UNIVERSITY OF HOHENHEIM

Institute of Crop Science (340)

AG Cropping Systems and Modelling

Prof. Dr. Simone Graeff-Hönninger

A cropping system for yacon (Smallanthus sonchifolius Poepp. Endl.) – optimizing tuber formation, yield and sugar composition under European conditions

Dissertation submitted in fulfillment of the regulations to acquire the degree "*Doctor scientiarum agriculturae*" (Dr.sc.agr. in Agricultural Sciences) to the Faculty of Agricultural Sciences

by

Larissa Kamp

Born in Radevormwald, Germany

Stuttgart

March 2020

This thesis was accepted as a doctoral thesis (Dissertation) in fulfillment of the regulations to acquire the doctoral degree “*Doctor scientiarum agriculturae*” by the Faculty of Agricultural Sciences at University of Hohenheim on August 13, 2019.

Dean Faculty of Agricultural Science: Prof. Dr. Ralf Vögele

Date of the oral examination: January 9, 2020

Examination Committee

Chairperson of the oral examination:	Prof. Dr.-Ing. Stefan Böttinger
Supervisor:	Prof. Dr. Simone Graeff-Hönninger
Co-Supervisor:	PD Dr. Feng Yan
Additional examiner:	Prof. Dr. Torsten Müller

Table of Contents

List of Abbreviation

€	Euro
°C	degree Celsius
a.s.l.	above sea level
AHA	American Heart Association
ANOVA	Analysis of Variance
DAP	days after planting
DM	dry matter
DP	Degree of Polymerization
e.g.	exempli gratia (for example)
ESPAGHAN	European Society for Paediatric Gastroenterology Hepatology and Nutrition
et al.	et alii, and others
FAO	Food and Agriculture Organization of the United Nations
FM	fresh matter
FOS	Fructooligosaccharide
g	gram
h	hour
ha	hectare
IOM	Institute of Medicine
kcal	calories
mm	millimeter
N	nitrogen
NO_3	nitrate
SACN	Scientific Advisory Committee on Nutrition
t	ton
WHO	World Health Organization

List of figures

List of tables

1. Introduction

1.1 Health-promoting food products

In recent years, nutritional and health aspects of foods have become increasingly important for consumers, especially in developed countries. According to a survey, conducted by the German Federal Ministry of Food and Agriculture, 92% of the interviewed consumers indicated, that they prefer healthy food. This is nearly the same approval rate as for the criteria good taste, which is strongly important for 99% of consumers (forsa, Politik- und Sozialforschung GmbH 2017). The term “healthy food” is hereby not clearly defined, but often associated to food with low caloric value as well as further health promoting benefits due to high amounts of fiber and phenols, antioxidant activity or bifidogenic effects. Closely related to healthy food is the term “functional food”, which is defined by the FAO as “A foodstuff that provides a health benefit beyond basic nutrition, demonstrating specific health or medical benefits, including the prevention and treatment of disease” (FAO 2005). The class of the functional foods was first characterized by the word “FOSHUA” (Food for specified health used), which was originally minted in Japan (de Almeida Paula et al. 2015). The awareness for consumption of health promoting food products and in general healthy food products increases steadily due to better education and information (Ärztekammer Niedersachsen 2017). Several dietary habits, that serve a specific purpose for example for athletes, vegans, and allergy suffers or gastroenteritis, need special food products which offer health benefits or act as a substitute for animal-based products or certain undesirable ingredients. Besides the health promoting benefits the caloric value of food products is a major issue, because of an increasing amount of obesity in developed countries. Between 1999 and 2017 the amount of obese people in Germany for example increased from 39 to 61% (Statista GmbH 2018). In addition, 39% of women and 32% of men are strongly interested in low-calorie-food (forsa, Politik- und Sozialforschung GmbH 2017). The widespread diseases in prosperous countries such as obesity, coronary heart failure, diabetes mellitus type II are strongly related to high consumption of free sugars (Deutsche Adipositas-Gesellschaft; Deutsche Diabetes Gesellschaft; Deutsche Gesellschaft für Ernährung 2018). Free sugars are defined as monosaccharides and disaccharides, which are added in food or occur naturally in honey, fruit juices or syrups (World Health Organization 2015). According to several professional associations like WHO, AHA, IOM, ESPGHAN and SACN the consumption of free sugar should be limited to ≤ 5 to ≤ 25% of total daily energy input (Deutsche Adipositas-Gesellschaft; Deutsche Diabetes

Gesellschaft; Deutsche Gesellschaft für Ernährung 2018). Consumption higher than these recommended levels are suspected to induce diseases like mentioned above and may lead to a nutrient displacement. However, sugar is not only of great importance in food products because of sweetening, but also because of a functional meaning. As a consequence the reduction of sugars is ambitious, as substitutes with lower caloric values and similar functional properties are required. (Max Rubner-Institut; Bundesforschungsinstitut für Ernährung und Lebensmittel 2018b). The searches for alternatives of added sugar is thus of crucial importance and requires attention. Especially the product groups of yoghurt, breakfast cereals and some kind of instant soups showed particularly high potential for replacement of sugar. Most notably is hereby the target group of children involved. Products, which are mainly advertised for children showed partially higher sugar amounts than products for adults (Max Rubner-Institut; Bundesforschungsinstitut für Ernährung und Lebensmittel 2018a). The European commission aspires to reduce added sugar by 10% with the focus on sugar sweetened drinks, dairy products and breakfast cereals (Max Rubner-Institut; Bundesforschungsinstitut für Ernährung und Lebensmittel 2018b). Therefore, different initiatives like, for example, the one of the Rewe trading group, have been started to reformulate relevant food products with the help of consumers. Products with different sugar amounts were successively launched and reformulated following after the customers decision (REWE Group Buying GmbH 2018).

1.2 Sugar substitutes

For sugar substitutes, a general distinction can be made between artificial and natural sweeteners. The **artificial sweeteners**, often labeled as sugar substitute, are synthetically manufactured (Chattopadhyay et al. 2014). They can be divided into two large subcategories: the high intensity sweeteners, which offer a very high sweetness power but only none to low caloric value and the nutritive sweeteners also known as sugar alcohols, which offer caloric value. They are often added to chewing gums or candies due to the lower risk of dental problems compared to normal sugar (Neacsu and Madar 2014). Artificial sweeteners like aspartame, cyclamate, neotame and saccharin have a sweetening power up to 13000 times higher than normal sugar, but are suspected of causing diseases like headaches, seizures, heart palpitations up to cancer. Also the acceptance of the consumer is low due to synthetic manufacturing. (Neacsu and Madar 2014; Chattopadhyay et al. 2014). Therefore, **natural sweeteners**, which are engendered naturally like agave nectar, blackstrap molasses, rapadura, rice syrup or honey are preferable. They are mainly processed by dehydration and often consist of complex carbohydrates or contain lower amounts of simple sugars or sucrose. Besides that, natural sweeteners also contain several vitamins and minerals and offer therewith further health promoting benefits. These reasons lead to higher acceptance of consumers compared to artificial sweeteners. However, the main barrier for using natural sweeteners is the high price for the products (Neacsu and Madar 2014).

One possible alternative to sugar substitutes could be fructooligsaccharides (FOS), which occurs naturally in several plants like onions, bananas, Jerusalem artichoke and yacon (Campbell et al. 1997). The use of FOS as a substitute for sugar offers several health-promoting benefits. FOS are polysaccharides with a degree of polymerization (DP) between 3 and 10 which cannot be digested by the human intestinal tract due to missing enzymes (Caetano et al. 2016a; Graefe et al. 2004; Campbell et al. 1997). Therefore, the blood glucose level does not increase significantly after consumption of FOS (Sumiyanto et al. 2012; Lachman et al. 2003). Because FOS are fermented by intestinal bacteria, their consumption offers prebiotic effects, promotes intestinal health and therewith positive effects on the organism due to a better absorption of minerals (Leidi et al. 2018; Caetano et al. 2016a; Kothari et al. 2014). The caloric value of FOS is up to 25 - 30% lower than the caloric value of other sugars (Manrique et al. 2005). The high sweetening power in combination with the low caloric value renders it an ideal substitute of added free sugars (Ojansivu et al. 2011; Campbell et al. 1997). The limited disadvantages of over consumption of FOS are also worth mentioning.. Excessively high quantities can lead to stomach as well as intestinal difficulties such as bloating, flatulence and diarrhea due to a general laxative effect (Caetano et al. 2016a).

Besides the replacement of free sugars, FOS can be used for texture modifying and as a fat replacer (Mensink et al. 2015). Overall the addition of FOS instead of free sugars offers two main advantages: on the one hand the replacement of free sugars and on the other hand several further health promoting benefits due to the chemical structure of FOS.

1.3 Yacon as a natural sweetener

One possible alternative for the exploitation of sugar substitutes in form of natural sweeteners could be yacon (*Smallanthus sonchifolius* (Poepp. &Endl.)). Yacon is a tuberous root crop native to the Andean region and belongs to the family of *Asteraceae.* It contains up to 70% FOS in dry matter (DM) (Goto et al. 2014; Campos et al. 2012). It is an perennial, herbaceous plant with dark green leaves (Fernández et al. 2007) and, according to the definition of FAO, are the tubers of yacon specified as functional food (FAO 2005). The average single tuber weight ranges from 200 to 500 gram and leads to a tuber yield of 3 to 5 kg per plant (Delgado et al. 2013; Douglas et al. 2005a). The color of tubers varies from creamy, white, red to purple (Graefe et al. 2004). On account of absent flower and fertile seed development, the propagation is carried out vegetative (Douglas et al. 2005b). Because of various distribution areas in the Andean region, where it is cultivated in altitudes ranging from 500 to 3500 m a.s.l., yacon is adaptable to a wide range of climatic conditions (Delgado et al. 2013; Fernández et al. 2006). Besides its origin, yacon is or was cultivated in Japan, Brazil, New Zealand, Korea, the United States and also in Europe in Czech Republic, France, Italy and Germany (Fernández et al. 2006; Bredemann 1948).

Yacon plants, especially the aboveground biomass, are frost sensitive and therewith annual in Europe (Douglas et al. 2007). The name yacon gives an indication of the ingredients of the tuber. It is composed of the two words “Yakku” and “Unu” which means “tasteless” and “water” in the Quechua language (de Almeida Paula et al. 2015; Zardini 1991). This is a reference to the bland, neutral taste immediately after harvest. This neutral taste exists due to storage of carbohydrates mainly in form of FOS and low amounts of fructose, glucose and sucrose. Only after exposing the tubers to the sun or storage for a few days, the sweet taste will increase along with enzymatic reduction of FOS to monosaccharides and sucrose (Graefe et al. 2004). A period of seven days is sufficient to reduce the amount of FOS by 30 to 40% (Manrique et al. 2005). This effect can be decelerated at lower temperatures (Doo 2000).

The possibilities for consumption of yacon are various. The tubers can be eaten raw, cooked like fruits or vegetables or used in processed form like syrup, juice, powder or chips (Manrique et al. 2004; Lachman et al. 2003). The processed form, especially syrup or powder, is a good option for sugar substitute and natural sweetener in a wide spectrum of food products. In this form they can substitute other syrups or honey in household use or even free sugars by using yacon powder for bakery or convenience food (Campbell et al. 1997). Besides this, yacon offers the advantage of being a vegan product and can be used as a natural sweetener from people with vegan dietary habits, which is one major benefit against honey.

The tubers have a saccharide content of up to 80% of dry matter and contain fructose, glucose, sucrose and mainly FOS. (DM) (Goto et al. 2014; Lachman et al. 2003). The amount of FOS in tubers ranges from 6.5 to 70% of DM (Goto et al. 2014; Campos et al. 2012). This wide range is due to several different factors influencing the composition of the tubers ingredients such as genotype, cultivation area and cultivation practice (Lachman et al. 2004). FOS is quite interesting for the food industry as the caloric value ranges from 14 to 22 kcal per 100 gram FM, which is quite low compared to other fruits like banana with an caloric value of 89 kcal per 100 gram FM (United States Department of Agriculture 2018; Manrique et al. 2004). Currently yacon is used mainly for producing syrup or powder as a sweetener or consumed fresh (Manrique et al. 2005). These two products offer a wide range of possible applications in professional processing and households as well. In addition to the FOS, yacon tubers contain valuable phenols and antioxidants, which also show health promoting effects (Khajehei et al. 2018; Andrade et al. 2014). Also the leaves of yacon contain huge amounts of phenols and antioxidants, which can be extracted and used for the preparation of infusions (Fernández et al. 2007; Lachman et al. 2003).

In 1941, preliminary yacon cultivation trials were already carried out in North Germany for sugar and alcohol extraction as a possible alternative to Jerusalem Artichoke (Bredemann 1948). In its area of origin, yacon is still mainly cultivated in subsistence farming by smallholders (Hermann et al. 1997). The small areas of cultivation are not sufficient to satisfy the increasing demand of natural sweeteners, like yacon, which rose annually by 15% in the last decade (Panesar et al. 2014). Besides insufficient area of production, the import of yacon and yacon products is difficult due to several reasons. The raw material is really sensitive to post-harvest treatment and storage conditions like mentioned above (Doo et al. 2000). Because of missing infrastructure and non-existing cooling chains, these problems cannot be solved in the Andean region (Graefe et al. 2004). In addition, the consumer´s preferences must be considered. In general is it very important for the consumer to be able to clearly retrace the origin and processing form of the product. A survey presented, that 78% of consumers attach importance to regional produced products and specified certification for organic regulations and fair trade signet (forsa, Politik- und Sozialforschung GmbH 2017). Therefore, cultivation of yacon in Europe would increase the acceptance of consumers due to regional produced products. Besides the mentioned arguments would offer a new crop the opportunity to increase biodiversity in agricultural cropping systems. Overall, the growing demand for sugar substitutes makes it reasonable to develop a cultivation system for yacon in Europe.

1.4 Critical aspects of cultivation

Main aspects, slowing down the implementation of yacon into European agriculture, are the various knowledge gaps with regard to the cultivation of yacon. Therefore, some fundamental parameters must be investigated in order to enable a sustainable yacon production in Europe. One major problem within the cultivation process of yacon is associated with the propagation.

