is feasible - but not necessarily within the planetary boundaries

The results suggest that through a vegan world, GHG-emissions could be reduced drastically and contribute to staying within the planetary boundaries. This was true for the organic and the conventional vegan scenarios. In contrast, considering the irrigation water use, only one of the feasible options (vegan-conventional with crop rotation *BAU*) was within the threshold of planetary boundary limits. The other feasible scenario (conventional, crop rotation *Optimized*) contains a high share of vegetables (55 %) and is associated with higher energy consumption, mineral N-fertilizer and irrigation water use than other scenarios. Irrigation water use of this scenario exceeded the planetary boundary threshold and can therefore not be considered as sustainable option.

4) Livestock plays a crucial role in organic farming systems

The results of this thesis showed that a complex pattern for the dynamics in vegan-organic food systems. One the one hand, the results indicate that vegan agriculture (or a reduction in animal numbers) could enhance the environmental performance of organic agriculture and the nutritional productivity related to calories. However, an increase in vegan agriculture reduced the nutritional performance of organic systems related to protein and fat production, due to necessary, but non-productive grassland areas in vegan systems. Further, an increase of vegan agriculture also has been found to affect nitrogen balance negatively, indicating that the chosen treatment options for grassland do not compensate for the nitrogen inputs through manure, which would arise in a non-vegan world. Since the viability of organic farming systems depends on a positive nitrogen balance, results suggest that vegan agriculture would have adverse effects on the productivity of these.

5) Three options to feed the world sustainably

The results suggest that, from a nutritional perspective, a conversion to more than 50% organic agriculture would not be compatible with a transition to vegan agriculture, assuming current production patterns and without additional measures. Up to a conversion of 50% to organic agriculture, many feasible options remain, to meet the global nutritional demand of calories, proteins and fat. The planetary boundaries for irrigation water use and GHG emissions could, however, only be respected in a scenario of an 80 % transition into vegan agriculture and an organic share of 25 %, or a 100 % transition into a vegan food system. However, then, as stated above, only with conventional agriculture.

6.2 Outlook

The results of this thesis suggest that a conversion to a vegan world might help to respect planetary boundaries and provide sufficient macro- and micronutrients, at the same time. However, it was found to be nearly incompatible with organic agriculture. These findings are based on assumptions about nutritional values, the utilization of temporary grasslands and crop rotations is organic agriculture. It was out of the scope of this thesis to analyze systematically all effects arising through uncertainties (e.g. in nutrient data), or, to explore the potential, which would arise through better management options (e.g. other crop rotation designs in organic agriculture). It was further neglected, that several other measures are available to reduce food system-related environmental impacts, such as the reduction of food waste and losses. Such accompanying measures could facilitate the implementation of fully or partly vegan-organic farming systems and decrease the environmental burden of the food system further. It could be part of a further study to explore the effects of all of these options and uncertainties in a more systematic manner.

Furthermore, this study did not include yield gap effects arising through limited nitrogen supply in organic systems. In future studies, this effect could be taken into account to gain a more refined insight into the dynamics and potential of vegan-organic agricultural systems.

Bibliography

Alexandratos, Nikos and Jelle Bruinsma (June 2012). *World agriculture towards 2030/2050: the 2012 revision.* 288998. Food and Agriculture Organization of the United Nations, Agricultural Development Economics Division (ESA). URL: https://ideas.repec.org/p/ags/faoaes/288998.html (visited on 07/07/2021).

Arsenault, Joanne E., Robert J. Hijmans, and Kenneth H. Brown (June 2015). "Improving nutrition security through agriculture: an analytical framework based on national food balance sheets to estimate nutritional adequacy of food supplies". In: *Food Security* 7.3, pp. 693–707. ISSN: 1876-4525. DOI: 10.1007/s12571-015-0452-y. URL: https://doi.org/10.1007/s12571-015-0452-y (visited on 08/22/2021).

Bakaloudi, Dimitra Rafailia et al. (Dec. 2020). "Intake and adequacy of the vegan diet. A systematic review of the evidence". In: *Clinical Nutrition.* ISSN: 0261-5614. DOI: 10.1016/j.clnu.2020.11.035. URL: https://www.sciencedirect.com/science/article/pii/S0261561420306567 (visited on 04/22/2021).

Barbieri, Pietro, Sylvain Pellerin, and Thomas Nesme (Dec. 2017). "Comparing crop rotations between organic and conventional farming". In: *Scientific Reports* 7.1, p. 13761. ISSN: 2045-2322. DOI: 10.1038/s41598-017-14271-6. URL: http://www.nature.com/articles/s41598-017-14271-6 (visited on 04/12/2021).

Barbieri, Pietro et al. (May 2019). "Changes in crop rotations would impact food production in an organically farmed world". In: *Nature Sustainability* 2.5, pp. 378–385. ISSN: 2398-9629. DOI: 10.1038/s41893-019-0259-5. URL: http://www.nature.com/articles/s41893-019-0259-5 (visited on 04/12/2021).

Barbieri, Pietro et al. (May 2021). "Global option space for organic agriculture is delimited by nitrogen availability". In: *Nature Food* 2.5, pp. 363–372. ISSN: 2662-1355. DOI: 10.1038/s43016-021-00276-y. URL: https://www.nature.com/articles/s43016-021-00276-y (visited on 08/12/2021).

Baroni, L. et al. (Feb. 2007). "Evaluating the environmental impact of various dietary patterns combined with different food production systems". In: *European Journal of Clinical Nutrition* 61.2, pp. 279–286. ISSN: 1476-5640. DOI: 10.1038/sj.ejcn.1602522. URL: https://www.nature.com/articles/1602522 (visited on 08/05/2021).

Benke, Anna Pia et al. (Apr. 2017). "Fertilizer value and nitrogen transfer efficiencies with clover-grass ley biomass based fertilizers". In: *Nutrient Cycling in Agroecosystems* 107.3, pp. 395–411. ISSN: 1385-1314, 1573-0867. DOI: 10.1007/s10705-017-9844-z. URL: http://link.springer.com/10.1007/s10705-017-9844-z (visited on 04/12/2021).

BLV (2017). *Fachinformation zu Vitamin D.* URL: https://www.blv.admin.ch/blv/de/home/lebensmittel-und-ernaehrung/ernaehrung/empfehlungen-informationen/naehrstoffe/hauptnaehrstoffe.html.

BNS (2017). *Biocyclic-vegan Standards - Version 1.02.* URL: http://www.biocyclic-vegan.org/documents/.

Böhler, Daniel et al. (2007). *Bodenschutz und Fruchtfolge.* URL: https://www.fibl.org/de/shop/1432-bodenschutz (visited on 08/22/2021).

Bonzheim, A. (2014). "Die bio-vegane Landwirtschaft in Deutschland: Definition, Motive und Beratungsbedarf". Bachelorarbeit. Eberswalde: Eberswalde: Hochschule für nachhaltige Entwicklung Eberswalde. URL: http://biovegan.org/wp-content/uploads/2014/02/Bonzheim_Bachelorarbeit_Bio-veganeLandwirtschaft.pdf.

Bullock, D. G. (Jan. 1992). "Crop rotation". In: *Critical Reviews in Plant Sciences* 11.4, pp. 309–326. ISSN: 0735-2689. DOI: 10.1080/07352689209382349. URL: https://doi.org/10.1080/07352689209382349 (visited on 08/22/2021).

Campbell, Bruce et al. (Oct. 2017). "Agriculture production as a major driver of the Earth system exceeding planetary boundaries". In: *Ecology and Society* 22.4. ISSN: 1708-3087. DOI: 10.5751/ES-09595-220408. URL: http://www.ecologyandsociety.org/vol22/iss4/art8/ (visited on 07/07/2021).

Chang, Winston and Barbara Borges Ribeiro (2018). *shinydashboard: Create Dashboards with 'Shiny'*. URL: https://CRAN.R-project.org/package=shinydashboard.

Chang, Winston et al. (2021). *shiny: Web Application Framework for R*. URL: https://CRAN.R-project.org/package=shiny.

Chiuve, Stephanie E. et al. (June 2012). "Alternative Dietary Indices Both Strongly Predict Risk of Chronic Disease123". In: *The Journal of Nutrition* 142.6, pp. 1009–1018. ISSN: 0022-3166. DOI: 10.3945/jn.111.157222. URL: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3738221/ (visited on 08/22/2021).

Clarys, Peter et al. (Mar. 2014). "Comparison of Nutritional Quality of the Vegan, Vegetarian, Semi-Vegetarian, Pesco-Vegetarian and Omnivorous Diet". In: *Nutrients* 6.3, pp. 1318–1332. DOI: 10.3390/nu6031318. URL: https://www.mdpi.com/2072-6643/6/3/1318 (visited on 04/22/2021).

Cohen, Tova (July 2015). "In the land of milk and honey, Israelis turn vegan". In: *Reuters*. Section: Lifestyle. URL: https://www.reuters.com/article/us-israel-food-vegan-idUSKCN0PV1H020150721 (visited on 07/14/2021).

Cordell, Dana and Stuart White (2014). "Life's Bottleneck: Sustaining the World's Phosphorus for a Food Secure Future \textbar Annual Review of Environment and Resources". In: *Annu. Rev. Environ. Resour* 39, pp. 161–188. URL: https://www.annualreviews.org/doi/10.1146/annurev-environ-010213-113300 (visited on 08/22/2021).

Craig, Winston J., Ann Reed Mangels, and American Dietetic Association (July 2009). "Position of the American Dietetic Association: vegetarian diets". In: *Journal of the American Dietetic Association* 109.7, pp. 1266–1282. ISSN: 1878-3570. DOI: 10.1016/j.jada.2009.05.027.

Cui, Zeng et al. (2019). "Potential of artificial grasslands in crop rotation for improving farmland soil quality". In: *Land Degradation & Development* 30.18, pp. 2187–2196. ISSN: 1099-145X. DOI: 10.1002/ldr.3415. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/ldr.3415 (visited on 08/22/2021).

Curl, Elroy A. (Oct. 1963). "Control of plant diseases by crop rotation". In: *The Botanical Review* 29.4, pp. 413–479. ISSN: 1874-9372. DOI: 10.1007/BF02860813. URL: https://doi.org/10.1007/BF02860813 (visited on 08/22/2021).

DeLuca, Kevin (2021). "Stickstoffverfügbarkeit in der biologischen Landwirtschaft". Master Thesis. Wädenswil: Zurich University of Applied Sciences (ZHAW).

Demeter (2021). *Anbau-Richtlinien - Zur Verwendung von Demeter, Biodynamisch und damit in Verbindung stehender Marken.*

Dewell, Antonella et al. (Feb. 2008). "A very-low-fat vegan diet increases intake of protective dietary factors and decreases intake of pathogenic dietary factors". In: *Journal of the American Dietetic Association* 108.2, pp. 347–356. ISSN: 0002-8223. DOI: 10.1016/j.jada.2007.10.044.

Dinu, Monica et al. (Nov. 2017). "Vegetarian, vegan diets and multiple health outcomes: A systematic review with meta-analysis of observational studies". In: *Critical Reviews in Food Science and Nutrition* 57.17, pp. 3640–3649. ISSN: 1040-8398. DOI: 10.1080/10408398.2016.1138447. URL: https://doi.org/10.1080/10408398.2016.1138447 (visited on 04/22/2021).

Dirkse, Steve, Michael Ferris, and Rishabh Jain (2020). *gdxrrw: An Interface Between 'GAMS' and R*. URL: http://www.gams.com.

Dyett, Patricia A. et al. (Aug. 2013). "Vegan lifestyle behaviors. An exploration of congruence with health-related beliefs and assessed health indices". In: *Appetite* 67, pp. 119–124. ISSN: 0195-6663.

DOI: 10.1016/j.appet.2013.03.015. URL: https://www.sciencedirect.com/science/article/pii/S0195666313001281 (visited on 04/23/2021).

EFSA (2019). *Dietary Reference Values for nutrients*. European Food Safety Authority (EFSA). URL: doi:%2010.2903/sp.efsa.2017.e15121.

Engelhardt, Helen, Mo Brüdern, and Ly Deppe (2020). *Niche innovations in Europe for the transformation of the food system - NEuropa - Collection of Profiles*. Ressortforschungsplan 120/2020. Dresden: German Environment Agency.