As mentioned above, is yacon almost exclusively propagated vegetative, because fertile seeds will not be developed (Douglas et al. 2005a; Hermann et al. 1997). Propagation of plant material is done with rhizome pieces or, in rare cases, with stem cuttings. However, the use of stem cuttings for propagation in Europe is not possible, because they cannot be stored over winter. Therefore, the production of seedlings out of rhizome pieces is the main way in Europe. Commonly propagation can be done in two ways; the first possibility is to produce seedlings from mother plants and the second to cut the rhizome in pieces. In both methods a pre-cultivation of seedlings in greenhouse before planting is necessary. Due to the high costs for seedlings of > 3.60 € per piece these approaches are quite expensive (Wersin, gardening Helenion 2018). The plant density of in minimum 10.000 plants ha^{-1} will lead to high investment costs, which are not attractive for farmers. Another critical aspect is inhomogeneous seedling development from propagation by divided seedlings from mother plants due to the time period for seedling production of up to 14 days. Inhomogeneous seedlings make mechanization in the further cultivation process more complex. Therefore opportunities, which reduce manual work and thereby costs, are necessary to make the cultivation of yacon more appealing to the farmer. The mechanization of the cultivation process could lead to a significant decrease in costs due totime and manual work savings.

Moreover, it must be investigated how far different propagation methods lead to different tuber yield potentials and thereby also to different costs and profits for the farmer. Because not only the cost but also the yield can differ between propagation methods (Doo et al. 2002). Besides the production costs for the farmer, also the consumer´s price for the end product is a decisive point. If the production costs can be reduced, the end product can be favorable as well. That would make yacon products affordable for a broad range of consumers.

Another uncertainty in the yacon cultivation process is the diversity of existing genotypes, especially with regard to their tuber yield and sugar composition. Due to different origins, there are also large differences between the genotypes with regard to tuber yield potential under European climatic conditions as well as sugar composition (Fernandez et al. 2013; Lachman et al.

2004). To enhance the profitability of yacon cultivation, it is important to know which genotype offers the most benefits, from both an ecological and economical point of view. Also the different possibilities for food processing after harvest of the many genotypes are fundamental. For farmers it is indispensable to know about the specific characteristics of each genotype. Depending on the way of commercialization, or processing, the selection of the genotype is decisively, because of the different tuber sizes, sugar compositions and colors as well (Valentova et al. 2006). For fresh market uniform tubers are mandatory for packaging (Codex Alimentarius Commission 2017). Contrary to that, size and form are irrelevant for the processing industry. Tuber yield, sugar composition and resulting sugar yield may differ significantly between the genotypes (Fernandez et al. 2013; Valentova et al. 2006). It has to be investigated, if the quality and amount of sugars, especially FOS, in tubers is equal to previously common cultivation areas. If there is a change in the quality, especially sugar composition, health promoting benefits may no longer exist.

One further crucial point for a successful and sustainable yacon cultivation is the fertilizer requirement, especially nitrogen, because of its enormous impact on vegetative growth (Mokrani et al. 2018). Currently there are no clear indications about nitrogen demand and nitrogen removal of yacon. The indications of demand range from 24 to 98 kg N ha^{-1} but do not clarify the removal of plants or the influence on tuber yield or even the influence on sugar composition (Sumiyanto et al. 2012; Douglas et al. 2007; Doo 2000; Doo et al. 2000). The demand of nitrogen and the remaining nitrogen in soil after cultivation must be considered in crop rotation planning. The amount of remaining nitrogen in plant residues is a decisive factor for nutrient supply of a subsequent crop. Therefore, it is necessary to determine the optimum nitrogen fertilization level to obtain highest tuber yields with the highest nitrogen use efficiency.

1.5 Aim of study and approach

The entire objective of the present thesis, was to develop a sustainable cultivation system for yacon in Europe. Therefore, fundamental agronomical parameters were investigated to develop recommendations for farmers for a successful integration of yacon in their cropping system. In order to enable commercial cultivation, the main focus was placed on propagation methods, genotype screening and the identification of influencing factors, e.g. nitrogen, on overall tuber yield and amount of sugars, especially amount of FOS. These aspects are highly relevant for the introduction of new crops as they might go along with possible changes in quality and yield due to different climatic conditions.

Based on the research gaps identified the specific objectives of this thesis are:

- to evaluate differences between direct planting and pre cultivation of rhizomes in two ways with regard to yacon growth, development, tuber yield formation and cost distribution;
- to investigate the yield potential of different yacon genotypes with regard to tuber yield, sugar yield and tuber composition under the given climatic conditions of Europe;
- to determine the influence of different nitrogen levels on nitrogen uptake, tuber yield formation and amount of monosaccharides and polysaccharides as well as total sugar;
- to investigate the environmental impact and the production costs of different yacon cultivation systems to determine the most sustainable cultivation method.

To achieve the above mentioned objectives, a three year field experiment was conducted from 2016 - 2018 at the experimental station 'Ihinger Hof' of the University of Hohenheim. Within the field trial separate trials were carried out focusing on the main topics *propagation*, *genotype screening*, *nitrogen uptake* and *optimization of the economic and environmental performance*. The field trials resulted in four publications which form the body of the present thesis. The **first chapter** deals with three different propagation methods and their influence on tuber yield formation and cost distribution. High costs for plant material induced by work intensive propagation make yacon cultivation unattractive for farmers. Furthermore, attention was paid on the tuber size influenced by the propagation method and therewith conditions for further processing or a suitable post-harvest strategy. The **second chapter** deals with the cultivation of nine different genotypes and the effect of genotypes on sugar composition and tuber yield formation under European conditions. Depending on the sugar composition, different options for using the tubers are conceivable. The aim of this chapter was to determine the most suitable genotype for cultivation under consideration of tuber quality. The **third chapter** covers the cultivation of two different genotypes under three nitrogen levels to investigate the nitrogen uptake in different plant parts and the possible nitrogen demand of yacon. Besides the nitrogen uptake the influence of the nitrogen level on tuber yield formation and sugar compositions were examined. The influence of the propagation method and genotype on tuber yield formations were already shown in chapter I and II. In **chapter four** the production costs and environmental impact of different yacon cultivation systems were examined, to identify a practice-orientated and most promising cultivation method. Fundamentals for this study were a combination of the obtained results from chapter I – III.

Publication I – IV represent the results of the present study and were already published in peer-reviewed journals. In accordance to the published and already discussed results, a general discussion is included in section 7 connecting the different parts and aspects of yacon cultivation. Special note is given in the thesis to the agronomical part, discussing which further innovations have to be implemented and which additional knowledge gaps will have to be solved within the given structure in Europe and the related chances and risks of new crops in general. Afterwards an outlook is given for ongoing research at this topic and a summary of the whole present study as well (section 8).

2. Publications

The present thesis consists of four scientific papers, which have been published in peer-reviewed journals. These four articles constitute the body of the thesis. Any further publications from conferences or non-peer-reviewed journals are listed in the Appendix (table A1). For citation of the four articles please use the reference given below.

Publication I (published, Impact Factor 3.8):

Kamp, L., Hartung, J., Mast, B., Graeff-Hönninger, S. (2019): Plant growth, tuber yield formation and costs of three different propagation methods of yacon (*Smallanthus sonchifolius*). Industrial Crops and Products, 132, pp. 1–11.

DOI: 10.1016/j.indcrop.2019.02.006

Publication II: (published, Impact Factor 2.25):

Kamp, L., Hartung, J., Mast, B., Graeff-Hönninger, S. (2019): Tuber yield formation and sugar composition of yacon genotypes grown in Central Europe. Agronomy 2019, 9, 301.

Doi:10.3390/agronomy9060301

Publication III (published, Impact Factor 2.25):

Kamp, L., Hartung, J., Mast, B., Graeff-Hönninger, S. (2019): Impact of nitrogen fertilization on tuber yield, sugar composition and nitrogen uptake of two yacon (*Smallanthus sonchifolius* Poepp. & Endl.) genotypes. Agronomy 2019, 9, 151.

DOI: 10.3390/agronomy9030151

Publication IV (published, Impact Factor 2.59):

Wagner, M., Kamp, L., Graeff-Hönninger, S., Lewandowski, I. (2019): Environmental and economic performance of yacon (*Smallanthus sonchifolius*) cultivated for fructooligosaccharide production. Sustainability, 2019, 11, 4581.

DOI:10.3390/su11174581

3. Chapter I: Plant growth, tuber yield formation and costs of three different propagation methods of yacon

<u>Publication I:</u>

Kamp, L., Hartung, J., Mast, B., Graeff-Hönninger, S. (2019): Plant growth, tuber yield formation and costs of three different propagation methods of yacon (*Smallanthus sonchifolius*). Industrial Crops and Products, 132, pp. 1–11.

Currently the cultivation of yacon is not particularly appealing to farmers due to high investment costs caused by the propagation method. Up to now, yacon is propagated exclusively vegetative because of missing fertile seeds or seeds in general. Plantlets are mostly obtained by dividing seedlings after budding. The resulting high investment costs are one of the major barriers and make large-scale cultivation of yacon unattractive for farmers. Besides the high costs the predominant use of manual labor is not really attractive for farmers. According to this, the paper "Plant growth, tuber yield formation and costs of three different propagation methods of yacon (Smallanthus sonchifolius)" investigated three different propagation methods with regard to tuber yield formation and costs. Special attention is paid on single tuber weight as an indicator for final marketing opportunities.

Plant growth, tuber yield formation and costs of three different propagation methods of yacon (Smallanthus sonchifolius)

Larissa Kamp[a], *, Jens Hartung[b], Benjamin Mast[a], Simone Graeff-Hönninger[a]
*Corresponding author, E-mail address: Larissa.Kamp@uni-hohenheim.de
[a]Institute of Crop Science, Cropping Systems and Modelling, University of Hohenheim,Stuttgart, Germany
[b]Institute of Crop Science, Biostatistics, University of Hohenheim, Stuttgart, Germany
Industrial Crops & Products 132 (2019) 1–11; https://doi.org/10.1016/j.indcrop.2019.02.006

Yacon (Smallanthus sonchifolius) ((Poepp. and Endl.) H. Robinson) is a tuberous root crop native to the Andean region. The tubers store carbohydrates mainly in form of fructooligosaccharide (up to 60% of DM) which are supposed to have a health promoting benefit. Due to high propagation costs the cultivation of yacon is currently limited. The current study investigated three different propagation methods i) divided seedling after budding from mother plants with pre-cultivation in the greenhouse (DSAB), ii) seedlings from rhizome pieces pre-cultivated in the greenhouse (RP1), and iii) rhizome pieces directly planted into the field (RP2) regarding plant growth, tuber yield formation and costs. The propagation methods DSAB (92cm) and RP2 (85cm) reached significant larger plants than RP1(70cm). Also, the trend of leaves and ramifications was similar. Furthermore, differed the number of ramifications between DSAB (24) and RP1 (16) significantly, but not to RP2 (18). The average rhizome weight at harvest was highest for DSAB with 871g and lowest for RP1 with 561 g. Relating to the tuber yield achieved RP1considerably highest tuber yields (29.8t FMha^{-1}) compared to DSAB and RP2 (21.3 and 17.8t FM ha^{-1}) respectively. For the mean fresh weight of tubers significant differences were detected between RP1 (308g) and RP2 (196g), whereas DSAB (255g) did not differ significantly from RP1 or RP2. Additionally, reached RP1 the highest number of tubers per plant (8.2) and DSAB and RP2 with 5.6 and 6.6, respectively, lower. Due to the highest tuber yield and low investment costs, RP1 turned out to be the most favourable propagation method for the cultivation of yacon regarding the costs. The major cost drivers are the procurement of plant material and pre-cultivation in greenhouse. A further mechanization of direct planting (RP2) would offer the chance to decrease the propagation costs within this method significantly.

4. Chapter II: Tuber yield formation and sugar composition of yacon genotypes grown in Central Europe

Publication II:

Kamp, L., Hartung, J., Mast, B., Graeff-Hönninger, S. (2019): Tuber yield formation and sugar composition of yacon genotypes grown in Central Europe. Agronomy 2019, 9, 301.

To evaluate the full potential of yacon cultivation in Europe, it is mandatory to screen different genotypes with respect to tuber yield and sugar composition. Due to a wide distribution area of yacon in its origin, a large spectrum of sugar amount and sugar composition is assumed. This high genetic diversity offers different possibilities for utilization. Especially differences in sugar composition in particular the amount of FOS and the average degree of polymerization (DP) are highly important for possibilities of further processing, post-harvest treatment and food product development. Because FOS were metabolized during storage, DP as high as possible is desirable for tubers that should be stored after harvest to maintain the health promoting benefit as long as possible after harvest.

agronomy

MDPI

Article

Tuber Yield Formation and Sugar Composition of Yacon Genotypes Grown in Central Europe

Larissa Kamp [1,*], Jens Hartung [2], Benjamin Mast [1] and Simone Graeff-Hönninger [1]

[1] Institute of Crop Science, University of Hohenheim, 70599 Stuttgart, Germany; Benjamin.Mast@gmx.de (B.M.); simone.graeff@uni-hohenheim.de (S.G.-H.)

[2] Department of Biostatistics, Institute of Crop Science, University of Hohenheim, 70599 Stuttgart, Germany; moehring@uni-hohenheim.de

* Correspondence: Larissa.Kamp@uni-hohenheim.de; Tel.: +49-711-459-24185

Received: 8 May 2019; Accepted: 6 June 2019; Published: 11 June 2019

check for updates

Abstract: Yacon (*Smallanthus sonchifolius*) is a tuberous root crop native to the Andean region. The eatable tubers contain up to 70% fructooligosaccharides (FOS) on a dry matter (DM) basis. These FOS are not digestible by the human intestinal tract and do not cause an increase of blood glucose level. Therefore, the consumption of yacon tubers offers health promoting benefits. With regard to cultivation, little to no information about yield potential and FOS content as well as sugar composition of diverse genotypes is known. However, this information is crucial for the development of new health beneficial food products out of different genotypes of yacon. In the present study nine different genotypes were studied in a field experiment in 2017 and 2018 regarding their tuber yield formation, sugar yield, and sugar composition. The genotypes red-shelled ('RG'), brown-shelled ('BG'), and 'Morado' reached the highest tuber yields of 46.6, 43.5, and 41.6 t ha^{-1} FM, respectively. These three genotypes also had the highest sugar yields in the same order (2.2, 2.0, and 1.9 t ha^{-1}). Considering the sugar composition and sugar content, these three genotypes were outstanding, with a sugar content up to 66% of DM ('RG', 2018). With regards to the development of possible food products, cv. 'Peru' can be considered as favorable for the fresh market due to high amounts of both monosaccharides and FOS. Genotypes 'BG', 'RG', and 'Morado' seem to offer various options for the food processing industry, due to their high amounts of FOS.