Erb, Karl-Heinz et al. (Apr. 2016). "Exploring the biophysical option space for feeding the world without deforestation". In: *Nature Communications* 7.1, p. 11382. ISSN: 2041-1723. DOI: 10.1038/ncomms11382. URL: https://www.nature.com/articles/ncomms11382 (visited on 08/12/2021).

FAO (2011). *Dietary protein quality evaluation in human nutrition*. Report of an FAO Expert Consultation 92. Rome: Food and Agriculture Organization.

FAOSTAT (2021a). *Statistical database*. URL: http://www.fao.org/faostat/en/#home.

— (2021b). *Supply Utilization Accounts*. URL: http://www.fao.org/faostat/en/#data/SCL.

FiBL (2021). "Organic farming. Basic principles and good practices". In: Dossier 2021 (No. 1141), p. 48.

GAMS (2021). *GAMS Distribution 34.2.0*. Place: Frechen.

Garnett, Tara (Jan. 2011). "Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)?" In: *Food Policy*. The challenge of global food sustainability 36, S23–S32. ISSN: 0306-9192. DOI: 10.1016/j.foodpol.2010.10.010. URL: https://www.sciencedirect.com/science/article/pii/S0306919210001132 (visited on 08/12/2021).

Hallström, E., A. Carlsson-Kanyama, and P. Börjesson (Mar. 2015). "Environmental impact of dietary change: a systematic review". In: *Journal of Cleaner Production* 91, pp. 1–11. ISSN: 0959-6526. DOI: 10.1016/j.jclepro.2014.12.008. URL: https://www.sciencedirect.com/science/article/pii/S0959652614012931 (visited on 08/19/2021).

IAASTD (2009). "Agriculture at a Crossroads - International Assessment of Agricultural Knowledge, Science and Technology for Development - Global Report". In: Place: Washington, D.C. Publisher: Island Press.

IFOAM (2021). *IFOAM Family of Standards \textbar IFOAM*. URL: https://ifoam.bio/our-work/how/standards-certification/organic-guarantee-system/ifoam-family-standards (visited on 04/21/2021).

Iguacel, Isabel et al. (Apr. 2021). "Vegetarianism and veganism compared with mental health and cognitive outcomes: a systematic review and meta-analysis". In: *Nutrition Reviews* 79.4, pp. 361–381. ISSN: 0029-6643. DOI: 10.1093/nutrit/nuaa030. URL: https://doi.org/10.1093/nutrit/nuaa030 (visited on 04/23/2021).

Jäger, Mareike (2013). *Merkblatt - Nährstoffversorgung im Bioackerbau*. URL: https://www.agridea.ch/old/de/publikationen/publikationen/pflanzenbau-umwelt-natur-landschaft/biologische-landwirtschaft/naehrstoffversorgung-im-bio-ackerbau/.

Janssen, Meike et al. (Oct. 2016). "Motives of consumers following a vegan diet and their attitudes towards animal agriculture". In: *Appetite* 105, pp. 643–651. ISSN: 0195-6663. DOI: 10.1016/j.appet.2016.06.039. URL: https://www.sciencedirect.com/science/article/pii/S0195666316302677 (visited on 04/23/2021).

Kearney, John (Sept. 2010). "Food consumption trends and drivers". In: *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 365.1554, pp. 2793–2807. ISSN: 1471-2970. DOI: 10.1098/rstb.2010.0149.

Kerschke-Risch, Pamela (June 2015). "Vegan diet: motives, approach and duration. Initial results of a quantitative sociological study. Ernaehrungs Umschau 62(6): 98–103. DOI: 10.4455/eu.2015.016". In: *Ernährungs Umschau* 62, pp. 98–103.

Kumssa, Diriba B. et al. (June 2015). "Dietary calcium and zinc deficiency risks are decreasing but remain prevalent". In: *Scientific Reports* 5.1, p. 10974. ISSN: 2045-2322. DOI: 10.1038/srep10974. URL: https://www.nature.com/articles/srep10974/briefing/signup/ (visited on 08/25/2021).

Li, Duo (Feb. 2011). “Chemistry behind Vegetarianism”. In: *Journal of Agricultural and Food Chemistry* 59.3, pp. 777–784. ISSN: 1520-5118. DOI: 10.1021/jf103846u.

Maas, Henrik et al. (2017). “Alternativen der Kleegrasnutzung in vieharmen und viehlosen Betrieben - Alternatives of clover-grass untilization in stockless organic farms”. In: *Beiträge zur 14. Wissenschaftstagung ökologischer Landbau. ökologischen Landbau weiterdenken - Verantwortung übernehmen - Vertrauen stärken.* Weihenstephan.

Mäder, Paul et al. (May 2002). “Soil fertility and biodiversity in organic farming”. In: *Science (New York, N.Y.)* 296.5573, pp. 1694–1697. ISSN: 1095-9203. DOI: 10.1126/science.1071148.

Maheshwari, Dinesh K. (2014). *Composting for Sustainable Agriculture.* Sustainable Development and Biodiversity. Springer International Publishing. ISBN: 978-3-319-08003-1. DOI: 10.1007/978-3-319-08004-8. URL: https://www.springer.com/gp/book/9783319080031 (visited on 08/23/2021).

Menzel, Juliane et al. (Feb. 2021). “Vegan Diet and Bone Health—Results from the Cross-Sectional RBVD Study”. In: *Nutrients* 13.2, p. 685. ISSN: 2072-6643. DOI: 10.3390/nu13020685. URL: https://www.mdpi.com/2072-6643/13/2/685 (visited on 04/22/2021).

Muller, Adrian et al. (Nov. 2017). “Strategies for feeding the world more sustainably with organic agriculture”. In: *Nature Communications* 8.1, p. 1290. ISSN: 2041-1723. DOI: 10.1038/s41467-017-01410-w. URL: https://www.nature.com/articles/s41467-017-01410-w (visited on 08/22/2021).

Müller, Adrian et al. (2020). *SOLm Model Documentation.* Bericht. Research Institute of Organic Agriculture FiBL, CH-Frick. URL: https://orgprints.org/id/eprint/38778/ (visited on 08/11/2021).

Notarnicola, Bruno et al. (Jan. 2017). “Environmental impacts of food consumption in Europe”. In: *Journal of Cleaner Production.* Towards eco-efficient agriculture and food systems: selected papers addressing the global challenges for food systems, including those presented at the Conference “LCA for Feeding the planet and energy for life” (6-8 October 2015, Stresa & Milan Expo, Italy) 140, pp. 753–765. ISSN: 0959-6526. DOI: 10.1016/j.jclepro.2016.06.080. URL: https://www.sciencedirect.com/science/article/pii/S0959652616307570 (visited on 08/12/2021).

Petti, Alessandra et al. (2017). “Vegetarianism and veganism: not only benefits but also gaps. A review”. In: *Progress in Nutrition* 19.3, pp. 229–242. DOI: DOI:10.23751/pn.v19i3.5229.

Poore, J. and T. Nemecek (June 2018). “Reducing food’s environmental impacts through producers and consumers”. In: *Science* 360.6392, pp. 987–992. ISSN: 0036-8075, 1095-9203. DOI: 10.1126/science.aaq0216. URL: https://science.sciencemag.org/content/360/6392/987 (visited on 08/05/2021).

R Core Team (2020). *R: A Language and Environment for Statistical Computing.* Vienna, Austria: R Foundation for Statistical Computing. URL: https://www.R-project.org/.

Reganold, John P. and Jonathan M. Wachter (Feb. 2016). “Organic agriculture in the twenty-first century”. In: *Nature Plants* 2, p. 15221. ISSN: 2055-0278. DOI: 10.1038/nplants.2015.221.

Richter, Margrit et al. (2016). “Vegan Diet - Position of the German Nutrition Society (DGE)”. In: *Ernährungs Umschau International* 63.4, pp. 92–102. DOI: DOI:10.4455/eu.2015.

Robertson, G. Philip and Peter M. Vitousek (Nov. 2009). “Nitrogen in Agriculture: Balancing the Cost of an Essential Resource”. In: *Annual Review of Environment and Resources* 34.1, pp. 97–125. ISSN: 1543-5938. DOI: 10.1146/annurev.environ.032108.105046. URL: https://www.annualreviews.org/doi/10.1146/annurev.environ.032108.105046 (visited on 08/22/2021).

Robinson, S. (2015). *The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model description for version 3.* URL: https://www.ifpri.org/publication/international-model-policy-analysis-agricultural-commodities-and-trade-impact-model-0 (visited on 08/12/2021).

Schader, Christian, Matthias Stolze, and Urs Niggli (2015a). “How the organic food system contributes to sustainability”. In: *Assessing sustainable diets within the sustainability of food systems. Proceedings of an International Workshop, 15–16 September 2014, CREA, Rome, Italy.* Ed. by Alexandre Meybeck et al. Food and Agriculture Organization of the United Nations

(FAO), pp. 27–36. ISBN: 978-92-5-108825-8. URL: https://orgprints.org/id/eprint/30481/ (visited on 08/11/2021).

Schader, Christian et al. (Dec. 2015b). “Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability”. In: *Journal of The Royal Society Interface* 12.113, p. 20150891. DOI: 10.1098/rsif.2015.0891. URL: https://royalsocietypublishing.org/doi/10.1098/rsif.2015.0891 (visited on 08/12/2021).

Schmidt, H. (2003). *Viehloser Ackerbau im ökologischen Landbau - Evaluierung des derzeitigen Erkenntnisstandes anhand von Betriebssbeispielen und Expertenbefragungen.* Schlussbericht Forschungsprojekt Nr.: 02OE458. Giessen: Justus-Liebig-Universität Giessen Institut für Pflanzenbau und Pflanzenzüchtung II, p. 211.

Schmidt, H. et al. (Jan. 1999). “Legume Breaks in Stockless Organic Farming Rotations: Nitrogen Accumulation and Influence on the Following Crops”. In: *Biological Agriculture & Horticulture* 17.2, pp. 159–170. ISSN: 0144-8765, 2165-0616. DOI: 10.1080/01448765.1999.9754835. URL: http://www.tandfonline.com/doi/abs/10.1080/01448765.1999.9754835 (visited on 04/12/2021).

Schmidt, Harald (1997). “Viehlose Fruchtfolge im Ökologischen Landbau”. Dissertation. Kassel: Universität Kassel.

Schmutz, U. and L. Foresi (2017). “Vegan organic horticulture: Standards, challenges, socio-economics and impact on global food security”. In: DOI: 10.17660/ACTAHORTIC.2017.1164.62.

Seufert, Verena, Navin Ramankutty, and Jonathan A. Foley (May 2012). “Comparing the yields of organic and conventional agriculture”. In: *Nature* 485.7397, pp. 229–232. ISSN: 1476-4687. DOI: 10.1038/nature11069. URL: https://www.nature.com/articles/nature11069 (visited on 08/22/2021).

Seymour, Mona (2019). Publication Title: Map of North American Veganic Farms. URL: https://arcg.is/1uOyPD (visited on 04/21/2021).

Seymour, Mona and Alisha Utter (June 2021). “Veganic farming in the United States: farmer perceptions, motivations, and experiences”. In: *Agriculture and human values*, pp. 1–21. ISSN: 1572-8366. DOI: 10.1007/s10460-021-10225-x. URL: https://europepmc.org/articles/PMC8184056 (visited on 08/22/2021).

Smith, P. et al. (Nov. 2014). “Chapter 11 - Agriculture, forestry and other land use (AFOLU)”. In: *Climate Change 2014: Mitigation of Climate Change. IPCC Working Group III Contribution to AR5.* Cambridge University Press. URL: http://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_chapter11.pdf (visited on 04/20/2021).

Springmann, Marco et al. (Oct. 2018). “Options for keeping the food system within environmental limits”. In: *Nature* 562.7728, pp. 519–525. ISSN: 1476-4687. DOI: 10.1038/s41586-018-0594-0. URL: https://www.nature.com/articles/s41586-018-0594-0%C2%A0 (visited on 08/12/2021).

Stabler, Sally P. and Robert H. Allen (2004). “Vitamin B12 deficiency as a worldwide problem”. In: *Annual Review of Nutrition* 24, pp. 299–326. ISSN: 0199-9885. DOI: 10.1146/annurev.nutr.24.012003.132440.

Stadlmayr, Barbara, Ramani Wijesinha-Bettoni, and David Haytowitz (2012). *Guidelines for Food Matching.*

Stehfest, Elke et al. (July 2009). “Climate benefits of changing diet”. In: *Climatic Change* 95.1, pp. 83–102. ISSN: 1573-1480. DOI: 10.1007/s10584-008-9534-6. URL: https://doi.org/10.1007/s10584-008-9534-6 (visited on 08/22/2021).

Swissveg (2020). *Umfrage zu den Vegetariern und Veganern in der Schweiz \textbar Swissveg.* URL: https://www.swissveg.ch/veg-umfrage?language=de#1 (visited on 07/14/2021).

Tuomisto, H. L. et al. (Dec. 2012). “Does organic farming reduce environmental impacts? – A meta-analysis of European research”. In: *Journal of Environmental Management* 112, pp. 309–320. ISSN: 0301-4797. DOI: 10.1016/j.jenvman.2012.08.018. URL: https://www.sciencedirect.com/science/article/pii/S0301479712004264 (visited on 08/22/2021).

USDA (2015). *Composition of Foods Raw, Processed, Prepared - USDA National Nutrient Database for Standard Reference, Release 28 (2015). Documentation and User Guide.* Beltsville: Agricultural Research Service, Nutrient Data Laboratory.

USDA (2016). *Nutrient Data Laboratory. USDA National Nutrient Database for Standard Reference, Release 28 (Slightly revised). Version Current: May 2016.* URL: http://www.ars.usda.gov/nea/bhnrc/mafcl.

— (2021). *Nutrient Data Laboratory. USDA National Nutrient Database. Full Download . Version Current: April 2021.* URL: https://fdc.nal.usda.gov/download-datasets.html.

vegan-farming.org (2021). *Vegan-Farming in Europe.* URL: http://www.vegan-farming.org/ (visited on 04/21/2021).

Vermeulen, Sonja J., Bruce M. Campbell, and John S.I. Ingram (Oct. 2012). "Climate Change and Food Systems". In: *Annual Review of Environment and Resources* 37.1, pp. 195–222. ISSN: 1543-5938. DOI: 10.1146/annurev-environ-020411-130608. URL: https://www.annualreviews.org/doi/10.1146/annurev-environ-020411-130608 (visited on 04/20/2021).

Visak, T. (2007). "Vegan agriculture: Animal-friendly and sustainable." In: *Sustainable food production and ethics. Zollitsch W, Winckler C, Waiblinger S, Haslberger A, editors.* Wageningen: Wageningen Academic Publishers, pp. 193–197.

White, Robin R. and Mary Beth Hall (Nov. 2017). "Nutritional and greenhouse gas impacts of removing animals from US agriculture". In: *Proceedings of the National Academy of Sciences* 114.48, E10301–E10308. ISSN: 0027-8424, 1091-6490. DOI: 10.1073/pnas.1707322114. URL: https://www.pnas.org/content/114/48/E10301 (visited on 08/26/2021).

Wickham, Hadley (2016). *ggplot2: Elegant Graphics for Data Analysis.* Springer-Verlag New York. ISBN: 978-3-319-24277-4. URL: https://ggplot2.tidyverse.org.

Wickham, Hadley et al. (2018). *dplyr: A Grammar of Data Manipulation.* URL: https://CRAN.R-project.org/package=dplyr.

Wickham, Hadley et al. (2019). "Welcome to the tidyverse". In: *Journal of Open Source Software* 4.43, p. 1686. DOI: 10.21105/joss.01686.

Wollenberg, Eva et al. (2016). "Reducing emissions from agriculture to meet the 2 °C target". In: *Global Change Biology* 22.12, pp. 3859–3864. ISSN: 1365-2486. DOI: 10.1111/gcb.13340. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.13340 (visited on 08/26/2021).

Zanten, Hannah H. E. Van et al. (2018). "Defining a land boundary for sustainable livestock consumption". In: *Global Change Biology* 24.9, pp. 4185–4194. ISSN: 1365-2486. DOI: 10.1111/gcb.14321. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.14321 (visited on 08/26/2021).

Zumwald, Joséphine Marie (Apr. 2017). "What are the Challenges of a Sustainable Agriculture and a Healthy Nutrition without Livestock? - Paving the way for Modelling a Vegan World". Masterarbeit. Zurich: ETH Zürich.

List of Figures

List of Tables

Appendix Content

Appendix A

Overview Codes

The codes developed for this thesis can be found under the following link:

`https://github.com/KrayerPatricia/masterthesis`.

Data files will be provided on request (patricia.krayer@gmail.com).

I) Data Preparation (nutritional data)

`1_load_210427.R`: load data from SR28 database
`1_1_HandleMissingData_210528_final.R`: apply imputation method to handle missing values
`2_sharesPerCountry_210427.R`: determine weights for aggregated food groups
`3_calculate_nutrient_contents_210428.R`: calculate individual and aggregated nutrient contents

II) SOLm: utilized version with adapted and the new modules

`xx_ahei_2010.gms`: calculate ahei-2010
`xx_includeNutrients.gms`: import nutrient contents
`xx_optimization_V3_country_210623.gms`: optimization problem, country-based (results not utilized for the analysis in this thesis).
`xx_optimization_V4_includeN_210623.gms`: optimization problem (organic agriculture), globally aggregated. For conventional agriculture, turn off agronomic constraints.

III) Data visualization: R Shiny app

`gdxToXls.gms`: GAMS-file to convert gdx into csv or gdx files.
`dashboard_final.R`: visualization of results, imported in csv format.

Appendix B

Further Results

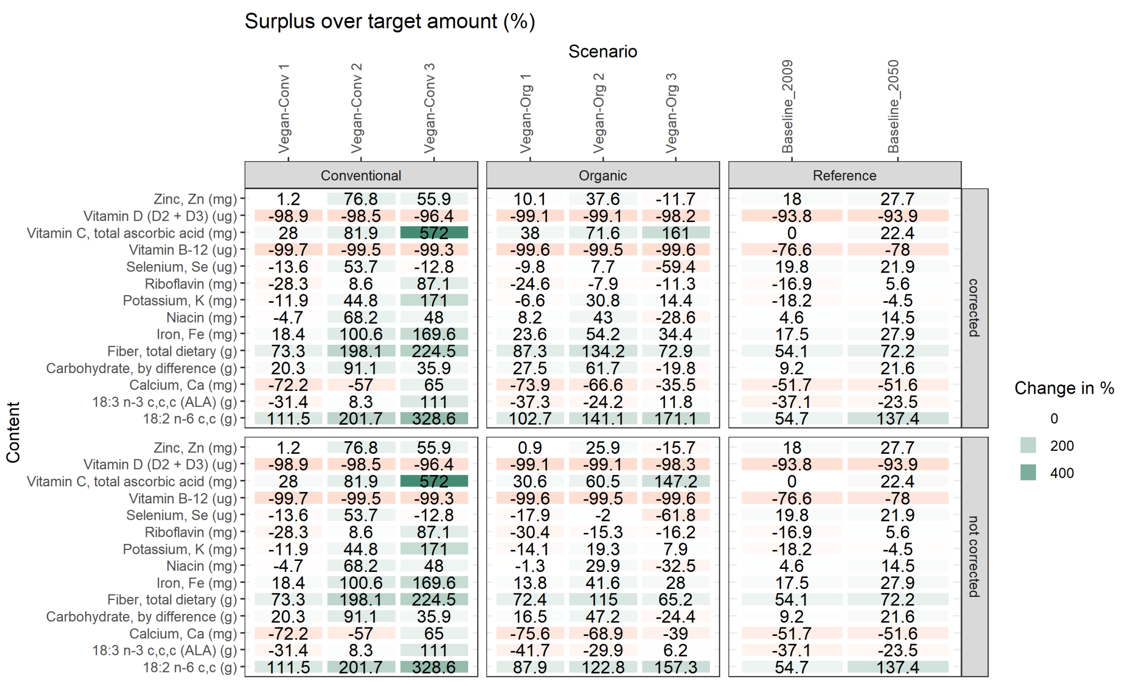


Figure B.1: Macro- and micronutrients surplus related to threshold values. "Corrected" refers to N-based yield gap correction.

Scenario

Indicator	Conventional: Vegan−Conv 1	Conventional: Vegan−Conv 2	Conventional: Vegan−Conv 3	Organic: Vegan−Org 1	Organic: Vegan−Org 2	Organic: Vegan−Org 3	Reference: Baseline_2009	Reference: Baseline_2050
Total GHG emissions − animals (t CO2e)							−32.7	0
Total cropland + grassland (ha)	−77.6	−66.4	−66.7	−66.5	−66.4	−66.6	−4.7	0
Total CED (MJ)	−32	−15.4	−3.8	−26.7	−24.8	−25.3	−7.2	0
Tot GHG em − crops/grass, with Defor/OrgSoils (t CO2e)	−20.4	0.5	22.3	−39.6	−39	−38.8	−19.4	0
Tot GHG em − crops/grass, no Defor/OrgSoils (t CO2e)	−26.6	−1.3	40.9	−68.3	−71.7	−70	−26	0
Tot GHG em − all act, with Defor/OrgSoils (t CO2e)	−68.6	−60.3	−51.7	−76.2	−75.9	−75.9	−27.4	0
Tot GHG em − all act, no Defor/OrgSoils (t CO2e)	−81.3	−74.8	−64.1	−91.9	−92.8	−92.4	−31	0
Soil water erosion (t soil lost)	−29.6	1.7	37.4	−24.3	−11.1	−7.1	−18.5	0
Self sufficiency proteins (share)	59.7	44.2	52.6	57.4	51.4	53	20.4	0
Self sufficiency calories (share)	28.5	24.9	21.9	26.8	27.9	19.5	18.4	0
Protein per capita (g/cap/day): total	−46.7	−14.3	−21.8	−52.3	−39	−50	−16.1	0
Protein per capita (g/cap/day): crop based	0	60.8	46.7	−10.5	14.5	−6.1	−7.7	0
Protein per capita (g/cap/day): animal based							17.3	0
Producer value − total ($)	−49.2	−24.1	92.4	−43.8	−44.2	−30.8	−35.4	0
Producer value − crops ($)	−23.9	13.7	188.1	−15.9	−16.4	3.7	−35.3	0
Producer value − animals ($)							−35.7	0
Pigs (heads)							−20.9	0
OECD N balance: outputs (tN)	−14.8	−3.4	14.4	−13.1	−13.5	−6.4	−13.5	0
OECD N balance: inputs (tN)	−83	−58.3	−66.1	−66.2	−71.3	−72.2	−78.5	0
OECD N balance: Inputs − outputs (tN)	−112.3	−81.9	−100.6	−89	−96.2	−100.5	−106.4	0
OECD N balance per ha (tN/ha)	−113.9	−81.8	−100.6	−88.9	−96.2	−100.5	−106.7	0
NH3 emissions − total (tNH3)	−87	−80.4	−69.8	−96.1	−97.2	−96.8	−29.3	0
NH3 emissions − areas (tNH3)	−45	−17.3	27.5	−83.7	−88.1	−86.3	−31.9	0
NH3 emissions − animals (tNH3)							−28.5	0
N inputs from seeds (tN)	−44.8	−18.1	−90.8	−31.5	−11.8	27.3	−15.2	0
N in manure (tN)							−29.2	0
N in crop res (tN)	−71.1	−58.3	−44	943	634.4	748.5	−33.7	0
N fixation (tN)	−33.8	−24.9	−45.2	−20	−20.8	15.1	−17	0
N deposition (tN)	−93	−64.8	−81.8	−64.2	−70.4	−75.3	−97.9	0
mineral N fert (tN)	−28.1	8.2	67.2				−33.7	0
Labour use − total, crops (h)	−19.8	36	204.5	60.5	45.5	130.4	−9.5	0
Labour use − total, animals (h)							7.7	0
Labour use − total (h)	−32.6	14.2	155.8	34.8	22.2	93.5	−6.8	0
Labour productivity − total ($/hour)	−24.5	−33.5	−24.8	−58.3	−54.3	−64.2	−30.7	0
Labour productivity − crops ($/hour)	−5.1	−16.4	−5.4	−47.6	−42.5	−55	−28.4	0
Labour productivity − animals ($/hour)							−40.3	0
Irrigation water (m3) − water stress adjusted	−26.1	−5	55.5	−27.8	−20.8	−5.3	−31	0
Irrigation water (m3)	−27.6	0.8	57.3	−28.9	−22	−2.3	−34	0
Grassland: total (ha)	−2.5	−2.5	−2.5	10.4	4.5	6	0	0
Grassland: temporary (ha)				410.2	178.7	237.4	0	0
Grassland: permanent (ha)	0	0	0	0	0	0	0	0
GHG emissions − animals, manure management (t CO2e)							−34.3	0
GHG emissions − animals, enteric ferment. (t CO2e)							−32.4	0
Cropland: temporary (without temp. grassland) (ha)	−35.1	6.3	4.9	−26.4	−11.4	−15.7	−15.5	0
Cropland: temporary (incl. temp. grassland) (ha)	−39	0	−1.3	−0.6	−0.2	−0.7	−14.5	0
Cropland: permanent (ha)	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−10.6	0
Chickens (heads)							−42	0
Cattle (heads)							−32.5	0
Calories per capita (kcal/cap/day): total	−29.9	8.8	−24.2	−39.1	−24.1	−53.1	−15.5	0
Calories per capita (kcal/cap/day): crop based	0	55.2	8.1	−13.1	8.3	−33.1	−2.7	0
Calories per capita (kcal/cap/day): animal based							16.3	0
Animal welfare: heat stress index 2050							−12.5	0
Animal welfare: antibiotics use index							−9.7	0
All Legumes (Nfixing) − incl. SetAside (no temp. grass)	−51.7	−24.4		−28.8	−19	106.6	−12.5	0
Aggreg. Pest. use level (index)	−31.5	2.8	2.2	−24.6	−10	−14.8	−14.8	0

Change in % 0 250 500 750

Figure B.2: Changes in all environmental and socio-economic indicators relative to reference 2050, average yield gap assumed.