Keywords: fructooligosaccharides; sugar yield; sugar content

1. Introduction

The tuberous root crop yacon ((*Smallanthus sonchifolius* (Poepp. et. Endl.) H. Robinson)) is native to the Andean region and belongs to the family of *Asteraceae*. The highest diversity of yacon genotypes can be found in Peru and Bolivia [1]. In addition to its area of origin, yacon is cultivated in Brazil, Czech Republic, New Zealand, Japan, and Italy [2,3]. There have already been cultivation attempts in Germany in the early 1940s [3]. Basically yacon is a perennial plant. As it is not frost tolerant, it is grown as an annual crop in Central Europe and other regions with frosts [4]. Aboveground biomass can achieve a plant height of up to 2–2.5 m and consists of dark green leaves [4,5]. Below ground yacon produces eatable tuberous roots. On average, each plant achieves a tuber yield of 2–3 kg, sometimes reaching up to 5 kg [6–8]. The color of the tuber's flesh and peel varies from white to yellow, red, purple, or brown [9]. Each tuber generally weighs between 200 and 500 g, but weights can reach up to 2000 g with a dry matter of 10–14% [5,10]. In contrast to other tuberous root crops, yacon stores carbohydrates in the form of fructooligosaccharides (FOS). These FOS are polysaccharides which cannot be digested by the human intestinal track and do not cause an increase of blood glucose level [11,12]. Therefore, the consumption of yacon products with high amounts of FOS offers health promoting benefits [13].

The main components of FOS in yacon are kestose (GF_2), nystose (GF_3), and fructofuranosylnystose (GF_4) at amounts generally between 34 to 60% of dry matter (DM), but also considerably less depending on the cultivar [6,14,15]. Major differences between yacon and other FOS containing crops like Jerusalem artichoke and chicory are the shorter chain length of FOS in yacon. Jerusalem artichoke and chicory had noticeable higher chain lengths with a degree of polymerization (DP) > 10 [16]. Due to a decreasing bifidogenic effect with increasing DP, lower DP, like in yacon tubers, is preferable [17,18]. Furthermore, yacon contains phenolic compounds and flavonoids [11,13] which offer health promoting benefits when consumed. The tubers can be commercialized for the fresh market as a fruit or for the food processing industry. They can be processed as natural sweeteners in the form of syrup or powder or dried to chips [11,19]. As sugar composition and DP are highly relevant for the technological properties and potential resulting health benefits of the intended food products, it is important to examine potential differences of sugar composition between the genotypes. In general tubers with high amounts of FOS are more preferable because of greater health promoting benefits.

In general, yacon tubers show a wide range of FOS amounts and DP indicating that several factors impact sugar composition and yield formation. The yacon genotype can be considered as a major influencing factor [20]. Hence, it is mandatory to examine the sugar compositions and yield potential of several genotypes grown in Central Europe. With regards to sugar composition and bioactive compounds in general, only little information is found in literature related to the choice of the genotype. In addition little to no information, related to tuber yield formation, is available about cultivation in Central Europe. Both characteristics are decisive for the market potential of the genotypes. Depending on single tuber weight, and the amount of FOS and fructose as well as glucose, different marketing options as well as final food products could be possible. For fresh market purposes, size and weight of the tuber, and of course taste are decisive. For the processing industry, weight and size of tubers is not relevant, but sugar composition and therefore processing characteristics are. Amount of FOS should be as high as possible to offer maximum health promoting benefit.

Therefore, the aim of the present study was to investigate the potential of different yacon genotypes with regard to (i) tuber yield formation and (ii) sugar composition and sugar yield. Different yield parameters and sugar compositions will result in different sugar yield potentials and marketing options as well as food products.

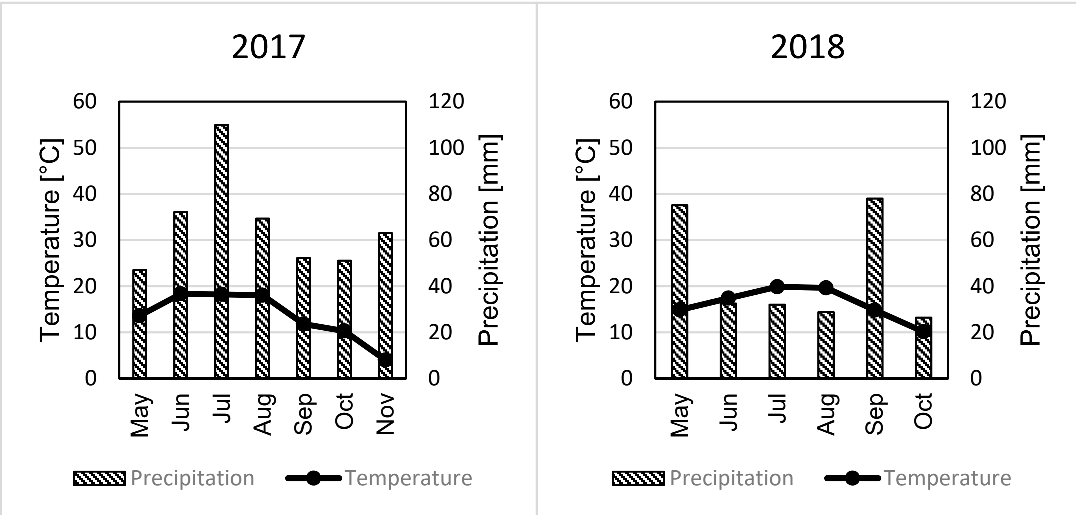
2. Materials and Methods

2.1. Field Site and Experimental Design

Field trials were carried out in 2017 and 2018 at the experimental station Ihinger Hof of the University of Hohenheim (48°44′ N, 8°55′ E and 475 a.s.l.) in south-west Germany from May–November. Mean annual rainfall was 653.9 mm in 2017 and 252.9 mm in 2018. Average annual temperature amounted to 9.2 °C in 2017 and 10.2 °C in 2018. During the cultivation period the average temperature was 13.5 °C in 2017 and 16.1 °C in 2018 (Figure 1a,b).

The soil of the experimental fields was classified as a Vertic Cambisol with winter wheat as the preceding crop in both years [21]. The trials were set up as alpha design (Figure A1) with three replicates each with two incomplete blocks of five plots. Each plot was 5 × 4 m. The trial was laid out in ridges (60 × 45 cm; 44 cm between the ridges; 114 cm between centers of ridges). Ridges were formed by using a common asparagus ridge planting machine (Leofant, HMF-Hermeler Maschinenbau GmbH, Füchtorf, Germany). The ridges were directed from east to west and formed four weeks before planting. Each plot was comprised of two ridges and 14 plants (0.7 × 1.14 m) resulting in a final plant density of 12,531 plants ha^{-1}. N_{min} content in the soil was determined shortly before planting (VDLUFA, 2004) and amounted to 119 and 53 kg NO_3 ha^{-1} in 2017 and 2018, respectively. Due to high amounts of N_{min} in 2017, no additional nitrogen fertilizer was added. In 2018, 66 kg N ha^{-1} were applied as ENTEC 26 (EuroChem Agro GmbH, Mannheim, Germany) shortly before planting to reach a similar nitrogen amount as in the year before.

To prevent water stress, in particular in the first development phase after transplanting and during hot and dry periods in 2018, plants were additionally irrigated. In 2017, irrigation was carried out four times (26 and 30 of May, 20 and 22 of June) and in 2018 12 times (30 of July and 3, 6, 7, 8, 9, 10, 13, 15, 16, 21, and 23 of August) with 1.4 L per plant each time. Weed control was done manually until the plant population was established.



(**a**) (**b**)

Figure 1. Temperature (●) and precipitation (bars) at the trial site Ihinger Hof for the cultivation period of yacon in 2017 (**a**) and 2018 (**b**). Plotted are the average temperatures in degree Celsius and the total rainfall in mm in each month. Temperature and precipitation in May and November (2017) and May and October (2018) include days within the cultivation period only.

2.2. Treatments

Within the field trial ten different genotypes were tested, but one showed no emergence in the first year. The nine remaining genotypes were: brown-shelled ('BG'), red-shelled ('RG'), 'Morado', 'Rojo', 'New Zealand', Cajamarca, 'Peru', 'Late Red', 'Early White', and 'Purple'. Rhizomes for cultivation of seedlings were received from different gardeners and a network of sustainers for biodiversity (Helenion, Berlin, Germany and Arche Noah, Austria). After harvest in 2017, rhizomes were stored for the next year's cultivation period according to the method described by Kamp et al. [22]. Rhizome pieces of each genotype were sliced into smaller pieces (20–40 g) with a sterile knife and then planted in square planters (9 × 9 × 9.5 cm) filled with a standard soil (classic, expert substrate, Einheitserde Werkverband e.V., Sinntal-Altengronau, Germany). Cultivation started six weeks before transplanting, on 7 of April in 2017 and 5 of April in 2018. Temperature in the greenhouse ranged from 15 °C at night to 21 °C during the day; humidity amounted in average to 65%. No artificial light was used for cultivation of seedlings. To avoid white bow ties and fungus gnats, sticky traps were placed above tables. Pots were irrigated every third day if required. Seedlings were transplanted into the field on 19 May 2017 and 17 May 2018. After transplanting, 6 kg ha^{-1} of slug pellet was applied manually (Arinex, ADAMA Deutschland GmbH, Cologne, Germany).

2.3. Field Measurements and Sample Preparation

Final harvest took place on 7 of November 2017 and 17 of October in 2018 (172 and 153 days after planting (DAP), respectively). Date of harvest was set immediately after the first frost to ensure a maximum utilization of the given vegetation period. For determination of tuber yield formation, six plants in the center of each plot were harvested. Plants were harvested manually by using a sickle and a digging fork. Afterwards, tubers were washed to remove soil residues. Weight of each single tuber was determined to assess dry matter. A bulked sample from each plot was frozen with liquid nitrogen (−196 °C) and finally freeze dried. By freezing samples with liquid nitrogen, any enzymatic process was stopped and no changes in sugar composition were assumed. For further analysis, freeze dried samples were milled with a GRINDOMIX GM 200 (Retsch GmbH, Haan, Germany) two times at a speed of 10,000 turns min^{-1} for 10 s each. Sugar composition of tubers were analyzed by using high performance liquid chromatography (HPLC) using the method described by Kamp et al. [23]. To determine the overall sugar yield the percentage of total sugar was multiplied by tuber yield (DM).

2.4. Statistical Analysis

A mixed model approach was used and the following model was fitted to all traits. For traits with a single observation per plot (tuber yield per plot, tuber dry matter, and sugar components) the model was as follows:

$$y_{ij} = \mu + b_j + a_i + (ab)_{ij} + e_{ij}$$

$$y_{ijkl} = \mu + a_j + r_{jk} + b_{jkl} + \tau_i + (\tau a)_{ij} + e_{ijkl} \quad (1)$$

where μ is the general effect, b_j is the fixed effect of the jth year, $a_i r_{jk}$ is the fixed effect of the kth replicate in year j, b_{jkl} is the random effect of the lth incomplete block in the jkth replicate, τ_i is the main effect of the ith genotype, and $(ab)_{ij}$ and $(\tau a)_{ij}$ is the fixed interaction effect of the ith genotype and jth year. e_{ij} is the error of y_{ij} with homogeneous or year-specific error variance. Studentized residuals were graphically checked for normal distribution and homogeneous variance.

After finding significant differences via the global F-test, significant differences were evaluated with a multiple *t*-test (Fisher´s least significant difference test) at a significance level of 5%. A letter display was used to present the results of multiple comparisons (Piepho 2004). Additionally, simple means were calculated for all traits for presentation purposes only.

For traits measured at each plant (number of tubers per plant and average single tuber weight), the model extended by a plot effect. The model is then:

$$y_{ijklm} = \mu + a_j + r_{jk} + b_{jkl} + \tau_i + (\tau a)_{ij} + p_{ijkl} + e_{ijklm} \quad (2)$$

where p_{ijkl} is the random plot effect of the lth plot and e_{ijklm} is the error of the mth plant. All other variables are analogous to model (1). Statistical analysis were performed using the PROC MIXED procedure of the SAS system, version 9.4 (SAS Institute Inc., Cary, NC, USA). Figures were generated using SigmaPlot, version 13.0 (Systat Software GmbH, Erkrath, Germany), and Excel 2013 (Microsoft Corporation, Redmond WA, USA).

3. Results

3.1. Tuber Yield Formation

The parameters tuber yield (t ha^{-1} FM, DM) and tuber DM% and number of tubers per plant were significantly affected by genotype-by-year interactions (Table 1). Single tuber weight was not affected by this interactions, but by genotype and year. In 2017, tuber yield (FM t ha^{-1}) ranged from 19.2 (‘Late Red’) to 46.6 t ha^{-1} (‘RG’). Genotypes ‘BG’, ‘RG’, and ‘Morado’ reached significantly higher tuber yields than the other six genotypes. In 2018, tuber yields ranged from 6.5 (‘Late Red’, ‘Rojo’) to 12.8 t ha^{-1} (‘BG’). Tuber yields of genotypes ‘Late Red’ and ‘Rojo’ were significantly lower than those of the other seven cultivars. In general, in 2018 tuber yield of all genotypes was significantly lower than in 2017. DM ranged from 11.0% (‘BG’) to 16.1% (‘RG’) and from 12.0% (‘Peru’) to 17.7% (‘New Zealand’) in 2017 and 2018, respectively. Genotypes ‘Rojo’, ‘New Zealand’, ‘Peru’, and ‘Purple’ had significantly higher tuber DM in 2018 than 2017. Genotypes ‘RG’ and ‘Morado’ had significantly higher DM than other genotypes (except ‘Late Red’ and ‘Purple’) in 2017. In 2018, genotypes ‘Morado’, ‘New Zealand’, and ‘Purple’ reached the significantly highest tuber DM. Regarding tuber yield (DM t ha^{-1}), all genotypes reached significantly higher tuber yields in 2017 than in 2018. In 2017, genotypes ‘RG’ and 'Morado' significantly achieved the highest tuber yields. In 2018, genotype 'New Zealand' reached the highest tuber yield and differed significantly from all other genotypes except 'RG' and 'Morado'.