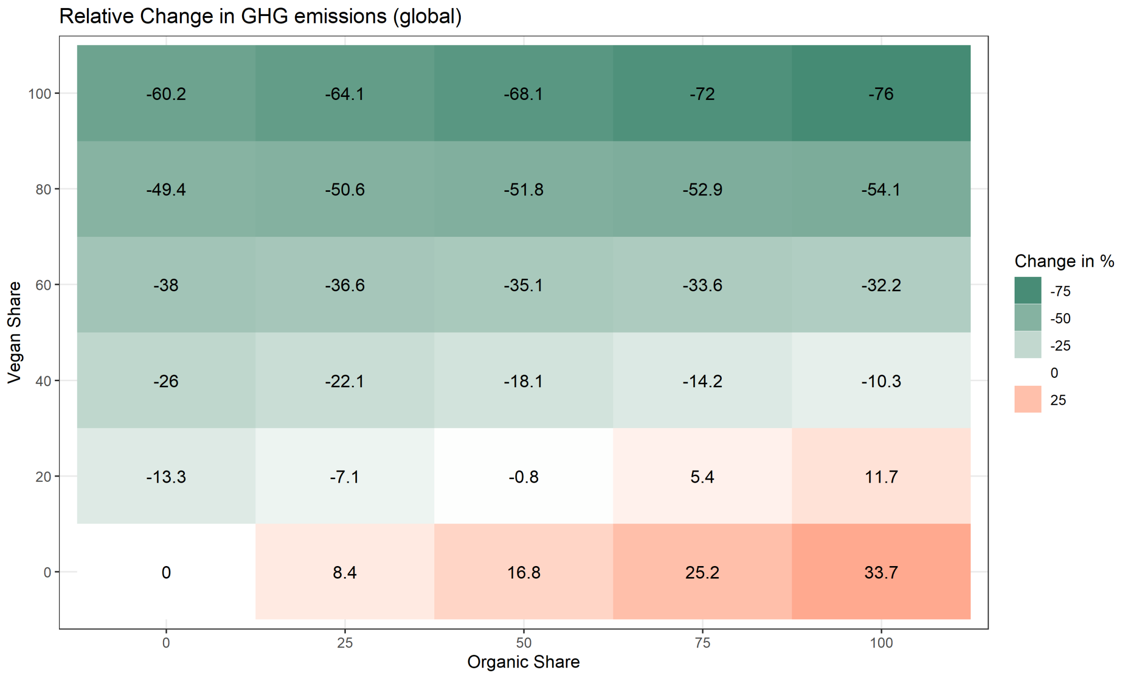


Figure B.3: Changes in GHG emissions, yield gap corrected.

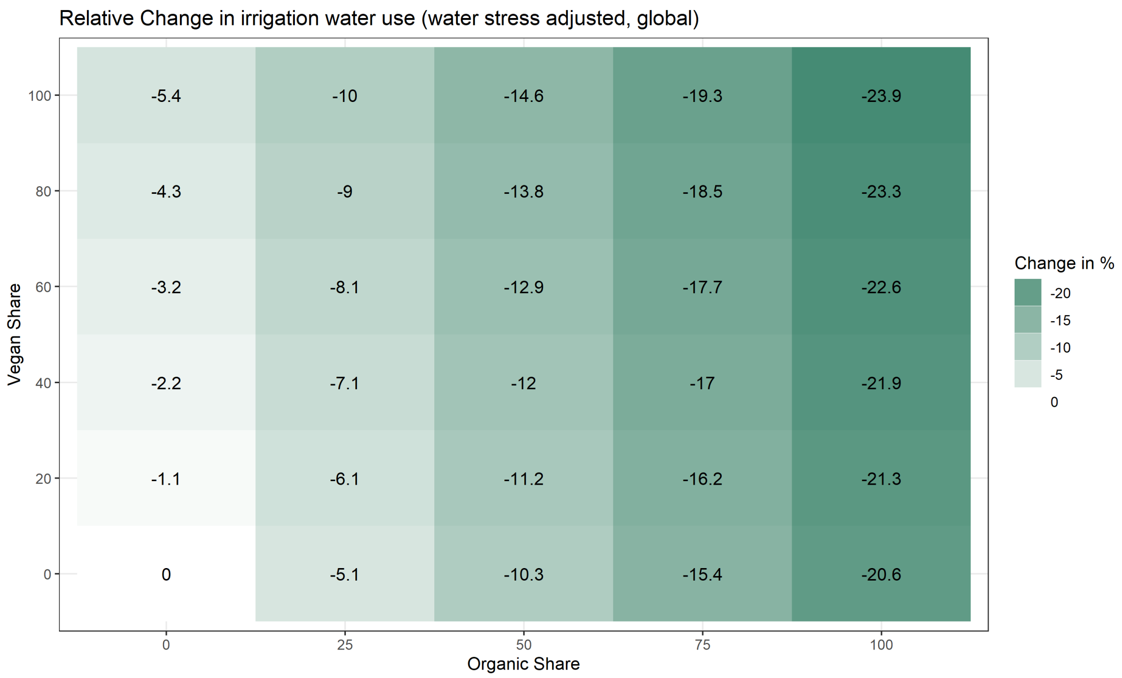


Figure B.4: Changes in water use (water stress adjusted), yield gap corrected.

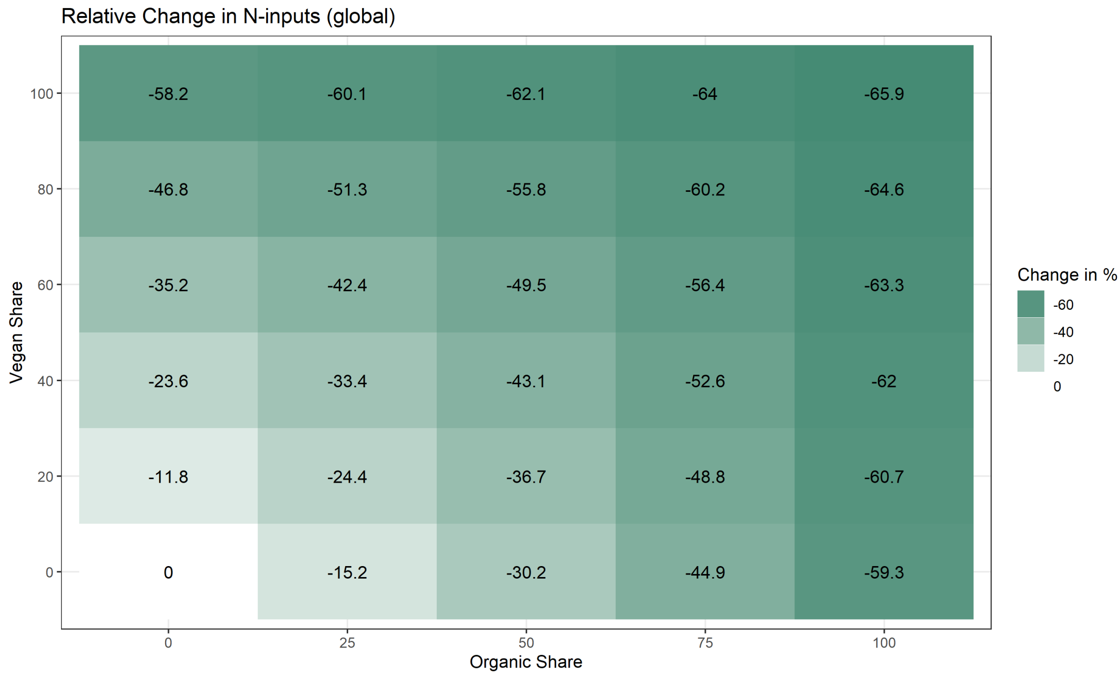


Figure B.5: Changes in N-input, yield gap corrected.

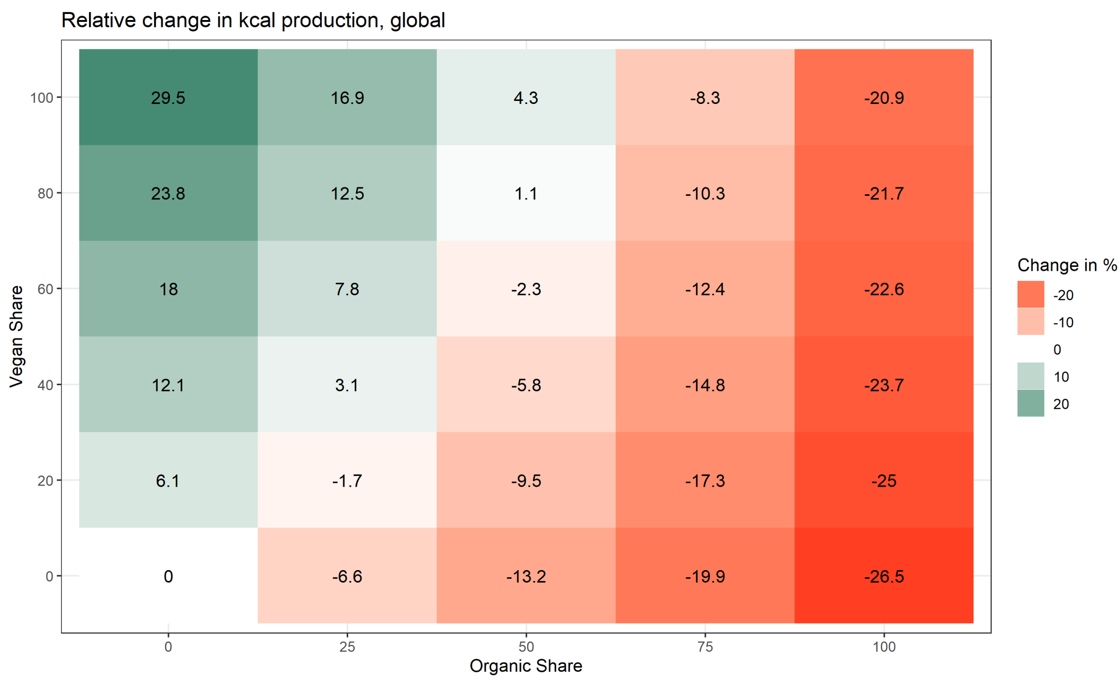


Figure B.6: Changein kcal production, yield gap corrected.