Number of tubers per plant ranged in 2017 from 8.3 ('Early White') to 14.8 ('RG'). Genotypes 'RG', 'Morado', and 'New Zealand' reached significantly higher numbers of tubers per plant than all other six genotypes, except 'BG' which did not differ from 'New Zealand'. In 2018, number of tubers per plant ranged from 5.1 ('Late Red') to 7.9 ('New Zealand'). Except for 'Rojo' all genotypes reached significantly lower numbers of tubers per plant in 2018 than in 2017.

In contrast, average single tuber weights were significantly higher in 2017 than 2018 (Table A1). Weights ranged from 174.9 g ('Late Red') to 314.0 g ('BG') in 2017 and from 91.4 g ('Rojo') to 220.7 g ('BG') in 2018. Over both experimental years, genotypes 'BG', 'Peru', 'RG', and 'Early White' (descending order) reached significantly higher tuber yields than the other genotypes.

Table 1. Tuber fresh matter yield (t ha^{-1} FM), tuber dry matter (DM in %), tuber dry matter yield (t ha^{-1} DM), mean number of tubers (per plant), and average single tuber weight (g) for the two years (2017 and 2018) of the nine genotypes ('BG', 'RG', 'Morado', 'Rojo', 'New Zealand', 'Peru', 'Late Red', 'Early White', and 'Purple') at harvest as mean value ± standard error.

Genotype	Tuber Yield (t ha^{-1} FM)	DM (%)	Tuber Yield (t ha^{-1} DM)	Number of Tubers (per Plant)	Tuber Weight (g)
2017					
BG	$43.54^{aA} \pm 3.3$	$11.01^{efB} \pm 0.5$	$4.68^{bA} \pm 0.4$	$11.1^{bcA} \pm 1.0$	314.00 ± 29.4
RG	$46.60^{aA} \pm 3.3$	$16.14^{aA} \pm 0.5$	$7.59^{aA} \pm 0.4$	$14.8^{aA} \pm 1.0$	265.32 ± 29.4
Morado	$41.66^{aA} \pm 3.3$	$15.50^{abA} \pm 0.5$	$6.44^{aA} \pm 0.4$	$14.2^{aA} \pm 1.0$	236.34 ± 29.3
Rojo	$22.94^{bcA} \pm 3.3$	$11.35^{eB} \pm 0.5$	$2.67^{dA} \pm 0.4$	$7.8^{dA} \pm 1.0$	252.75 ± 29.4
New Zealand	$30.66^{bA} \pm 3.3$	$13.41^{cdB} \pm 0.5$	$4.08^{bcA} \pm 0.4$	$13.1^{abA} \pm 1.0$	197.7 ± 29.4
Peru	$27.16^{bcA} \pm 3.3$	$9.40^{fB} \pm 0.5$	$2.58^{dA} \pm 0.4$	$8.5^{cdA} \pm 1.0$	288.17 ± 29.7
Late Red	$19.21^{cA} \pm 3.3$	$14.23^{bcA} \pm 0.5$	$2.76^{dA} \pm 0.4$	$9.3^{cdA} \pm 1.0$	174.9 ± 29.4
Early White	$23.71^{bcA} \pm 3.3$	$12.43^{deA} \pm 0.5$	$2.97^{cdA} \pm 0.4$	$8.3^{dA} \pm 1.0$	231.9 ± 29.4
Purple	$21.91^{bcA} \pm 3.3$	$14.39^{bcB} \pm 0.5$	$3.10^{cdA} \pm 0.4$	$9.7^{cdA} \pm 1.0$	202.99 ± 30.1
2018					
BG	$12.75^{aB} \pm 1.0$	$14.03^{cA} \pm 0.6$	$1.76^{bcB} \pm 0.2$	$5.2^{cB} \pm 0.6$	220.72 ± 26.6
RG	$11.75^{aB} \pm 1.0$	$16.03^{bA} \pm 0.6$	$1.89^{abB} \pm 0.2$	$5.6^{bcB} \pm 0.6$	182.01 ± 26.0
Morado	$10.85^{aB} \pm 1.0$	$17.03^{abA} \pm 0.6$	$1.84^{abB} \pm 0.2$	$5.8^{bcB} \pm 0.6$	175.48 ± 26.0
Rojo	$6.55^{bB} \pm 1.0$	$13.46^{cdA} \pm 0.6$	$0.88^{eB} \pm 0.2$	$6.8^{abA} \pm 0.6$	91.43 ± 26.6
New Zealand	$12.36^{aB} \pm 1.0$	$17.71^{aA} \pm 0.6$	$2.22^{aB} \pm 0.2$	$7.9^{aB} \pm 0.6$	152.8 ± 27.4
Peru	$11.36^{aB} \pm 1.0$	$12.02^{dA} \pm 0.6$	$1.35^{cdB} \pm 0.2$	$5.7^{bcB} \pm 0.6$	175.38 ± 26.0
Late Red	$6.46^{bB} \pm 1.0$	$15.84^{bA} \pm 0.6$	$1.01^{deB} \pm 0.2$	$5.1^{cB} \pm 0.6$	114.73 ± 26.0
Early White	$11.56^{aB} \pm 1.0$	$13.59^{cdA} \pm 0.6$	$1.57^{bcB} \pm 0.2$	$5.7^{bcB} \pm 0.6$	215.45 ± 26.0
Purple	$10.06^{aB} \pm 1.0$	$16.49^{abA} \pm 0.6$	$1.66^{bcB} \pm 0.2$	$5.7^{bcB} \pm 0.6$	167.6 ± 26.0

Results of statistical analysis

Factor	DF	p-value for the corresponding F test				
Year*Rep	4	0.4384	0.0187	0.4352	0.9208	0.9241
G	1	<0.0001	0.9366	<0.0001	<0.0001	0.0003
year	1	<0.0001	<0.0001	<0.0001	<0.0001	0.0032
Year*G	1	<0.0001	0.0020	<0.0001	<0.0001	0.2237

ANOVA table (replication = Rep; genotype = G, year = year, degree of freedom (DF), and p-value) carried out for tuber yield (t ha^{-1} FM), tuber DM (%), tuber yield (kg ha^{-1} DM), mean number of tubers (per plant), and average single tuber weight (g). Within years, same lower case letters in one column indicate non-significant differences between genotypes at $p < 0.05$. Within each genotype, same capital letters in one column indicate non-significant differences between years at $p < 0.05$.

3.2. *Sugar Yield*

Sugar yield (t ha^{-1}) was significantly affected by genotype × year interactions. In 2017, the genotypes 'BG', 'RG', and 'Morado' reached the significantly highest sugar yields and differed from all other genotypes. Genotype 'RG' reached the highest sugar yield with 2.2 t ha^{-1}. 'BG' and 'Morado' had slightly lower amounts in the range of 2.0 and 1.9 t ha^{-1}, respectively (Figure 2). 'Rojo' reached the lowest sugar yield of 0.5 t ha^{-1} and differed significantly from all other genotypes. The other genotypes 'New Zealand', 'Peru', 'Late Red', 'Early White', and 'Purple' did not differ significantly from each other and reached sugar yields in a similar range. In 2018, sugar yield ranged from 0.4 ('Rojo') to 1.3 t ha^{-1} ('RG'). Genotypes 'RG', 'BG', and 'Morado' reached sugar yields in a similar range in decreasing order. The lowest sugar yield of 0.4 t ha^{-1} was reached by 'Rojo' and showed significant differences to all genotypes, except 'Late Red' which was also in a lower range with 0.5 t ha^{-1}. Genotypes 'Rojo', 'New Zealand', 'Peru', 'Early White', and 'Purple' did not differ significantly between the two experimental years. The four genotypes 'BG', 'RG', 'Morado', and 'Late Red' reached significantly higher sugar yields in 2017 than 2018. All genotypes reached lower sugar yields in 2018 than in 2017.

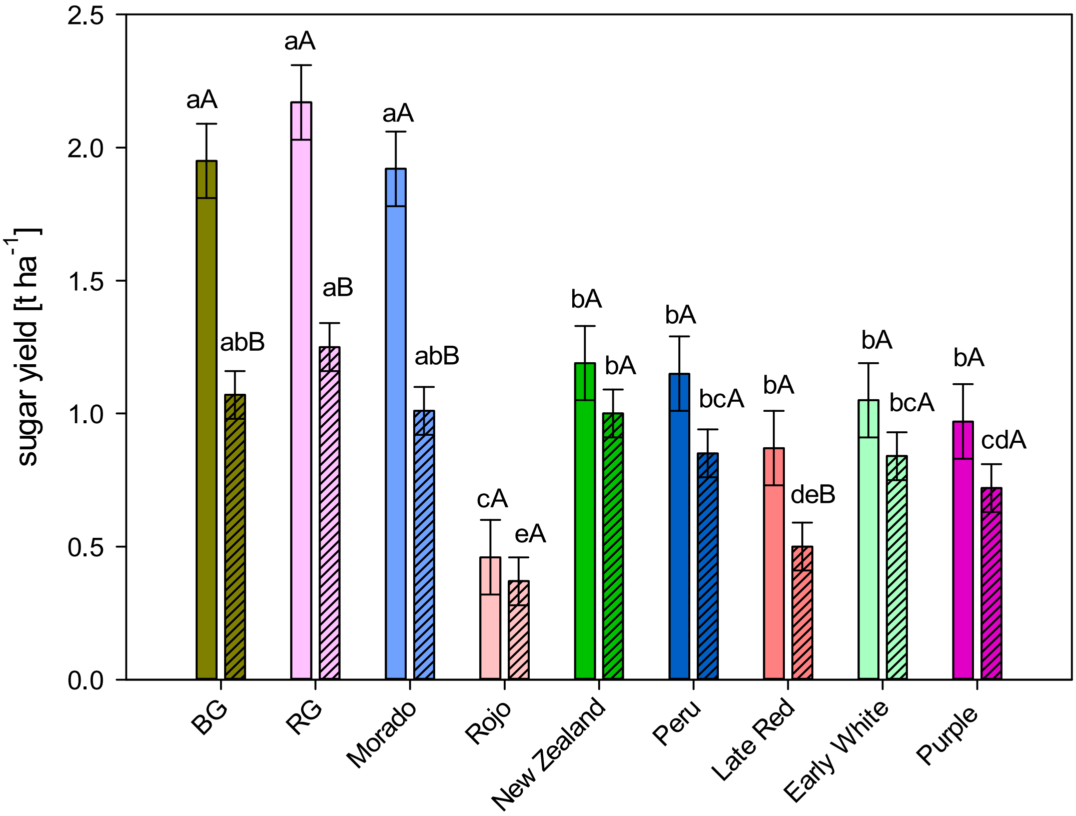


Figure 2. Sugar yield (t ha^{-1}) for the two years (2017 monochrome and 2018 pattern) of the nine genotypes at harvest. Same lower case letters indicate no significant differences between the genotypes within one year. Same capital letters indicate no significant differences between one genotype across the years.

3.3. Sugar Composition

The fructose and GF_4 fractions were significantly affected by year × genotype interactions. The glucose, sucrose, and GF_3 fractions were significantly affected by year and genotype in each case. GF_2 was only affected by year (Table 2).

Amount of fructose ranged from 0.86% ('RG') to 5.91% ('Peru') and from 0.43% ('Late Red') to 2.89% ('Rojo') in 2017 and 2018, respectively. In 2017, 'Peru' and 'Rojo' (5.6%) reached the highest amounts of fructose and differed significantly from all other genotypes. In 2018, 'Rojo' and 'BG' (2.4%) reached the highest amounts of fructose und differed significantly from all other genotypes. All other seven genotypes did not differ from each other, but had significantly lower amounts of fructose than 'Rojo' and 'BG'. The exception was 'Peru', which did not differ significantly from any genotype. In 2017, the genotypes 'BG', 'Rojo', 'New Zealand', and 'Peru' reached significantly higher amounts of fructose than in 2018. All other genotypes did not differ significantly between the years.

The amounts of glucose were significantly higher in 2017 than in 2018 and differed significantly between the genotype averages across the years (Table A1). In 2017, amounts ranged from 1.4 ('RG') to 5.5% ('Peru') and in 2018 from 1.3% ('New Zealand') to 4.4% ('Early White'). Across years, genotypes 'Rojo', 'Peru', 'Early White', and 'BG' significantly reached the highest amounts of glucose and significantly differed partially from some of the other genotypes. The lowest amounts of glucose were reached by 'Late Red' with 1.5%.

Contrary to findings for the other monosaccharides, amounts of sucrose were significantly higher in 2018 than 2017. Genotypes 'BG', 'Peru', and 'Early White' reached the highest amounts of sucrose across both experimental years. 'Late Red' reached the lowest amount of sucrose (2.5%).

Considering the different fractions of FOS, amounts of GF_2 were significantly higher in 2018 than 2017. In 2017, the amount of GF_2 ranged from 1.3% ('Rojo') to 9.6% ('BG'). Noticeably higher were the ranges. In 2018, the range of GF_2 was from 10.4% ('New Zealand') to 24.0% ('Peru'). The amount of GF_3 was significantly higher in 2018 than in 2017. In 2017, amounts ranged from 1.7% ('Rojo') to 13.2% ('BG') and in 2018 from 11.4% ('Rojo') to 25.9% ('RG'). Averages of genotypes across both experimental years showed significant differences. The genotype 'Rojo' reached significantly lower amounts of GF_3 than all other genotypes. Furthermore, genotype 'New Zealand' differed significantly from 'RG'. All other genotypes did not differ significantly from each other.

In 2017 GF_4 ranged from 2.5% ('Rojo') to 9.0% ('Morado'). 'Rojo' differed significantly from all other genotypes. All other genotypes were in a similar range and did not differ significantly from each other. In 2018, amounts ranged from 6.5% ('Rojo') to 15.3% ('RG'). 'RG' reached the highest amounts of GF_4 and differed significantly from all other genotypes. Similar to findings in GF_2 and GF_3, all genotypes reached significantly or noticeable higher amounts of GF_4 in 2018 than 2017.

Total FOS were affected by year and by genotype. Similar to findings of single FOS, the amount of total FOS was significantly higher in 2018 than in 2017. In 2017, the amount of total FOS ranged from 5% ('Rojo') to 31.2% ('BG'). In 2018, the range was from 30.6% ('Rojo') up to 58.3% ('BG'). The average of genotypes across both experimental years showed that genotype 'Rojo' differed significantly from all other genotypes and reached the lowest amounts of total FOS. All other genotypes did not differ significantly from each other.

Total sugar amount was not affected by year nor by genotype. It ranged from 17.6% ('Rojo') to 44.5% ('Peru') and from 41.1% ('Rojo') to 66.0% ('RG') in 2017 and 2018, respectively. However there were no significant differences between the years, and all genotypes reached noticeable higher total sugar amounts in 2018 than in 2017.

Table 2. Fructose, glucose, sucrose, kestose (GF_2), nystose (GF_3), and fructofuranosylnystose (GF_4), total fructooligosaccharides (FOS) and total sugar content in % of DM for the two years (2017 and 2018) of the nine genotypes at harvest as mean value ± standard error.

Genotype		Fructose	Glucose	Sucrose	GF_2	GF_3	GF_4	Total FOS	Total Sugars
					2017				
BG		3.84^{bA} ± 0.6	4.04 ± 0.6	4.00 ± 0.2	9.61 ± 0.9	13.21 ± 1.3	7.96^{acA} ± 0.9	31.23 ± 2.9	41.43 ± 2.3
RG		0.86^{cA} ± 0.6	1.36 ± 0.6	1.97 ± 0.2	5.24 ± 0.9	11.21 ± 1.3	7.93^{acB} ± 0.9	24.48 ± 3.0	28.67 ± 2.3
Morado		1.13^{cA} ± 0.6	2.58 ± 0.6	2.14 ± 0.2	5.10 ± 0.9	11.12 ± 1.3	8.98^{aB} ± 0.9	25.58 ± 2.9	39.85 ± 2.3
Rojo		5.61^{aA} ± 0.6	3.97 ± 0.6	1.33 ± 0.2	1.30 ± 0.9	1.71 ± 1.3	2.47^{dB} ± 0.9	5.05 ± 2.9	17.63 ± 2.3
New Zealand		2.52^{bcA} ± 0.6	3.08 ± 0.6	2.36 ± 0.2	5.19 ± 0.9	8.81 ± 1.3	6.78^{acB} ± 0.9	20.68 ± 3.0	28.62 ± 2.3
Peru		5.91^{aA} ± 0.6	5.54 ± 0.6	4.34 ± 0.2	10.12 ± 0.9	12.23 ± 1.3	6.26^{cA} ± 0.9	28.72 ± 3.0	44.52 ± 2.3
Late Red		1.84^{cA} ± 0.6	1.62 ± 0.6	1.98 ± 0.2	4.90 ± 0.9	12.61 ± 1.3	8.68^{abA} ± 0.9	26.31 ± 3.0	31.76 ± 2.3
Early White		2.39^{bcA} ± 0.6	2.98 ± 0.6	2.96 ± 0.2	7.26 ± 0.9	12.57 ± 1.3	6.43^{bcA} ± 0.9	25.81 ± 2.9	35.82 ± 2.3
Purple		1.75^{cA} ± 0.6	2.98 ± 0.6	2.97 ± 0.2	5.96 ± 0.9	11.25 ± 1.3	6.61^{bcB} ± 0.9	23.77 ± 2.9	31.36 ± 2.3
					2018				
BG		2.44^{aB} ± 0.3	2.55 ± 0.5	6.23 ± 0.8	21.56 ± 4.5	19.37 ± 3.0	9.74^{deA} ± 0.8	50.22 ± 8.0	62.01 ± 8.2
RG		1.08^{bA} ± 0.3	2.07 ± 0.5	4.51 ± 0.8	16.99 ± 4.5	25.91 ± 3.0	15.34^{aA} ± 0.8	58.26 ± 8.0	66.02 ± 8.2
Morado		0.86^{bA} ± 0.3	2.18 ± 0.5	3.83 ± 0.8	14.51 ± 4.5	20.95 ± 3.0	13.05^{bA} ± 0.8	48.49 ± 8.0	55.27 ± 8.2
Rojo		2.89^{aB} ± 0.3	3.45 ± 0.5	4.75 ± 0.8	12.54 ± 4.5	11.39 ± 3.0	6.49^{fA} ± 0.8	30.62 ± 8.0	41.12 ± 8.2
New Zealand		0.67^{bB} ± 0.3	1.32 ± 0.5	2.80 ± 0.8	10.39 ± 4.5	17.78 ± 3.0	12.35^{bcA} ± 0.8	40.54 ± 8.0	45.41 ± 8.2
Peru		1.80^{abB} ± 0.3	3.57 ± 0.5	6.54 ± 0.8	24.00 ± 4.5	18.09 ± 3.0	7.80^{dfA} ± 0.8	49.37 ± 14.3	62.39 ± 8.2
Late Red		0.43^{bB} ± 0.3	1.37 ± 0.5	3.06 ± 0.8	13.66 ± 4.5	20.23 ± 3.0	10.75^{cdA} ± 0.8	44.86 ± 8.0	49.62 ± 8.2
Early White		1.27^{bA} ± 0.3	4.35 ± 0.5	5.24 ± 0.8	16.28 ± 4.5	18.39 ± 3.0	8.26^{efA} ± 0.8	43.44 ± 10.0	53.80 ± 8.2
Purple		0.72^{bA} ± 0.3	1.44 ± 0.5	3.48 ± 0.8	11.08 ± 4.5	17.36 ± 3.0	9.68^{deA} ± 0.8	38.32 ± 8.0	43.40 ± 8.2
					Results of statistical analysis				
Factor	DF				*p*-Value for the F test of the corresponding factor				
Year*Rep	4	0.9828	0.9752	0.2029	0.4030	0.9209	0.9179	0.8986	<0.0001
G	1	<0.0001	0.0002	0.0009	0.1813	0.0025	<0.0001	0.0236	0.3929
year	1	0.0006	0.0467	0.0014	0.0015	0.0009	0.0019	0.0011	0.0553
Year*G	1	0.0180	0.0784	0.1940	0.9366	0.6421	0.0095	0.8770	0.6907

ANOVA table (replication = REP; genotype = G; year = year; degree of freedom (DF) and *p*-value) carried out for the sugar fractions GF_4, GF_3, GF_2, sucrose, fructose, glucose, total FOS, and total sugar content in % of DM. Within years, same lower case letters in one column indicate no significant difference between genotypes at $p < 0.05$. Across years, same capital letters in one column indicate no significant differences between one genotype between the years at $p < 0.05$.

4. Discussion

4.1. Tuber Yields

In 2017, tuber yields (t ha^{-1} FM) of the genotypes 'RG', 'BG', and 'Morado' were higher than the tuber yields reached under comparable climatic conditions in Czech Republic which ranged from 21.43 to 29.18 t FM ha^{-1} [24,25]. In general, tuber yields of yacon indicate a wide range depending on location, climatic conditions, and genotype, ranging from 13.4 to 90.0 t FM ha^{-1} [7,26]. In this regard, different planting densities used in various studies have to be taken into account. In the above described studies, plant densities were between 20,408 and 28,500 plants ha^{-1}, which is noticeably higher than the plant density of 12,531 plants ha^{-1} in the present study [24,26]. Doo et al. reported that tuber yield increased with increasing plant density up to a plant density of 70 × 50 cm [27]. Therefore, tuber yields of the present study could be maximized by higher plant densities, even though yields were already quite high. Significant differences between tuber yields of various yacon genotypes were also reported by Fernández et al. and Kim and Koike et al. [24,28,29]. In the year 2018 of the present study, tuber yields of all genotypes were significantly lower, probably due to climatic conditions. During the cultivation period in 2018, temperatures were 2.6 °C higher and precipitation was 401 mm lower when compared to 2017. Especially the long-lasting period without significant rainfall events led to significantly lower tuber yields below expectations. Several other studies showed that an adequate precipitation of minimum 550 mm of water during the growing period is a key factor for exploiting the full yield potential of yacon [7,30]. This is similar to the findings of Fernández et al., who reported on average the lowest tuber yields in the year with the lowest precipitation [24]. This is also true for other tuberous root crops like Jerusalem artichoke and potato [31,32].

Determined tuber DM was within the normal range of 9.8 to 18.6% [14,33]. In accordance with lower tuber yields in 2018, DM content was similar or significantly higher in 2018 than 2017, which can also be attributed to the lower precipitation amount. The results are similar to the findings of Mastro et al., who also reported higher DM content in Jerusalem artichocke and chicory in years with lower precipitation [34]. Significant differences of DM content of yacon tubers between the genotypes were also reported in several other studies and seem to be a characteristic of each genotype [14,29,33].

Dry matter tuber yields (t ha^{-1} DM) were in a normal and partially above average range of 1.2 to 6.36 t ha^{-1}. DM yields differed significantly between the years because of lower precipitation, as mentioned above. [7]. The genotype 'RG' especially attracted interest due to having the highest tuber yields (both FM and DM) and highest DM content. The DM content, and therefore DM tuber yield, is particularly important with regard to the intended processing. A high DM content is preferable due to higher outputs of sugar and dried products when considering e.g., powder, chips, or flour. For commercialization to the fresh market, the parameters number of tubers and average tuber weight are more important. With regards to other crops like sweet cassava or eggplant, there are clear restrictions for commercialization at the fresh market. Cassava must have a minimum weight of 300 g, and eggplant has to be uniform in size [35,36].

Currently, regulations for commercialization of yacon at fresh markets are really low with respect to size and weight [37]. With increasing demand and therefore increasing supply in fresh market, more regulations might arise. Besides the aspect of commercialization, number of tubers are a decisive factor for mechanization of harvesting. With increasing number of tubers per plant, the cut surface of each tuber decreases. While this is advantageous for harvest, because of an easier separation of tubers and rhizomes, it also meets commercialization regulations, as the cut surface is limited to a maximum size of 1 to 2.5 cm [37]. In general, the number of tubers per plant in the present study was in the normal range. Bredemann reached an average 14.4 tubers per plant in field trials in Germany [3]. Several other studies reported 6 to 12.5 tubers per plant [27,29]. However Douglas et al. achieved up to 27 tubers per plant, but with a higher plant density of 28,986 plants ha^{-1} [18]. Reasonable therefore are the increasing numbers of tubers per plant with increasing plant density [27]. Besides the plant density and precipitation, genotype is a relevant factor for the number of tubers per plant. All genotypes (except

'Rojo') had significantly lower number of tubers per plant in 2018, the year with lower precipitation. As the average single tuber weight did not show an effect of genotype × year interaction, it seems that plants compensate for lower precipitation by decreasing the number of tubers. This coincides with the findings of Douglas et al., who reported lower numbers of tubers per plant at lower precipitation [7]. Similar to that are the results of Onder et al. and Bélanger et al. who also reported a decreasing number of tubers with decreasing amount of water and a lower amount of tuber weight, respectively [38,39].

Average single tuber weights achieved in the present study were mainly above common values, ranging from 115 to 184 g, but similar to findings of Kamp et al., who reported single tuber weights up to 308 g in Central Europe [18,22,29]. Polreich reported a positive correlation between average single tuber weight and total tuber yield [40]. This goes along with the findings of the present study, as average single tuber weights across all genotypes were significantly lower in 2018 than 2017 as well as total tuber yields. Overall the study indicated significant differences between genotypes and the two experimental years.

4.2. Sugar Yield

Compared to other FOS containing crops, obtained sugar yields of the different genotypes were quite low. Jerusalem artichoke and chicory normally reach sugar yields ranging from 4.1 to 9.1 t ha^{-1} and 4 to 18 t ha^{-1}, respectively [31,34]. This is primarily due to higher amounts of tuber yields. Similar to findings regarding the tuber yield formation in 4.1, sugar yield differed significantly between the genotypes as well. Genotypes 'RG', 'BG', and 'Morado' had the highest sugar yields in 2017 and showed also a huge decrease of sugar yield from 2017 to 2018. All other genotypes, except 'Late Red', showed no significant differences between the years. This might point to a sensitivity of these genotypes to water limiting conditions or, in the reverse direction, that the genotypes with significant differences between the years had a better water use efficiency. Precipitation is considered a key factor for tuber yield formation [24,41] and may be the major reason for the significant differences in sugar yield between the two experimental years. This is also true for Jerusalem artichoke und chicory [34,42]. Depending on the given climatic conditions some genotypes may be better adapted to drought and hot conditions than other genotypes. The given climatic differences of the Andean region with altitudes from sea level to 2000 m above sea level may result in different adaptations of the genotypes [43,44].

In general, sugar yield depends on the amount of tuber yield DM and sugar content. Therefore, both parameters have to be considered. Sugar yield was lower in years with lower precipitation due to lower tuber yields. However, the genotype 'Rojo' attracted attention due its significant lowest sugar yields, which was basically a result of low tuber yield, low DM%, and low sugar content. All other genotypes can be divided into two groups; 'RG', 'BG', and 'Morado' with high sugar yields and significant differences between the years, and all other genotypes with a similar sugar yield without significant differences between years (except 'Late Red').

4.3. Sugar Composition

The total sugar content of yacon tubers ranges commonly from 70% to 80% of DM, which is higher than the findings in the present study, but similar to findings of Kamp et al., who also reported total sugar contents ranging from 35% to 73% of DM, under comparable climatic conditions [6,11,23]. In general, more information on FOS content and monosaccharides than total carbohydrates are available. Reported FOS contents in literature ranged from 6.4% to 70% of DM, depending on genotype or cultivation site [6,10,33]. In general sugar fractions showed a wide range in the literature, because of different genotypes, cultivation practices, and storage conditions [2,14]. Reported ranges in literature are in range with the results of the present study. Also the FOS content of Jerusalem artichoke differed significantly between the genotypes [17]. This is similar to findings of the present study, where genotypes differed significantly across years. Higher FOS contents in 2018 can be explained by higher DM contents (3.1). This is similar to findings of Sprague et al., who reported higher sugar contents in Jerusalem artichoke in years with higher DM% due to lower precipitation and soil moisture [45].

Single fractions of FOS (GF_2, GF_3, and GF_4) changed according to changes in total FOS content. Several findings in literature described a decreasing amount of total FOS with an increase of DP [2,15,46]. This is similar to findings of the present study, where in 2017, the year with lower FOS content, all genotypes had a higher percentage of FOS in GF_3 or even GF_4 ('Rojo'). Whereas in 2018, the year with higher amounts of FOS, degree of polymerization approximately balanced between GF_3 and GF_2. This also points to a positive correlation between amount of sucrose and amount of FOS [2,8,47]. In 2018, amount of sucrose was significantly higher than in 2017 as well as the amount of FOS.