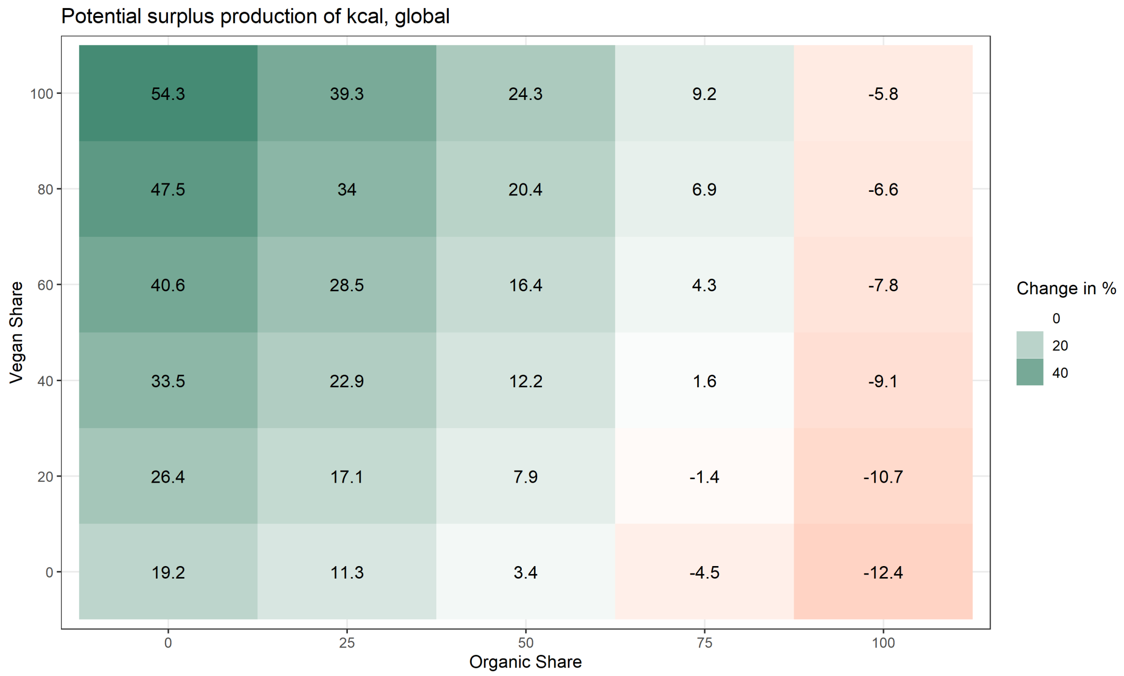


Figure B.7: Surplus kcal production, yield gap corrected.

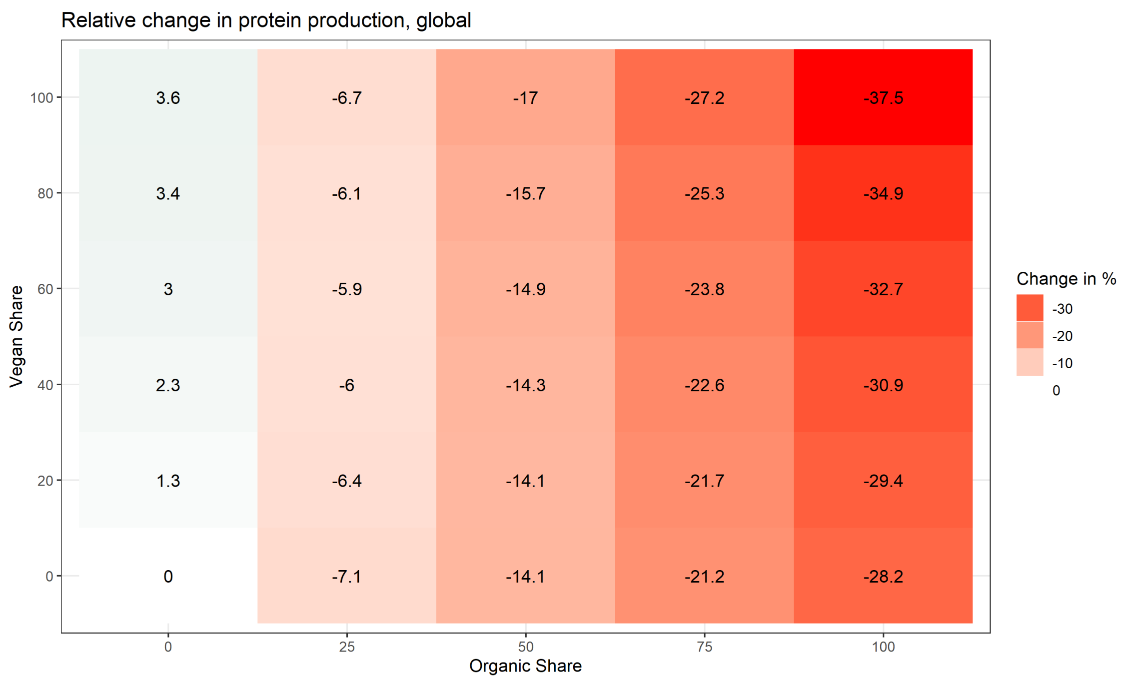


Figure B.8: Changes in protein production, yield gap corrected.

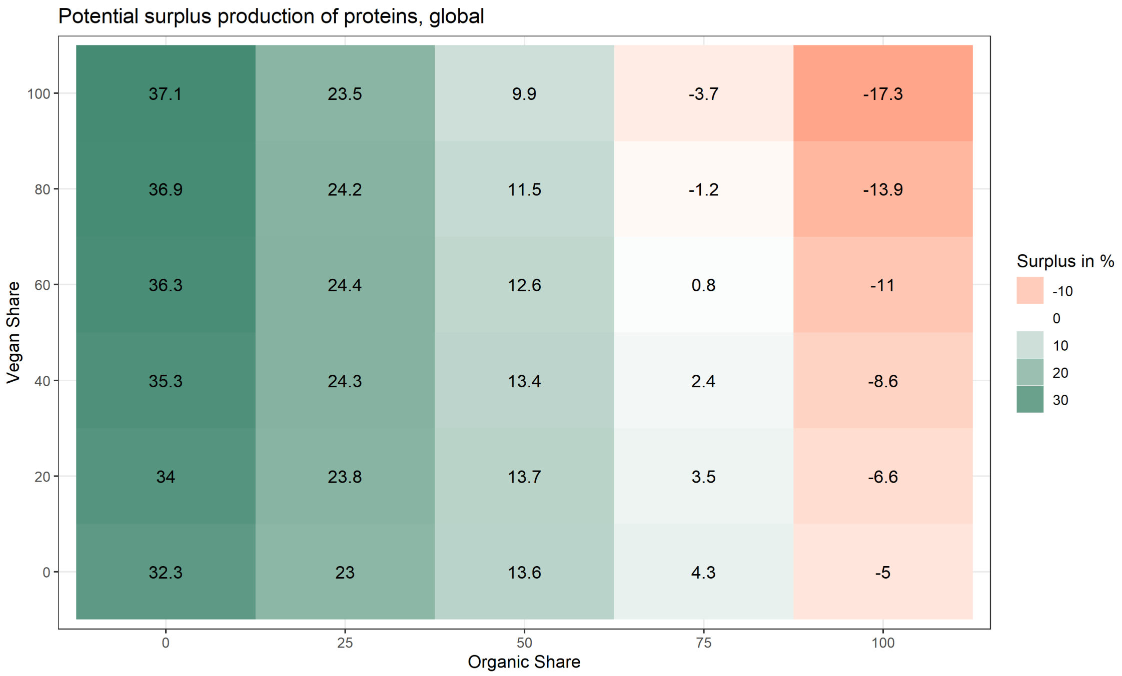


Figure B.9: Surplus in protein production, yield gap corrected.

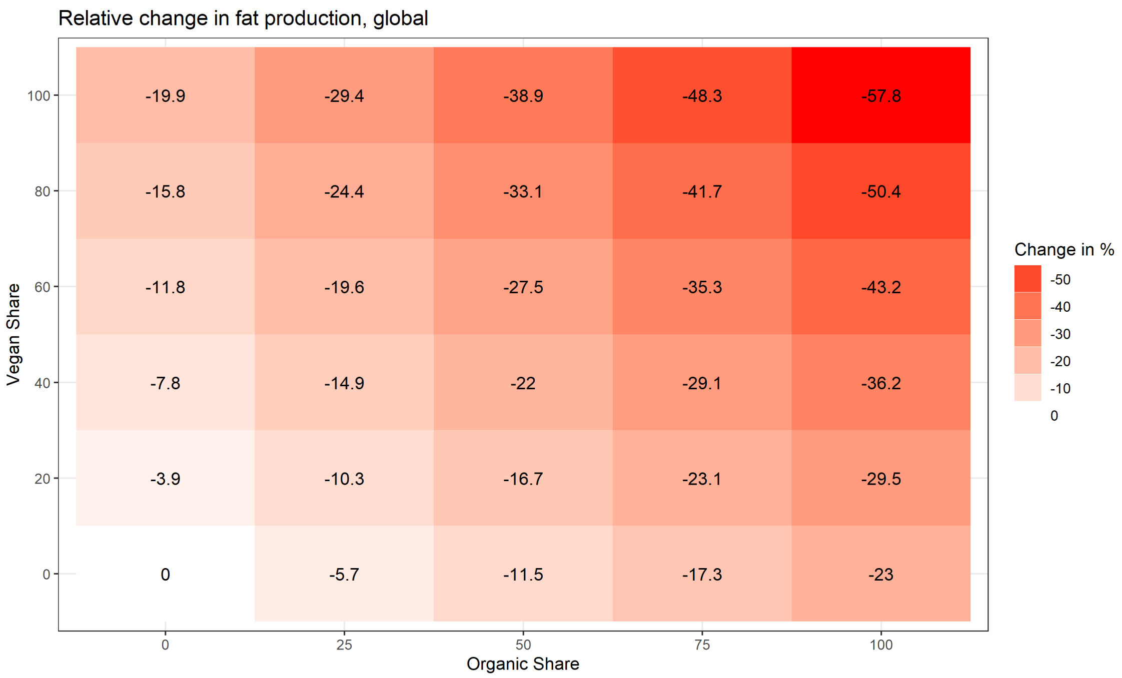


Figure B.10: Changes in fat production, yield gap corrected.

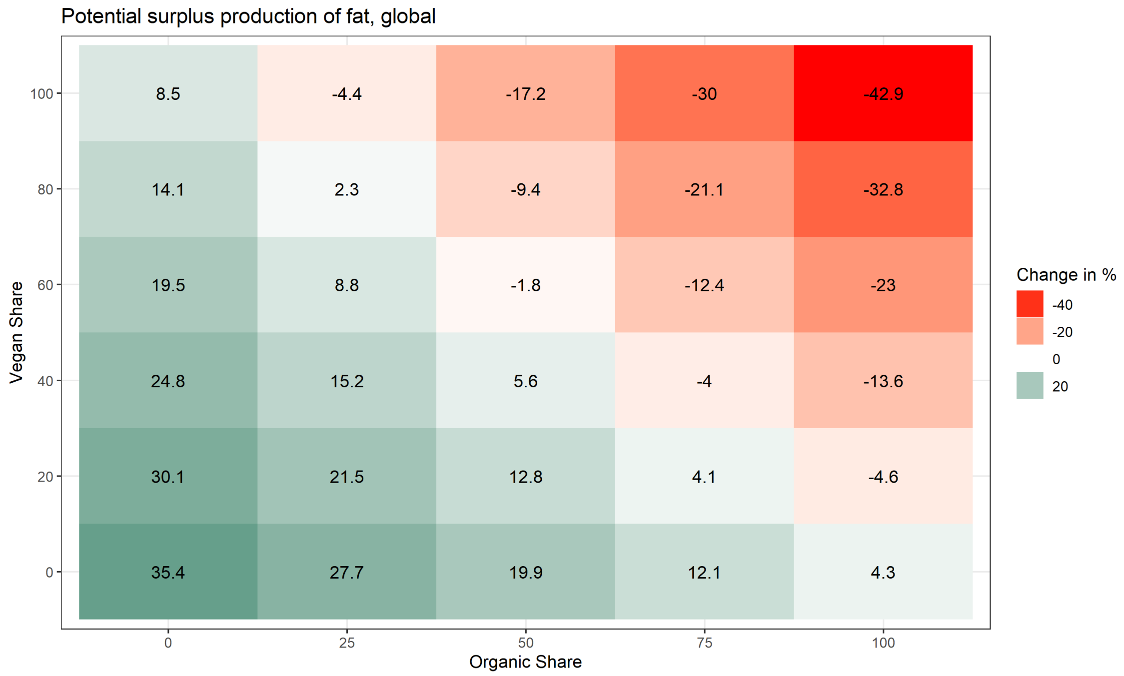


Figure B.11: Surplus in fat production, yield gap corrected.