The amount of fructose was also widely dispersed and ranged from 0.6 to 21.6% of DM, depending on the chosen genotype [6,15,33]. In the present study, genotypes differed significantly in fructose content which ranged from really low (0.72% 'Purple' 2018) to rather high amounts (5.61% 'Rojo' 2017). All genotypes, except RG, had significantly higher amounts of fructose in 2017 than 2018. A similar trend was observed for glucose. In general, amounts of fructose reached in the present study were in a normal range from 0.9% to 9% of DM [6,15,33,46]. This is also true for sucrose, which normally ranged from 2.2 to 14% of DM [15,46]. The quantities of monosaccharides reached in the present study were similar to those reported by Khajehei et al., who also examined the genotypes 'Early White', 'Late Red', 'Morado', and 'New Zealand'. The resulting order of genotypes regarding their amounts of fructose and glucose were similar to findings of Khajehei et al. [48]. Results in the present study indicated that mainly the genotypes with high amounts of fructose had the lowest amounts of total FOS. This is similar to findings of Herman et al., who reported a negative correlation between fructose and amount of fructans [33]. Overall, different sugar compositions may lead to different commercialization and food product development strategies. Genotypes with higher amounts of monosaccharides and FOS with average lower DP are preferable for the fresh market, because of the sweet taste and poor storability of FOS. During storage the amount of FOS decreases and the amount of monosaccharides duplicates [10]. The FOS contained in yacon tubers are really sensitive to storage conditions like temperature and humidity [49,50]. Therefore, genotypes like 'Rojo' and 'Peru' were preferable for the fresh market, because of already high amounts of monosaccharides at harvest and their sweet taste. During storage the amount of monosaccharides will further increase and health promoting benefits would potentially fade away. Besides sugar compositions, these genotypes were preferable for the fresh market due to the attractive color of the peel and products consisting thereof.

Beyond the appropriateness for the fresh market, the tested genotype 'Peru' offers both high amounts of monosaccharides and FOS which are beneficial due to a sweet taste and health promoting benefits. Therefore 'Peru' is considered to be a good choice for fresh market purposes regarding its sugar composition. However tuber yield was disregarded for this recommendation.

On the other side, the genotypes 'BG', 'RG', and 'Morado' seem to be potential good options for the processing industry, due to their high amounts of FOS. Certainly 'Peru' had high amounts of FOS, but predominant with lower DP.

5. Conclusions

The parameters tuber yield, sugar composition, and sugar content determine decisively the final sugar yield of yacon. The current study revealed that across all parameters (tuber yield, sugar composition, and sugar yield) the three genotypes 'RG', 'BG', and 'Morado' were outstanding and can be recommended for cultivation in Southwestern Germany due to highest amount of tuber yield, sugar yield, and FOS. The combination of high tuber yields and sugar content led to the highest sugar yields. Depending on the intended commercialization strategy, a certain genotype has to be chosen. The three genotypes 'RG', 'Peru', and 'Morado' are preferable for the fresh market, powder, or flour production because of lower single tuber weight and the color of peel. Red peel leads to optically attractive flour which can be commercialized in several ways. 'BG' was favorable for the processing industry. Also the fresh market could be possible, for example, for key accounts with larger demands, like gastronomy, etc.

With regard to sugar composition major differences in fructose and GF_4 content were observed between genotypes. Genotypes with high amounts of fructose had lower amounts of GF_4 and vice versa. Therefore different commercialization options are possible. In general, genotypes with higher amounts of monosaccharides and FOS with lower average DP seem to be favorable for fresh market purposes while genotypes with higher amounts of FOS and higher average DP can be recommended for the processing industry as they potentially withstand longer storage periods without total loss of quality.

Author Contributions: Conceptualization, L.K. and S.G.-H.; methodology, B.M. and L.K.; formal analysis, L.K.; investigation, L.K.; resources L.K. and S.G.-H.; data curation, L.K.; software, J.H; writing—original draft preparation, L.K.; writing—review and editing, S.G.-H.; visualization, L.K.; supervision, S.G.-H.; project administration, S.G.-H.; funding acquisition, S.G.-H.

Funding: This research was funded by the German Federal Ministry for Economic Affairs and Energy within the Central Innovation Program for SMEs, grant number 16KN050526.

Acknowledgments: The authors would like to thank the technical staff of the Experimental Station Ihinger Hof of the University of Hohenheim. The authors would also like to thank Fabian Görzgen from the department of biochemical and chemical engineering, TU Dortmund, for answering questions on sugar formation and composition.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Appendix A

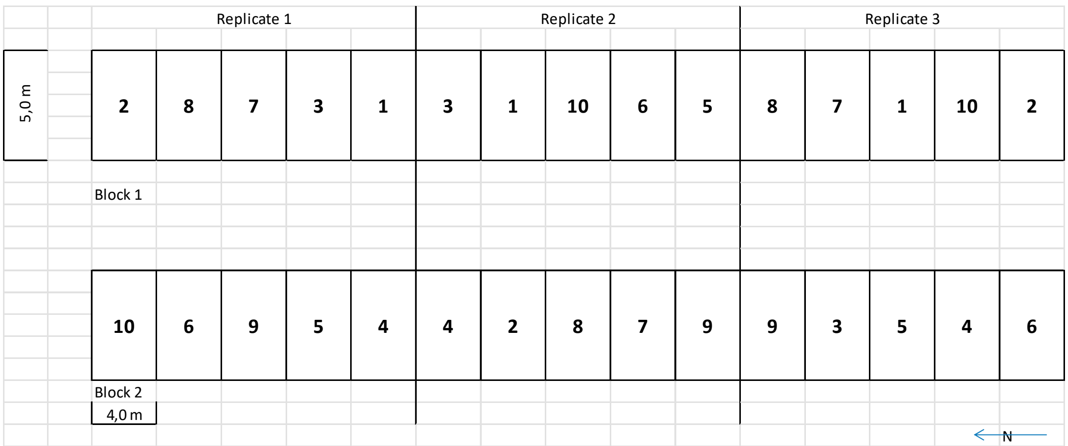


Figure A1. α-Design of the field trials exemplary for the experimental year 2017 with three replicates and two blocks. For 2018 same design with new randomization were used. Replicates were complete, blocks were incomplete due to missing germination of one genotype. Each number represents one genotype. Genotype number 6 did not germinate and was therefore deleted from the analysis.

Table A1. Results of a multiple t-test at a significance level of 5% after finding significant differences via global F-test for the factor genotype across both experimental years. Same lower case letters indicate non-significant differences between genotypes.

Genotype	Single Tuber Weight (g)	Glucose (%)	Sucrose (%)	GF_3 (%)	Total FOS (%)
'BG'	267.4^{a}	3.29^{ab}	5.12^{a}	16.29^{ab}	40.72^{a}
'RG'	223.7^{ac}	1.71^{c}	3.24^{bc}	18.56^{a}	41.37^{a}
'Morado'	205.9^{bc}	2.38^{bc}	2.98^{bc}	16.04^{ab}	37.04^{a}
'Rojo'	172.1^{cd}	3.71^{a}	3.04^{bc}	6.55^{c}	17.83^{b}
'New Zealand'	175.3^{cd}	2.19^{c}	2.58^{c}	13.30^{b}	30.61^{a}
'Peru'	231.8^{ab}	4.56^{a}	5.44^{a}	15.16^{ab}	39.04^{a}
'Late Red'	144.8^{d}	1.50^{c}	2.52^{c}	16.42^{ab}	35.60^{a}
'Early White'	223.7^{ac}	3.67^{a}	4.10^{ab}	15.48^{ab}	34.63^{a}
'Purple'	185.3^{bcd}	2.21^{bc}	3.22^{bc}	14.30^{ab}	31.05^{a}

Table A2. ANOVA table (replication = REP; genotype = G; year = year; degree of freedom (DF) and *p*-value) carried out for sugar yield (t ha^{-1}) according to Figure 2.

Factor	DF	*p*-Value for the F-test of the Corresponding Factor
Year × Rep	4	0.1666
G	8	<0.0001
Year	1	0.0002
Year × G	8	0.0001

References

1. Hermann, M. *Andean Roots and Tubers: Ahipa, Arracacha, Maca and Yacon*; International Plant Genetic Resources Institute: Rome, Italy, 1997; Volume 21, pp. 191–243.
2. Ohyama, T.; Ito, O.; Yasuyoshi, S.; Ikarashi, T.; Minamisawa, K.; Kubota, M.; Tsukihashi, T.; Asami, T. Composition of storage carbohydrate in tubers of yacon (Polymnia sonchifolia). *Soil Sci. Plant Nutr.* **1990**, *36*, 167–171. [CrossRef]
3. Bredemann, G. *Über Polymnia Sonchifolia Poepp. et Endl. (P. edulis Wedd.), die Yacon - Erdbirne*; Botanische Oeconomie: Hamburg, Germany, 1948; pp. 65–85.
4. Zardini, E. Ethnobotanical notes on "Yacon" Polymnia sonchifolia (*Asteraceae*). *Econ. Bot.* **1991**, *40*, 72–85. [CrossRef]
5. Fernández, E.C.; Viehmannova, I.; Bechyne, M.; Lachman, J.; Milella, L. The cultivation and phenological growth stage of yacon [*Smallanthus Sonchifolius* (Poepp. et Endl.) H. Robinson]. *Agric. Trop. Et. Subtrop.* **2007**, *40*, 71–77.
6. Delgado, G.T.C.; Tamashiro, W.M.d.S.C.; Marostica, M.R., Jr.; Pastore, G.M. Yacon (*Smallanthus sonchifolius)*: A functional food. *Plant Foods Hum. Nutr.* **2013**, *68*, 222–228. [CrossRef] [PubMed]
7. Douglas, J.A.; Follett, J.M.; Douglas, M.H.; Deo, B.; Scheffer, J.J.C.; Littler, R.A.; Manley-Harris, M. Effect of environment and time of planting on the production and quality of yacon (*Smallanthus sonchifolius*) storage roots. *N. Z. J. Crop. Hor. Sci.* **2007**, *35*, 107–116. [CrossRef]
8. Valentova, K.; Lebeda, A.; Dolezalova, I.; Jirovsky, D.; Simonovska, B.; Vovk, I.; Kosina, P.; Gasmanova, N.; Dziechciarkova, M.; Ulrichova, J. The biological and chemical variability of yacon. *J. Agric. Food Chem.* **2006**, *54*, 1347–1352. [CrossRef] [PubMed]
9. Manrique, I.; Parraga, A.; Hermann, M. Yacon Syrup: Principles and Processing. Available online: http://cipotato.org/wp-content/uploads/2014/07/1919-Yacon_Syrup.pdf (accessed on 19 July 2014).
10. Graefe, S.; Hermann, M.; Manrique, I.; Golombek, S.; Buerkert, A. Effects of post-harvest treatments on the carbohydrate composition of yacon roots in the Peruvian Andes. *Field Crop. Res.* **2004**, *86*, 157–165. [CrossRef]
11. Lachman, J.; Fernández, E.C.; Orsák, M. Yacon [*Smallanthus sonchifolia* (Poepp. et Endl.) H. Robinson] chemical composition and use – a review. *Plant Soil Environ.* **2003**, *49*, 283–290. [CrossRef]
12. Goto, K.; Fukai, K.; Hikida, J.; Nanjo, F.; Hara, Y. Isolation and Structural Analysis of Oligosaccharides from Yacon (Polymnia sonchifolia). *Biosci. Biotechnol. Biochem.* **2014**, *59*, 2346–2347. [CrossRef]
13. de Almeida Paula, H.A.; Abranches, M.V.; de Luces Fortes Ferreira, C.L. Yacon (*Smallanthus sonchifolius*): A food with multiple functions. *Crit. Rev. Food Sci. Nutr.* **2015**, *55*, 32–40. [CrossRef]
14. Campos, D.; Betalleluz-Pallardel, I.; Chirinos, R.; Aguilar-Galvez, A.; Noratto, G.; Pedreschi, R. Prebiotic effects of yacon (*Smallanthus sonchifolius* Poepp. & Endl), a source of fructooligosaccharides and phenolic compounds with antioxidant activity. *Food Chem.* **2012**, *135*, 1592–1599. [CrossRef] [PubMed]
15. Fukai, K.; Miyazaki, S.; Nanjo, F.; Hara, Y. Distribution of carbohydrates and related enzyme activities in yacon (*Polymnia Sonchifolia*). *Soil Sci. Plant Nutr.* **1993**, *39*, 567–571. [CrossRef]
16. Campbell, J.M.; Bauer, L.L.; Fahey, G.C.; Hogarth, A.J.C.L.; Wolf, B.W.; Hunter, D.E. Selected Fructooligosaccharide (1-Kestose, Nystose, and 1 F -β-Fructofuranosylnystose) Composition of Foods and Feeds. *J. Agric. Food Chem.* **1997**, *45*, 3076–3082. [CrossRef]
17. Slimestad, R.; Seljaasen, R.; Meijer, K.; Skar, S.L. Norwegian-grown Jerusalem artichoke (*Helianthus tuberosus* L.): morphology and content of sugars and fructo-oligosaccharides in stems and tubers. *J. Sci. Food Agric.* **2010**, *90*, 956–964. [CrossRef] [PubMed]