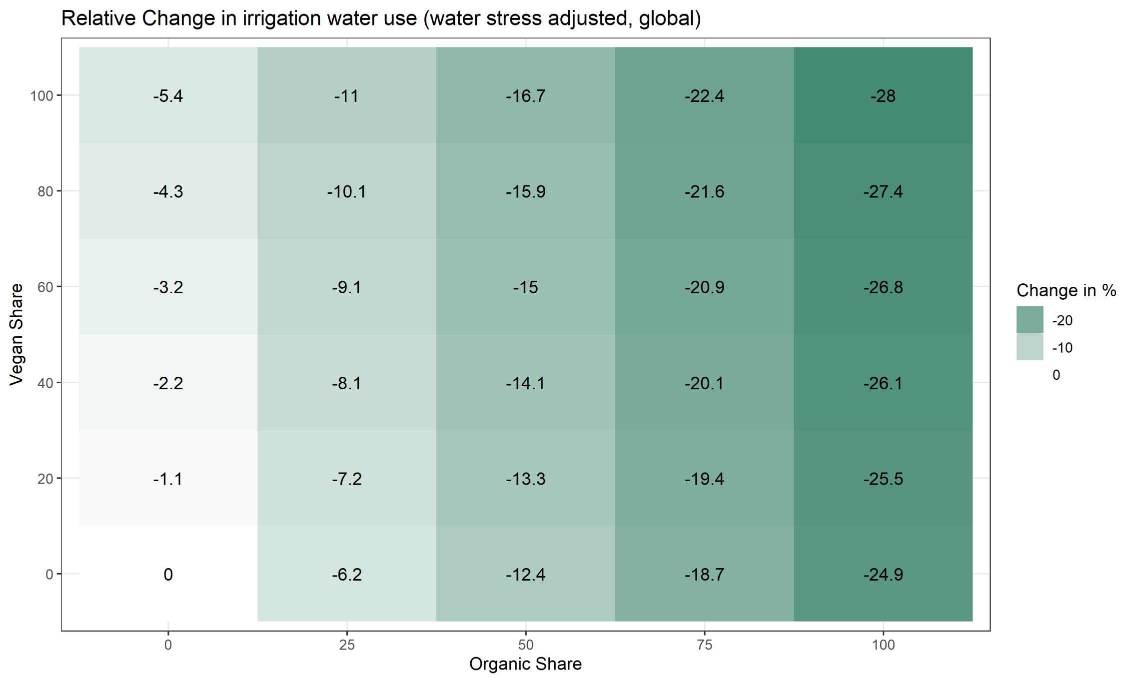


Figure B.12: Change in irrigation water use (water stress adjusted)

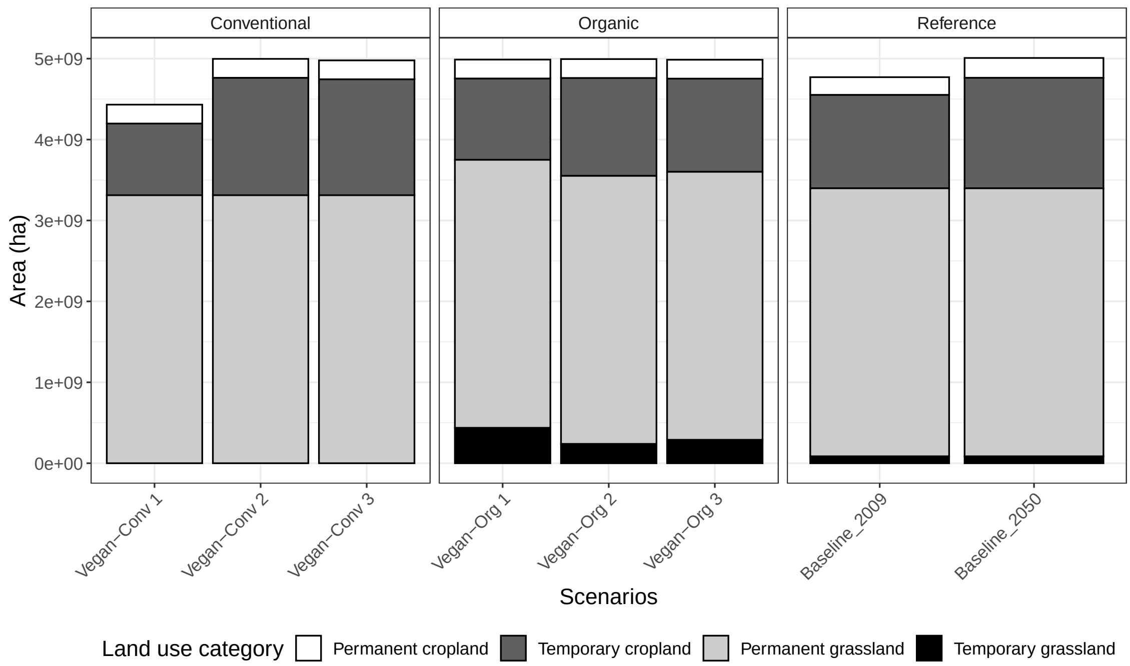


Figure B.13: All land use categories

Appendix C

GAMS Sets: Crop Rotation

The following table shows sets in GAMS with activities for each crop rotation group.

Cereals 1	Cereals 2	Oil crops	Pulses	Starchy roots (all crops)	Vegetables	Fruits	Set aside
Wheat	Barley	Castor oil seed	Bambara beans	Cassava	Artichokes	Strawberries	Temporary meadows and pastures
Rice, paddy	Buckwheat	Hempseed	Beans, dry	Potatoes	Asparagus	Berries nes	temporary grasslands
Maize	Canary seed	Linseed	Broad beans, horse beans, dry	Roots and Tubers, nes	Beans, green	Blueberries	Clover For Forage+Silage
	Cereals, nes	Mustard seed	Chick peas	Sweet potatoes	Cabbages and other brassicas	Cranberries	Alfalfa For Forage+Silag
	Fonio	Oilseeds Nes	Cow peas, dry	Taro (cocoyam)	Carrots and turnips	Currants	Leguminous Nes,For+Sil
	Millet	Poppy seed	Lentils	Yams	Cauliflowers and broccoli	Gooseberries	Forage Products Nes
	Oats	Rapeseed	Lupins	Yautia (cocoyam)	Chicory roots	Raspberries	'Vetches'
	Quinoa	Safflower seed	Peas, dry	Turnips For Fodder*	Chillies and peppers, dry		Other grasses, for forage
	Rye	Sesame seed	Pigeon peas	Beets For Fodder*	Chillies and peppers, green		Rye grass, for forage
	Sorghum	Sunflower seed	Pulses, nes	Swedes For Fodder*	Cucumbers and gherkins		
	Triticale*	Melonseed	Soybeans	Vegetables+Roots,Fodder*	Eggplants (aubergines)		
	Maize For Forage+Silage*				Garlic		
	Spelt				Leeks, other alliaceous vegetables		
	Sorghum, for forage				Vegetables, leguminous nes		
					Lettuce and chicory		
					Maize, green		
					Mushrooms and truffles		
					Okra		
					Onions, shallots, green		
					Onions, dry		
					Peas, green		
					Pumpkins, squash and gourds		
					Spinach		
					String beans		
					Tomatoes		
					Vegetables, fresh nes		
					Melons, other (inc.cantaloupes)		
					Watermelons		

Figure C.1: Crop rotation categories

Appendix D

Imputation

The following pages contain information about missing data in nutritional data from the SR28 database. Figure D.4 shows the share of missing values of the contained nutrients. Figure D.5 and Figure D.6 are examples for the analysis of imputation effects for different imputation methods.

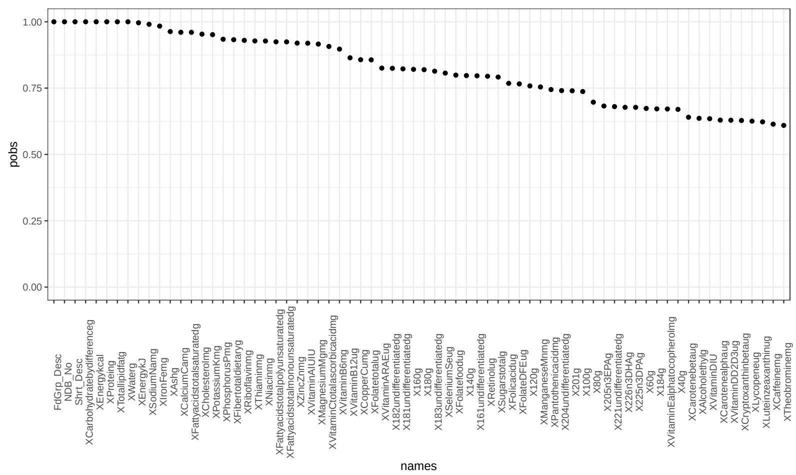


Figure D.1: Share of missing values for nutrients in SR28 data (I)

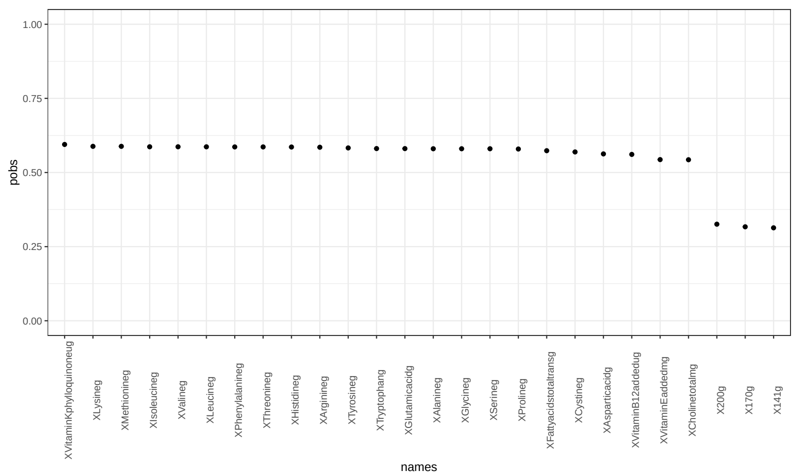


Figure D.2: Share of missing values for nutrients in SR28 data (II)

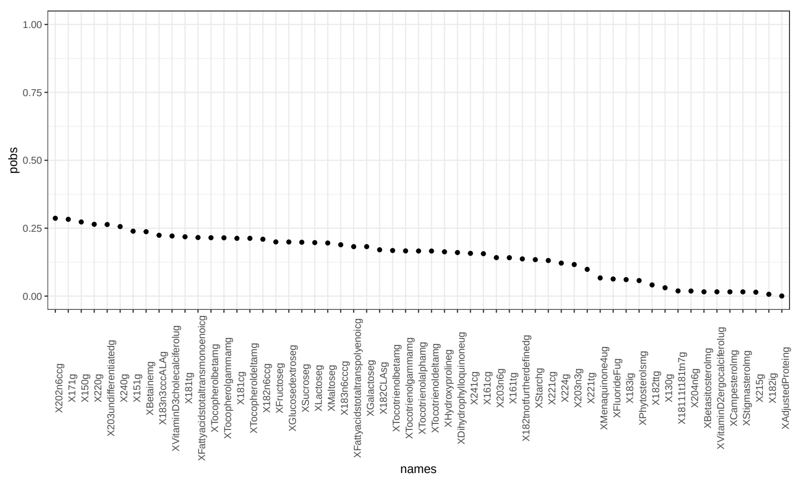


Figure D.3: Share of missing values for nutrients in SR28 data (III)

Figure D.4: Share of missing values for all nutrients and food items in SR28.

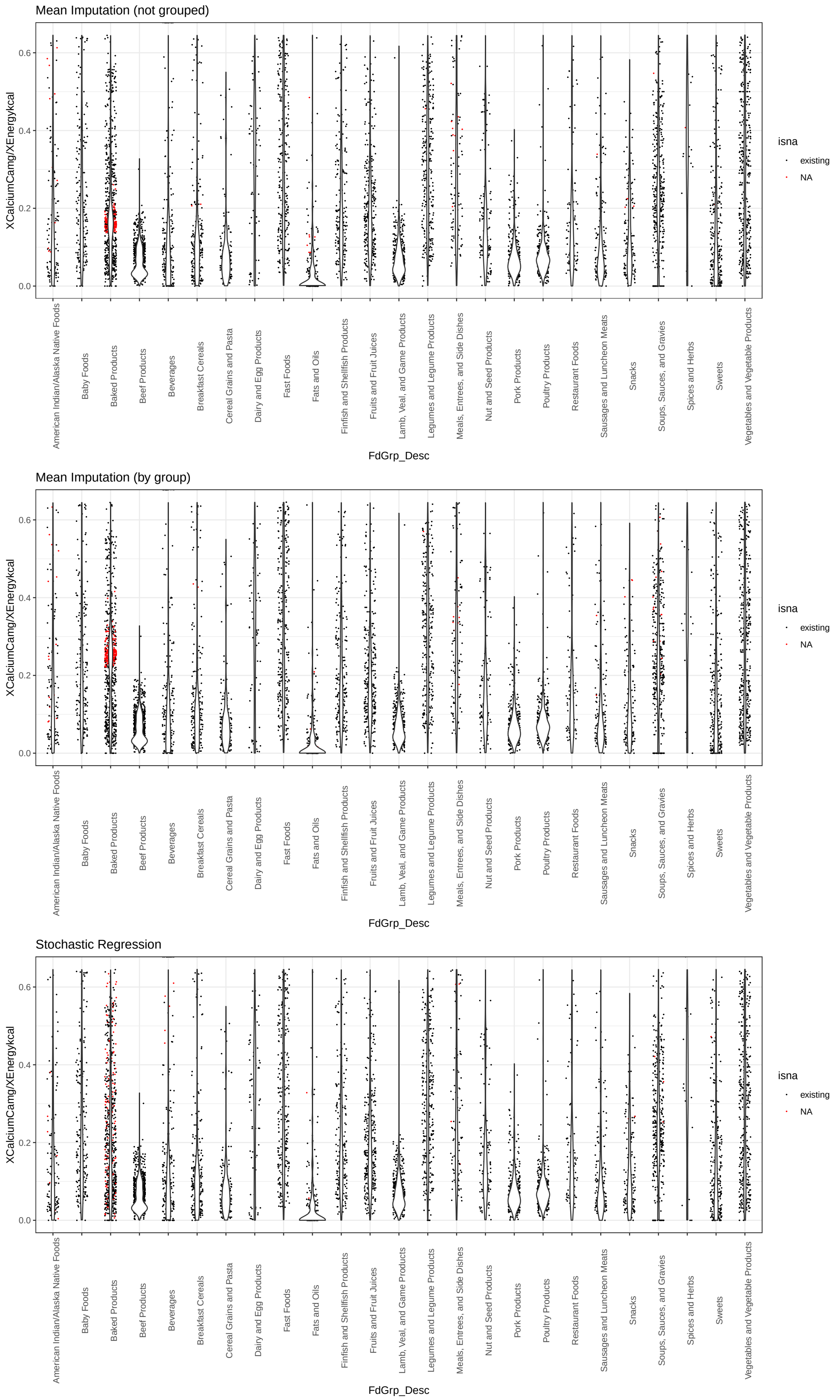


Figure D.5: Calcium: Comparison of selected imputation methods, used for the analysis and handling of missing data.

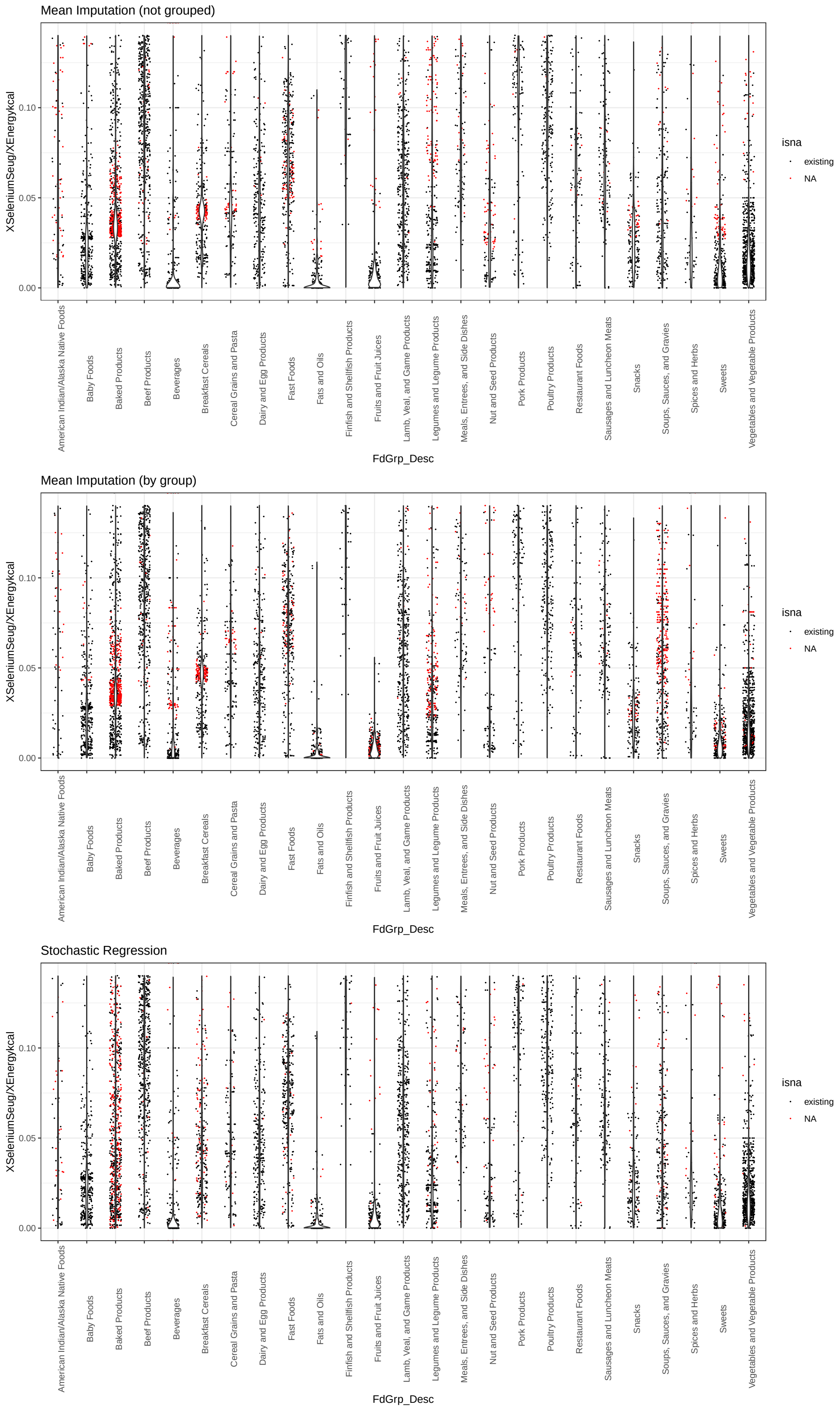


Figure D.6: Calcium: Comparison of selected imputation methods, used for the analysis and handling of missing data

Appendix E

Results Optimization

The optimization problem with nutritional constraints (feed the world) for the conventional production systems resulted in a total required area of 955 million hectares. The optimization problem for the organic production systems with additional agronomic constraints (feed the world without synthetic fertilizers) resulted in a total required area of 1.44 hectares. Currently, the global temporary cropland area size is approximately 1.6 hectares owidlanduse.

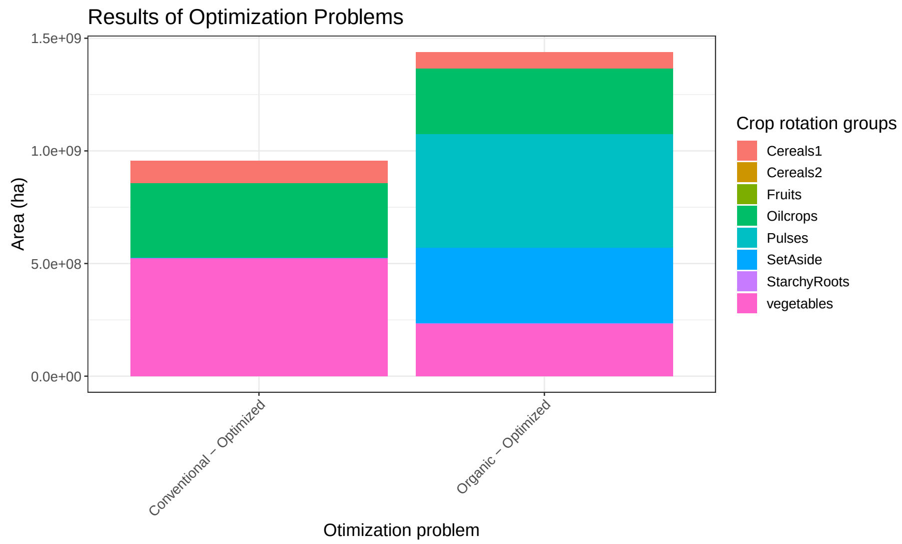


Figure E.1: Solution for optimization problem with nutritional restrictions (left), nutritional and agronomic restrictions (right), based on average values for yields and extraction rates.

Appendix F

Problem Proposal

N-FO-Aufgabenstellung für die Masterarbeit

Zürcher Hochschule für Angewandte Wissenschaften

Life Sciences und Facility Management

Stabsbereich Studium

Allgemeine Informationen	
Name StudentIn	Patricia Krayer
Studienbeginn (Semester)	HS19
Pensum	☐ Vollzeit ☒ Teilzeit
Vertiefung in	☐ V1: Food and Beverage Innovation ☐ V2: Pharmaceutical Biotechnology ☐ V3: Chemistry for the Life Sciences ☐ V4: Natural Resource Sciences ☒ V5: Applied Computational Life Sciences
Institut / Arbeitsort	ZHAW IAS / Wädenswil & FiBL / Frick
Titel der Masterarbeit	Modellierung des Potentials und der ökologischen Auswirkungen eines Ernährungssystems mit reduzierten Nutztierbeständen
Fachstelle/-gruppe	Bio-Inspired Modeling & Learning Systems
Vertraulich	Vertrauliche Aufbewahrung/Korrektur ☐ ja ☒ nein Geheimhaltungsvereinbarung ☐ ja ☒ nein Poster vertraulich* ☐ ja ☒ nein *Sofern das Poster nicht vertraulich ist, wird es an Ihrer Diplomfeier aufgehängt.
V1, V2 oder V3: Zeitplan Masterarbeit (40 ECTS)	**Milestone 1:** proposal / literature research (10 ECTS) ☐ HS ☐ FS **Milestone 2:** experimental strategy I (10 ECTS) ☐ HS ☐ FS **Milestone 3:** experimental strategy II (10 ECTS) ☐ HS ☐ FS **Milestone 4:** final conclusions (10 ECTS) ☐ HS ☐ FS
V4 oder V5: Zeitplan Masterarbeit (30 ECTS)	**Milestone 1:** proposal / literature research(10 ECTS) ☒ HS20 ☐ FS **Milestone 2:** experimental strategy (10 ECTS) ☐ HS ☒ FS21 **Milestone 3:** final conclusions (10 ECTS) ☐ HS ☒ FS21
Abgabetermin Masterarbeit (entspricht Milestone 3 oder 4)	**KW 2** ☐**, Jahr: Montag um 12:00 Uhr** (Studiensekretariat Campus Grüental) **KW 27** ☒**, Jahr: 2021 Freitag um 12:00 Uhr** (Studiensekretariat Campus Grüental) *Achtung: der Abgabetermin kann nur in begründeten Fällen verschoben werden. Die Verlängerung muss mit einem schriftlichen Antrag bei der Studiengangleitung eingehen und von dieser bewilligt werden. Die Kosten belaufen sich auf eine reduzierte Semestergebühr (vgl. Merkblatt zur Masterarbeit).*
KorrektorInnen	1. Zürcher Hochschule für Angewandte Wissenschaften Name: Dr. Matthias Nyfeler Adresse: ☒ Grüental ☐ Reidbach Postfach, 8820 Wädenswil Tel.Nr.: 058 934 51 16 E-Mail: nyfe@zhaw.ch