18. Douglas, J.A. Maximising fructo-oligosacharide production in yacon. *Agron. N. Z.* **2002**, *32*, 49–55.
19. de Andrade, E.F.; Leone, R.d.S.; Ellendersen, L.N.; Masson, M.L. Phenolic profile and antioxidant activity of extracts of leaves and flowers of yacon (*Smallanthus sonchifolius*). *Ind. Crop. Prod.* **2014**, *62*, 499–506. [CrossRef]
20. Leidi, E.O.; Altamirano, A.M.; Mercado, G.; Rodriguez, J.P.; Ramos, A.; Alandia, G.; Sørensen, M.; Jacobsen, S.-E. Andean roots and tubers crops as sources of functional foods. *J. Funct. Foods* **2018**, *51*, 86–93. [CrossRef]
21. IUSS Working Group WRB. *World Reference Base for Soil Resources 2006. Ein Rahmen für Internationale Klassifikation, Korrelation und Kommunikation. Erstes Update 2007. Deutsche Ausgabe*; BGR: Hannover, Germany, 2008; ISBN 978-3-00-024824-5.
22. Kamp, L.; Hartung, J.; Mast, B.; Graeff-Hönninger, S. Plant growth, tuber yield formation and costs of three different propagation methods of yacon (*Smallanthus sonchifolius*). *Ind. Crop. Prod.* **2019**, *132*, 1–11. [CrossRef]
23. Kamp, L.; Hartung, J.; Mast, B.; Graeff-Hönninger, S. Impact of Nitrogen Fertilization on Tuber Yield, Sugar Composition and Nitrogen Uptake of Two Yacon (*Smallanthus Sonchifolius* Poepp. & Endl.) Genotypes. *Agronomy* **2019**, *9*, 151. [CrossRef]
24. Fernández, E.C.; Viehmannová, I.; Bechyne, M.; Lachman, J.; Milella, L. Yacon [*Smallanthus sonchifolius* (Poeppig & Endlicher) H. Robinson]: A new crop in the Central Europe. *Plant Soil Environ.* **2006**, *12*, 564–570.
25. Leemans, R.; Cramer, W. *The IIASA Database for Mean Monthly Values of Temperature, Precipitation and Cloudiness on a Global Terrestrial Grid*; Research Report; IIASA: Laxenburg, Austria, 1991; Volume 61, p. RR-91-018.
26. Doo, H.S. Response of Different Seedlings to Growth and Yield in Yacon. *Korean J. Crop Sci.* **2002**, *5*, 356–360.
27. Doo, H.S. Effect of Plant Density on Growth Response and Yield in Yacon. *Korean J. Crop Sci.* **2001**, *10*, 407–410.
28. Kim, S.J. Domestic and Overseas Status and Future Trends of Yacon Production. *Korean J. Int. Agric.* **2012**, *24*, 417–424.
29. Koike, A.; Murata, T.; Matsuda, Y.; Masuoka, C.; Okamoto, C.; Kabata, K. Cultivation and ensilage of yacon plants (*Smallanthus sonchifolius* [Poepp. & Endl.] H. Robinson) and the function of yacon silage. *Grassl. Sci.* **2009**, *55*, 6–10. [CrossRef]
30. Cabrera, M.V. Manual del cultivo de yacon. *Productores y mercados Del. Agro. De. La. Sierra.* **2005**. Available online: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=11&ved=2ahUKEwjIsLj8wN7iAhUF3aQKHceUBHgQFjAKegQIABAC&url=http%3A%2F%2Fwww.asocam.org%2Fsites%2Fdefault%2Ffiles%2Fpublicaciones%2Ffiles%2F74455093814a213d6976637f4f71ad5f.pdf&usg=AOvVaw3gvGyIMlYKr97e2OlelbDn (accessed on 10 June 2019).
31. Losavio, N.; Lamascese, N.; Vonella, A.V. Water requirements and nitrogen fertilization in jerusalem artichoke (*Helianthus tuberosus* L.) grown under mediterranean conditions. *Acta Hortic.* **1997**, *1*, 205–209. [CrossRef]
32. Müller, S.; Beer, K. The relationships between soil inorganic nitrogen levels and nitrogen fertilizer requirements. *Agric. Ecosyst. Environ.* **1986**, *17*, 199–211. [CrossRef]
33. Hermann, M.; Freire, I.; Pazos, C. Compositional Diversity of the Yacon Storage Root. *Impact Chang. World Program Rep.* **1997**, *98*, 425–432.
34. de Mastro, G.; Manolio, G.; Marzi, V. Jerusalem artichoke (*Helianthus tuberosus* L.) and chicory (*Chicorium intybus* L.): Potential crops for inulin production in the mediterranean area. *Acta Hortic.* **2004**, 365–374. [CrossRef]
35. FAO. Standard for Aubergines. 2018. Available online: http://www.fao.org/fao-who-codexalimentarius/codex-texts/list-standards/en/ (accessed on 10 June 2019).
36. Brisco; Gracia. STANDARD FOR SWEET CASSAVA. CODEX STAN 238-2003. 2003. Available online: http://www.fao.org/fao-who-codexalimentarius/codex-texts/list-standards/en/ (accessed on 10 June 2019).
37. FAO. Regional Standards for Yacon. 2017. Available online: http://www.fao.org/fao-who-codexalimentarius/codex-texts/list-standards/en/ (accessed on 10 June 2019).
38. Onder, S.; Caliskan, M.E.; Onder, D.; Caliskan, S. Different irrigation methods and water stress effects on potato yield and yield components. *Agric. Water Mgmt.* **2005**, *73*, 73–86. [CrossRef]
39. Bélanger, G.; Walsh, J.R.; Richards, J.E.; Milburn, P.H.; Ziadi, N. Nitrogen fertilization and irrigation affects tuber characteristics of two potato cultivars. *Am. J. Potato Res.* **2002**, *79*, 269–279. [CrossRef]
40. Polreich, S. Establishment of a Classification Scheme to structure the Establishment of a Classification Scheme to structure the Post-Harvest Diversity of Yacon Storage Roots (*Smallanthus sonchifolius* (Poepp. & Endl.) H. Robinson). Master' Thesis, University of Kassel, Kassel, Germany, 2003.

41. Douglas, J.A. Research and Development of Yacon Production in New Zealand. *Acta Hortic.* **2005**, *670*, 79–85. [CrossRef]
42. Meijer, W.J.M.; Mathijssen, E.W.J.M.; Borm, G.E.L. Crop characteristics and inulin production of jerusalem artichoke and chicory. *Stud. Plant Sci.* **1993**, *1991*, 29–38.
43. FAO. Ecuador Country Profile. Available online: http://www.fao.org/countryprofiles/index/en/?iso3=ECU (accessed on 10 April 2019).
44. FAO. Peru Country Profile. Available online: http://www.fao.org/countryprofiles/index/en/?iso3=PER (accessed on 10 April 2019).
45. Sprague, H.B.; Farris, N.F.; Colby, W.G. Effect of Soil Conditions and Treatment on Yields of Tubers and Sugar from the American Artichoke (*Helianthus tuberosus*). *J. Am. Soc. Agrono.* **1935**, 392–399. [CrossRef]
46. Delgado, G.T.C.; Thomé, R.; Gabriel, D.L.; Tamashiro, M.S.C.; Pastore, G.M. Yacon (*Smallanthus sonchifolius*)-derived fructooligosaccharides improves the immune parameters in the mouse. *Nutr. Res.* **2012**, *32*, 884–892. [CrossRef]
47. Lebeda, A.; Dolezalova, I.; Valentova, K.; Gasmanova, N.; Dziechciarkova, M.; Ulrichova, J. Yacon (*Smallanthus sonchifolius*) - A traditional crop of the Andean Indians as a challenge for the future - The news about biological variation and chemical substances content. *Acta Hortic.* **2008**, 127–136. [CrossRef]
48. Khajehei, F.; Merkt, N.; Claupein, W.; Graeff-Hoenninger, S. Yacon (*Smallanthus sonchifolius* Poepp. & Endl.) as a Novel Source of Health Promoting Compounds: Antioxidant Activity, Phytochemicals and Sugar Content in Flesh, Peel, and Whole Tubers of Seven Cultivars. *Molecules* **2018**, *23*. [CrossRef]
49. Doo, H.S. Changes of chemical composition in tuberous root of yacon by different curing conditions. *Korean J. Crop. Sci.* **2000**, *45*, 79–82.
50. Minamisawa, K. Fluctuations of oligofructan contents in tubers of yacon (Polymnia sonchifolia) during growth and storage. *Jpn. Soc. Soil Sci. Plant Nutr.* **1991**, *43*, 621–627.

5. Chapter III: Impact of nitrogen fertilization on tuber yield, sugar composition and nitrogen uptake of two yacon (*Smallanthus sonchifolius* Poepp. & Endl.) genotypes

---

Publication III:

Kamp, L., Hartung, J., Mast, B., Graeff-Hönninger, S. (2019): Impact of nitrogen fertilization on tuber yield, sugar composition and nitrogen uptake of two yacon (*Smallanthus sonchifolius* Poepp. & Endl.) genotypes. Agronomy 2019, 9, 151.

In Chapter II the results clearly indicated that tuber yield and sugar content as well as sugar composition highly depend on genotype. In the previous chapter it could be determined, that the genotypes brown-shelled and red-shelled are the two with the biggest potential for both tuber yield and sugar content. Besides the factor genotype there are other factors that potentially influence tuber yield and sugar content. One key factor is nitrogen fertilization. Therefore, the following chapter deals with the impact of different nitrogen fertilization levels on tuber yield and sugar composition. Furthermore, were observed the nitrogen concentration of different plant parts for outlining nitrogen uptake and potential nitrogen demand of yacon. When determining nitrogen content in different plant parts, possibilities for further exploitations of plant material could be taken into consideration as well.

agronomy

MDPI

Article

Impact of Nitrogen Fertilization on Tuber Yield, Sugar Composition and Nitrogen Uptake of Two Yacon (*Smallanthus sonchifolius* Poepp. & Endl.) Genotypes

Larissa Kamp [1,*], Jens Hartung [2], Benjamin Mast [1] and Simone Graeff-Hönninger [1]

[1] Institute of Crop Science, Fruwirthstr. 23, University of Hohenheim, 70599 Stuttgart, Germany; Benjamin.Mast@gmx.de (B.M.); simone.graeff@uni-hohenheim.de (S.G.-H.)

[2] Department of Biostatistics, Institute of Crop Science, Fruwirthstr. 23, University of Hohenheim, 70599 Stuttgart, Germany; moehring@uni-hohenheim.de

* Correspondence: Larissa.Kamp@uni-hohenheim.de; Tel.: +49-711-459-24185

Received: 25 February 2019; Accepted: 19 March 2019; Published: 22 March 2019

check for updates

Abstract: The tuberous root crop, yacon, is native to the Andean region and contains high amounts of fructooligosaccharides (FOS) with up to 70% of dry matter. Due to FOS, consumption of tubers may have health-promoting effects. However, regarding the overall cultivation system, no recommendations exist for farmers on nitrogen fertilization and nitrogen (N) uptake of yacon. Therefore, three different N fertilization levels (0, 40, and 80 kg N ha^{-1}) and two genotypes (brown-shelled (BG) and red-shelled (RG)) were examined in a two-year field experiment regarding their tuber yield, sugar composition, and nitrogen uptake. Tuber yields increased with increasing fertilization level and were highest for B80 and R80 (50 and 67 t FM ha^{-1}), while significant differences between the genotypes existed. Sugar and the amount of FOS slightly decreased with increasing N fertilization level, and ranged between 36% and 73% and 30% and 58% of dry matter, respectively. An overall decreasing amount of FOS led to a slight increase in the amount of FOS with a higher degree of polymerization. Regarding the N-use efficiency of tubers and the total plant, an N fertilization level of 40 kg N ha^{-1} seems to favor tuber yield.

Keywords: fructooligosaccharide; yacon; nitrogen content

1. Introduction

The tuberous root plant, yacon (*Smallanthus sonchifolius*) ((Poepp. and Endl.) H. Robinson) is native to the Andean region and related to the family of *Asteraceae*. Apart from the Andean region, yacon has also been cultivated in Japan, Brazil, New Zealand, Czech Republic, Italy, and Germany [1,2]. Yacon is a perennial, herbaceous plant, which is not frost-tolerant. The plant grows to be 2–2.5 m, and the generally arrow-shaped leaves are dark green [3,4]. The average tuber yield of each plant amounts to 2–3 kg, or up to 5 kg [5–7]. Each tuber weighs between 200 and 500 g on average, but can reach a weight of up to 2000 g. The dry-matter content commonly ranges between 10–14% [3,8]. The color of the peel and flesh of the tubers can vary from white, creamy, yellow, and orange red, to purple [9].

In its tuberous roots, yacon mainly stores carbohydrates in the form of fructans, and particularly fructooligosaccharides (FOS) and inulin. FOS and inulin account for up to 70% of dry matter. The main components of FOS are kestose, nystose, and fructofuranosylnystose [5]. These polysaccharides may not be digested by the human intestinal tract, wherefore no increase in blood glucose level occurs after the consumption of fresh yacon [10,11]. Other carbohydrates stored in the tubers are sucrose, and the monosaccharides fructose and glucose. The composition of stored carbohydrates depends on various factors, such as the origin, growing conditions, and farming system [5].

As the interest in yacon has increased over the last 2–3 years, due to its potential as a natural sugar replacement, a proper crop management and cultivation system needs to be developed in order to cover the increasing demand. Up until now, only very limited information on the nitrogen (N) fertilization requirement of yacon and the influence of N on the sugar composition of yacon tubers has been available. Furthermore, the influence of N fertilization on tuber yield formation has not yet been reported.

Nitrogen is one of the most important nutrients in plant growth due to its direct effect on vegetative growth and related impacts on leaf area and light interception [12]. The expected N requirement of yacon reported in the literature ranges from 24 to 98 kg N ha^{-1} [6,13–15]. These values are below the N requirement of sweet potatoes and potatoes, which require up to 200 kg N ha^{-1} [12,16], while simultaneously having lower yield potentials per ha. In order to determine yacons' need for N fertilization, it is critically important to measure the N uptake of different plant parts, and thus to determine complete N removal.

Additionally, the impact of the N-level of tuber yield formation and sugar content has not been clearly defined. However, the impact of N-level on the root yield of sugar beet has been well-investigated. Increasing amounts of N fertilizer could lead to higher tuber yields, but decreasing sugar content [17–19]. Furthermore, N concentration in vegetative parts increases with increasing amounts of N application [20].

Besides the impact of N on plant growth and development, an adjusted fertilization strategy is also needed due to economic, as well as environmental reasons [21,22]. In the case where the applied amount of N exceeds the N uptake of the plant, the risk of N losses in ground water rises [23]. Due to a lack of knowledge about N fertilizer requirements of yacon, it is assumed that the amounts which are currently being applied do not meet the actual demand of the plant.

The aims of the present study are therefore to investigate the effect of different N fertilization levels on tuber yield formation and sugar composition, and also to evaluate the N uptake of different plant parts (above and below ground) of two different yacon genotypes. Based on the obtained results, the N fertilization requirement of yacon can be identified, and a specific fertilization strategy can be developed. The results of the current study can be used to considerably improve the environmental performance of yacon cultivation.