Zürcher Hochschule für Angewandte Wissenschaften

N-FO-Aufgabenstellung für die Masterarbeit

Life Sciences und Facility Management

Stabsbereich Studium

	2.	Name: Dr. Adrian Müller Adresse: FiBL, Ackerstrasse 113, 5070 Frick Tel.Nr.: +41 (0)62 865-7252 E-Mail: adrian.mueller@fibl.org
Entschädigung des 2. Korrektors, falls extern		☒ ja ☐ nein

Aufgabenstellung	
Aufgabenstellung • **Ausgangslage** • **Zielsetzung (z.B. geplante Experimente, Untersuchungen)** • **Ausstattung**	Ernährung ist für einen beträchtlichen Teil der globalen Umweltauswirkungen verantwortlich. So führen die verschiedenen Aktivitäten der Ernährungssysteme weltweit beispielsweise zu rund einem Viertel der Treibhausemissionen, beanspruchen 70% der Frischwasserressourcen und verursachen rund 80% der aquatischen Eutrophierung (Poore & Nemecek, 2018) (FAO, 2011). Zudem werden zunehmend Landressourcen verwendet, was mit einem Rückgang der Biodiversität verbunden ist. Insbesondere in Anbetracht der wachsenden Weltbevölkerung (und der damit voraussichtlich einhergehenden Erhöhung der landwirtschaftlichen Produktion) sind Lösungsstrategien gesucht, welche die – bereits heute hohen - Umweltauswirkungen des gesamten Ernährungssystems reduzieren und gleichzeitig die Ernährung sicherstellen können. Eine solche Strategie könnte eine Reduktion der Tierbestände sein, da die Nutztierhaltung mit vergleichsweise hohen Umweltbelastungen einhergeht. Beispielsweise erzeugt die tierische Produktion weltweit nur 37% der konsumierten Proteine, verwendet aber rund drei Viertel der Landwirtschaftsflächen und ist für rund die Hälfte der produzierten Treibhausgasgase des Ernährungssystems verantwortlich (Poore & Nemecek, 2018). Die Reduktion oder Abschaffung tierischer Bestände hätte jedoch weitreichende Folgen, nicht nur für den Konsum: Heutzutage sind tierische Hilfsstoffe ein wichtiger Bestandteil der gängigen Landwirtschaftspraxis. Insbesondere im biologischen Anbau werden tierische Düngemittel verwendet, um auf energieintensive Mineraldünger zu verzichten und Nährstoffkreisläufe zu schliessen. Der Verzicht auf die tierischen Nährstoffquellen bedingt daher den Einsatz anderer, pflanzlicher Nährstoffquellen, beispielsweise den Einsatz von Leguminosen als Gründüngung oder Transfermulch. Bisher ist aber noch ungeklärt, wie gross das globale Produktionspotential einer solchen Landwirtschaftspraxis unter Berücksichtigung der nutzbaren Ackerflächen wäre und mit welchen Umweltauswirkungen und Trade-Offs dies verbunden wäre. Zudem ergäben sich, einerseits durch die Veränderungen der angebauten Kulturen (keine Futtermittel mehr notwendig), andererseits durch das Wegfallen tierischer Nahrungsmittel, Veränderungen der Ernährungsmuster, deren gesundheitliche Auswirkungen untersucht werden sollten. Das Ziel dieser Masterarbeit ist daher, das Produktionspotential einer Landwirtschaft ohne tierische Hilfsmittel, also einer «veganen Landwirtschaft», sowie ökologische und gesundheitliche Auswirkungen einer solche Praxis, mittels einer Modellierung abzuschätzen. Das Modell soll auf dem bereits existierenden SOLm Modell basieren (V6). Dieses Massen- und Nähstoffflussmodell des globalen Ernährungssystems wurde in der Programmiersprache General Algebraic Modelling System (GAMS) entwickelt und umfasst Aktivitäten, Inputs und Outputs der globalen Tier- und Pflanzenproduktion. Es wurde ursprünglich im

	Rahmen eines FAO-Projekts von 2011 bis 2013 entwickelt (Schader et al., 2013) und seither in diversen Projekten für unterschiedliche Fragestellungen weiterentwickelt und genutzt. Für die geplante Masterarbeit werden einzelne Aspekte des Modells verfeinert, welche für die Fragestellung besonders relevant sind; namentlich die Abbildung der Fruchtfolgen und Zwischenfruchtfolgen. Für die Abschätzung der Auswirkungen sollen durch die Kombination unterschiedlicher Rahmenbedingungen (z.B. % Food Waste, % vegane Produktion) verschiedene Szenarien und deren Auswirkungen auf diverse Indikatoren modelliert werden. Zusätzlich können Szenarien mit alternativen Proteinquellen (z.B. Insekten) untersucht werden. Mögliche Umweltindikatoren sind beispielsweise Treibhausgasemissionen, die benötigte Ackerfläche und Stickstoff. Als Indikatoren für gesundheitliche Aspekte könnten Nährstoffgehalte (kcal, Proteine) und allenfalls ein geeigneter, aggregierter Index herbeigezogen werden.
Bemerkungen (z.B. notwendige Anschaffungen, Budgetplan, zusätzliche Rahmenbedingungen)	
Allgemeine Bedingungen	
Formale Anforderungen	Zusätzlich zur schriftlichen Abfassung gelten gemäss *Merkblatt zur Masterarbeit* folgende Anforderungen: • Poster: als Alternative (mit den Korrektoren schriftlich vereinbaren) kann auch eine Website oder Publikation erstellt werden. • Mündliche Prüfung in Form einer Präsentation der Arbeit in einem Kolloquium oder vor einem Gremium der beteiligten Partner: - das Format wird durch die KorrektorInnen festgelegt; - die Prüfung soll bis KW04 resp. KW30 erfolgen; - die mündliche Prüfung wird nicht gewichtet und nicht benotet, sie wird mit „erfüllt" / „nicht erfüllt" bewertet.
Wichtige Hinweise und Richtlinien	Das Dokument Arbeitsanleitung zum Abfassen von Projekt-, Literatur-, Semester-, Bachelor- und Masterarbeiten muss gelesen werden. Das Merkblatt zur Masterarbeit muss erfüllt werden. (vgl. https://www.zhaw.ch/de/lsfm/studium/studiweb/master-ls/masters-thesis/) Plagiate verstossen gegen die Urheberrechte. Eine Verletzung dieser Rechte wird gemäss der Rahmenprüfungsordnung für Bachelor- und Masterstudiengänge an der Zürcher Hochschule für Angewandte Wissenschaften vom 29. Januar 2008 in § 39 geregelt.
Abgabetermin Note	Jeweils 3 Wochen nach der effektiven Abgabe der Masterarbeit. Wenn die Masterarbeit termingerecht an das Studiensekretariat Master abgegeben gilt: KW30 (FS) / KW04 (HS).

Zürcher Hochschule
für Angewandte Wissenschaften

N-FO-Aufgabenstellung für die Masterarbeit

Life Sciences und Facility Management

Stabsbereich Studium

Die Aufgabenstellung ist jeweils zwei Wochen vor Semesterbeginn, in welchem die Masterarbeit abgegeben wird, an das Studiensekretariat einzureichen.

Unterschrift KorrektorIn 1	**Unterschrift StudentIn**
Ort, Datum Wädenswil, 27.8.2020	Ort, Datum Winterthur, 27.08.2020

(ersetzt Vorgängerdokument F235-02)

Erlassverantwortliche/-r	Leiter/in Stabsbereich Studium	Ablageort	2.05.00 Erlasse Lehre Studium
Beschlussinstanz	Leiter/in Stab	Publikationsort	Public

Appendix G

Declaration

Anhang 6

Beispiel: Masterarbeit (gilt für alle studentischen Arbeiten)

Erklärung betreffend das selbstständige Verfassen einer Masterarbeit im Departement Life Sciences und Facility Management

Mit der Abgabe dieser Masterarbeit versichert der/die Studierende, dass er/sie die Arbeit selbständig und ohne fremde Hilfe verfasst hat.

Der/die unterzeichnende Studierende erklärt, dass alle verwendeten Quellen (auch Internetseiten) im Text oder Anhang korrekt ausgewiesen sind, d.h. dass die Masterarbeit keine Plagiate enthält, also keine Teile, die teilweise oder vollständig aus einem fremden Text oder einer fremden Arbeit unter Vorgabe der eigenen Urheberschaft bzw. ohne Quellenangabe übernommen worden sind.

Bei Verfehlungen aller Art kann ein Disziplinarverfahren gemäss §§ 39 und 40 der Rahmenprüfungsordnung für die Bachelor- und Masterstudiengänge an der Zürcher Hochschule für Angewandte Wissenschaften vom 29. Januar 2008 i.V.m. der Verordnung zum Fachhochschulgesetz des Kantons Zürich eröffnet werden.

25.8.2021 Wädenswil ....

(Ort, Datum) (Unterschrift)

(Gilt nur für Bachelor- und Masterarbeiten)

Einverständniserklärung Autor/-in zur elektronischen Veröffentlichung einer Masterarbeit auf der ZHAW Digitalcollection

Einwilligung zur elektronischen Veröffentlichung in der ZHAW digitalcollection (basierend auf § 16 Abs. 1 lit. b FaHG).

☒ Ich erkläre mich damit einverstanden, dass

a) meine Arbeit (Volltext) in digitaler Form in der ZHAW digitalcollection veröffentlicht und in einschlägigen Verzeichnissen (z.B. Google Scholar) nachgewiesen wird. Das Recht, die Arbeit an anderer Stelle zu veröffentlichen, wird durch diese Erklärung nicht berührt.
b) meine Arbeit (Volltext) unter der vom Departement erteilten Nachnutzungslizenz veröffentlicht wird.
c) die Datei zum Zweck der langfristigen Verfügbarkeit in andere Dateiformate konvertiert oder anderweitig technisch verändert wird.
d) die beschreibenden Daten sowie die Arbeit selbst dauerhaft elektronisch gespeichert und öffentlich zugänglich ist und nur bei Verletzung von Rechten Dritter entfernt werden kann.

Ich versichere, dass der Veröffentlichung der Arbeit keine Rechte Dritter, insbesondere in Bezug auf im Volltext enthaltene Abbildungen oder andere urheberrechtlich geschützte Inhalte, entgegenstehen.

☐ Ich erkläre mich nicht mit der elektronischen Veröffentlichung einverstanden.

Wädenswil, 25.8.2021 ....

(Ort, Datum) (Unterschrift Autor/-in)

Fortsetzung Anhang 6 nächste Seite - Bitte ausfüllen.

Zürcher Hochschule für Angewandte Wissenschaften

Life Sciences und Facility Management

Stabsbereich Bildung

N-AA-Abfassung studentischer Arbeiten

Fortsetzung Anhang 6

Titel der Arbeit: Modeling Environmental and Nutritional Impacts of Vegan Agriculture

Name der/des Studierenden: Patricia Krayer

Name der/des 1. Korrigierenden: Matthias Nyfeler

Welche Schlagwörter schlagen Sie für die öffentliche online Suche vor?

Food System Analysis | Food System Model | Vegan Agriculture

Das Original dieses Formulars ist bei allen abgegebenen Masterarbeiten im Anhang mit Original-Unterschriften und -Datum (keine Kopie) einzufügen.

Masterstudiengang ENR:
Im Masterstudiengang ENR erfolgt die Abgabe der Abschlussarbeit, die Erklärung betreffend das selbstständige Verfassen einer studentischen Arbeit sowie die Erklärung betreffend Einwilligung zur elektronischen Veröffentlichung einer Masterarbeit auf der ZHAW Digitalcollection direkt in Complesis.

(ersetzt Vorgängerdokument W235-08)

Erlassverantwortliche/-r	Leiter/in Stabsbereich Bildung		Ablageort	2.05.00 Lehre Studium
Beschlussinstanz	Leiter/in Stab		Publikationsort	Public
Genehmigungsinstanz				

Version	Beschluss	Beschlussinstanz	Inkrafttreten	Beschreibung Änderung
1.0.0	20.03.2017	Leiter/in Stab	20.03.2017	Anpassung Layout und ZHAW Digitalcollection
2.0.0	05.09.2018	Leiter/in Stab	06.09.2017	Inhaltliche Anpassungen, Ergänzung MSc ENR
2.1.0	05.09.2018	Leiter/in Stab	06.09.2018	Datum Inkrafttreten von 2017 auf 2018 korrigiert.
3.0.0	29.09.2020	Leiter/in Stab	29.09.2020	Einverständniserklärung Autor/-in angepasst