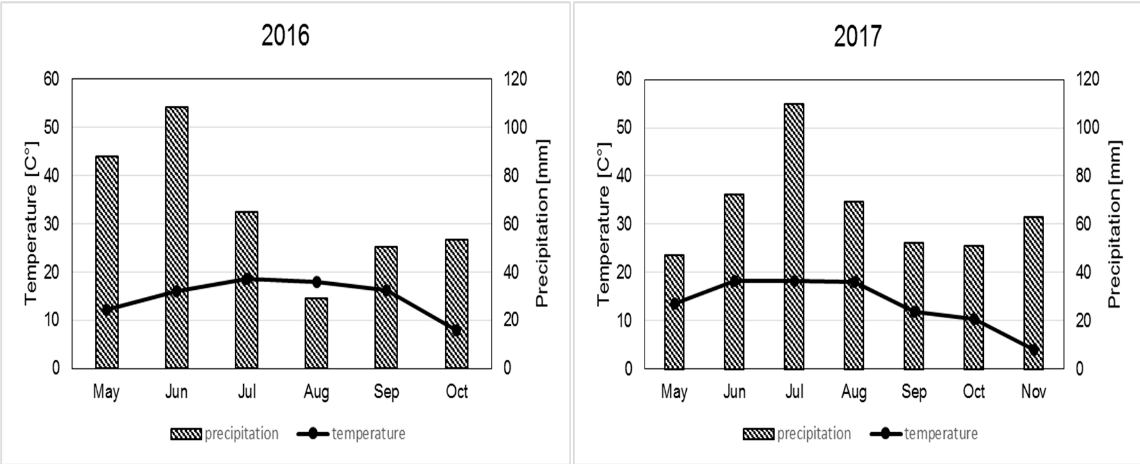
2. Materials and Methods

2.1. Field Site and Experimental Design

In 2016 and 2017, field experiments were carried out at the experimental station, Ihinger Hof of the University of Hohenheim (48° 44′ N, 8° 55′ E, and 475 a.s.l.) in Southwest Germany from May to October. The mean annual rainfall was 646.5 mm in 2016 and 653.9 mm in 2017. The average annual temperature was 9.1 °C in 2016 and 9.2 °C in 2017, respectively. During the cultivation period of yacon, the average temperature was 14.8 °C in 2016 and 13.5 °C in 2017. The rainfall amounted to 394.3 mm in 2016 and 464.7 mm in 2017 (Figure 1A,B).

The soil of both experimental years was a Vertic Cambisol [24]. In 2016, sugar beet was the preceding crop, while in 2017, winter wheat served as the preceding crop. The trials were set up as a randomized complete block design with three replicates. Each plot was 5 × 4 m. Yacon was planted in ridges (60 × 45 cm; 44 cm between the ridges; 114 cm between the center of ridges), which were formed using a common asparagus ridge-planting machine (Leofant, HMF-Hermeler Maschinenbau GmbH, Füchtorf, Germany). Each plot contained two ridges, which were directed from east to west, and 14 plants (0.7 × 1.14 m). Ridges were formed four weeks before planting. N_{min} in the soil was determined shortly before planting [25] and amounted to 28.8 kg NO_3 ha^{-1} in 2016 and 119 kg NO_3 ha^{-1} in 2017. To ensure that no water stress occurred, plots were irrigated by hand, twice in 2016 (27 May and 7 June) and four times in 2017 (26 and 30 May, 20 and 22 June) with 1.4 L per plant.

Weed control was done by hand once a week until the plant population was established and no weeds occurred anymore.



(a) **(b)**

Figure 1. Temperature (●) and precipitation (bars) at the trial site, Ihinger Hof for the cultivation period of yacon in (**a**) 2016 and (**b**) 2017. Plotted are the average temperatures in degree Celsius, and the total rainfall in mm in each month. Temperature and precipitation in May and October (2016) and May and November (2017) only include the days, which were within the cultivation period.

2.2. Treatments

Two different genotypes with three different N fertilization levels were investigated over both experimental years. The two genotypes were a brown-shelled (B) and red-shelled (R) genotype. These two genotypes were chosen because of the known yield differences from other studies. Further, they are the most commonly distributed and available genotypes. As the genotypes differ also in their development and total duration of cultivation period, it was assumed that this will point out important differences in yield and the final N uptake. First, seedlings were received from a plant nursery (Helenion, Berlin, Germany), and then the rhizomes were stored after each harvest for the next year's cultivation period.

The different N fertilization levels were 0 (control), 40, and 80 kg N ha^{-1}. This resulted in six treatments (Table 1). In both years, all treatments were fertilized with ENTEC 26 (EuroChem Agro GmbH, Mannheim, Germany) prior to planting. ENTEC 26 is a stabilized fertilizer, and consists of 26% total N (18% ammonium nitrogen, 7.5% nitrate nitrogen) and 13% hydro-soluble sulphur with nitrification inhibitors 3.4-dimethyl-1H-Pyrazolphosphat (DMPP), with an effect duration of four to ten weeks, depending on the climate, weather, and soil. In 2016, divided seedlings after budding (DSAB) were generated from mother plants and pre-cultivated for six to eight weeks in the greenhouse (Doo et al., 2002). In 2017, the propagation method was adjusted and seedlings were obtained from rhizome pieces which were pre-cultivated for six to eight weeks in the greenhouse. Cultivation of mother plants began ten days later on 15 April 2016, and seedlings were produced over a period of seven days. Mother plants were cultivated in round pots (37 cm height, Ø 32 cm on ground, Ø 44 cm top, 0.035 m^3) filled with 14 kg of standard soil (classic, expert substrate, Einheitserde Werkverband e.V., Sinntal-Altengronau, Germany) without further fertilization. To establish seedlings from the mother plant, the whole rhizomes were dug out every second day and rooted shoots were separated. Seedlings were transplanted into square planters (9 × 9 × 9.5 cm) filled with a standard soil (classic, expert substrate, Einheitserde Werkverband e.V., Sinntal-Altengronau, Germany) for further cultivation.

In 2017, cultivation of rhizome pieces started on 27 March. Whole rhizomes were sliced with a sterile knife into smaller segments (20–40 g), which were planted in square planters (9 × 9 × 9.5 cm) and filled with a standard soil (classic, expert substrate, Einheitserde Werkverband e.V., Sinntal-Altengronau, Germany). In both years, seedlings were cultivated in the greenhouse for six to eight weeks at 21 °C during the day and 15 °C during the night, where the humidity was about 65%. No artificial light was used. Pots were irrigated every third day.

Seedlings were transplanted manually on 18 May 2016 and 11 May 2017. Plants were placed with a distance of 1.14 m between rows and 0.7 m between plants in rows. Consequentially, the plant density was 12.531 plants ha^{-1}. Immediately after planting 6 kg ha^{-1}, slug pellets (Arinex, ADAMA Deutschland GmbH, Cologne, Germany) were applied manually.

Table 1. List of two used genotypes (B = brown-shelled, R = red-shelled) and three different N fertilization levels (0, 40, and 80 kg N ha^{-1}). Given abbreviations for each treatment will be used throughout the text.

Abbreviation Treatment	Genotype	Fertilization (kg N ha^{-1})
B0	brown-shelled	0
B40	brown-shelled	40
B80	brown-shelled	80
R0	red-shelled	0
R40	red-shelled	40
R80	red-shelled	80

2.3. Field Measurements and Sample Preparation

The traits of plant height (from soil surface to youngest leaf, end of stem), number of leaves on the main stem, and number of ramifications on the main stem were determined non-destructively on six plants in the central part of each plot, every second week from transplanting until harvest. Four destructive measurements were conducted every four weeks from the beginning of tuberous root formation until harvest (Table 2). For each destructive measurement, one single plant per plot (in 2016) or two plants per plot (in 2017) were harvested manually with a sickle and a digging fork. Plants were washed to remove soil residues. Afterwards, plants were separated into four parts: leaf, stem, tuber, and rhizome. Fresh weight and dry weight was determined for every part and every plant. Additionally, the weight of every single tuber was determined. For determination of the dry weight of the leaf and stem, bulked samples of each plot were dried at 60 °C until they reached a constant weight. For determination of the dry weight of tubers and rhizomes, mixed samples of each plot were frozen with liquid N (−196 °C) in order to prevent any further enzymatic reactions, and were finally freeze-dried.

The final harvest took place on 28 October 2016 and 2 November 2017 (163 and 175 days after planting (DAP), respectively). The date of harvest was scheduled depending on the outside temperature, and took place immediately after the first frost. The six central plants in each plot, which were measured non-destructively during the cultivation period, were harvested to obtain final yield data as before plants were subdivided into parts and washed. Again, the fresh weight of each part and plant was recorded. Additionally, the single tuber weight was recorded. Subsequently, a bulked sample of each part and plot was frozen with liquid N and freeze-dried.

For further plant analysis, all samples were milled. Freeze-dried samples (tubers and rhizomes) were milled with GRINDOMIX GM 200 (Retsch GmbH, Haan, Germany). Leaf and stem samples were milled with Ultra-Zentrifugalmühle ZM 200 (Retsch GmbH, Haan, Germany).

The nitrogen concentration in each freeze-dried sample was analyzed with near-infrared spectroscopy analysis (NIRS) by using a Model 5000 NIRS spectrometer (Agilent Technologies, Inc., Santa Clara, CA, USA). 3 mg of dried or freeze-dried milled samples of each plant part were placed in a cuvette. Double determination of each sample was also performed. For validation, 25% of the whole sample set was chosen randomly by the NIRS software, and the rest was assigned to the calibration set. Samples for validation were analyzed with a macro-elemental analyzer, Vario MAX CNS (Elementar, Hanau, Germany), according to the Dumas combustion method. The software WIN

ISI™ (Intrasoft Intl. S.A., Luxembourg) was used to perform validation and calibration. Throughout these procedures, aboveground (leaves and stems) and belowground (tubers and rhizomes) plant parts were handled separately.

The sugar composition of tubers was analyzed by using high-performance liquid chromatography (HPLC). Therefore, 0.5 g freeze-dried and milled samples were placed in Corning™ Falcon™ 50 mL (Fisher Scientific GmbH, Schwerte, Germany) and filled with a 25 mL mixture of HPLC-grade 70:30 Ethanol: Water (Chemsolute, Hamburg, Germany). Subsequently, mixtures were sonicated at 60 °C for 30 min, and then cooled at room temperature. Afterwards, the extract was filtered with an attached syringe filter holder (0.2 μm).

HPLC was performed using the Agilent 1290 Infinity (Agilent Technologies, Inc., Santa Clara, CA, USA). A Column A Phenomenex Rezex RSO (Phenomenex, Aschaffenburg, Germany) was used at a temperature of 85 °C. The eluent was 100% HPLC-grade water, and as the detector, a refractive index detector with a temperature of 40 °C was applied. The injection volume was 1 mL, and the flow rate was 0.4 mL min^{-1}. The content of fructofuranosylnystose (GF_4), nystose (GF_3), kestose (GF_2), fructose, glucose, and sucrose was determined using a standard curve drawn by an injection of standards (Merck KGaA, Darmstadt, Germany) of analyzed sugar.

In 2017, after each destructive measurement, soil samples in each plot were collected to determine N_{min} [25]. Therefore, the soil samples were immediately taken in each plot (besides the destructively measured plant) using an auger at a depth of 0–30 and 30–60 cm. Additionally, in both experimental years, soil samples after harvest were collected to determine N_{min} [25]. Therefore, two soil samples were taken from each plot at a depth of 0–30, 3–60, and 60–90 cm.

Table 2. Dates of transplanting, and the number of measurements and harvests in both experimental years, 2016 and 2017. Description includes the date and date of measurement (DAP) corresponding to all six tested treatments.

Year	Transplanting Date	Date of Measurement (DAP)				Harvest
		1.	2.	3.	4.	
2016	18.05	27.07. (70)	30.08. (104)	27.09. (132)	26.10. (161)	28.10. (163)
2017	11.05	27.07. (77)	24.08. (105)	21.09. (133)	23.10. (165)	02.11. (175)

2.4. Data Collection

For the calculation of N uptake, the dry matter of different plant fractions were multiplied with analyzed N concentration according to the following equation:

$$\text{N uptake (kg N ha}^{-1}) = \text{dry matter yield (kg ha}^{-1}) * (\%\ \text{N}/100).$$

For the determination of tuber N utilization efficiency ($TNUtE_D$), tuber yields (kg ha^{-1} DM) were divided by tuber N uptake (kg ha^{-1}). For the tuber N utilization efficiency of sugar ($TNUtE_{S,}$), the sugar yield (kg ha^{-1}) (data not shown) were divided by tuber N uptake (kg ha^{-1}). Total plant N utilization efficiency for sugar ($PNUtE_S$) was determined by dividing the sugar yield (kg ha^{-1}) by the N uptake of the total plant (kg ha^{-1}).

Total monosaccharides are given as a sum of glucose and fructose. Total FOS are given as a sum of GF_2, GF_3, and GF_4 [26]. Total sugar content is the sum of all analyzed sugar fractions (fructose, glucose, sucrose, and FOS).

2.5. Statistical Analysis

A mixed-model approach was used, and the following model was fitted to all traits:

$$y_{ijkl} = \mu + b_j + r_{jk} + a_i + \beta_l + (a\beta)_{il} + (ba)_{ij} + (b\beta)_{jl} + (ba\beta)_{ijl} + e_{ijkl},$$

where μ is the general effect, b_j is the fixed effect of the j^{th} year, r_{jk} is the fixed effect of the k^{th} replicate in the j^{th} year, a_i is the main effect of i^{th} genotype, β_l is main effect of l^{th} fertilizer, $(a\beta)_{il}$ is the interaction effect of the i^{th} genotype and l^{th} fertilizer, and e_{ijkl} is the error of y_{ijkl} with homogeneous or year-specific variances. $(ba)_{ij}$, $(b\beta)_{jl}$, and $(ba\beta)_{ijl}$ are random interaction effects between genotype and fertilizer, or their interactions and year, respectively. The Akaike information criterion (AIC) was used to select the error variance structure, and thus was used to select a model with homogeneous or year-specific error variance [27]. As the fertilizer is numeric (0, 40, and 80 kg N ha^{-1}), a linear regression for each genotype was fitted too, but was consequently not used as the lack of fit was significant (results not shown). Thus, the fertilizer trend is not linear. Residuals were checked graphically for normal distribution and homogeneous variance. After finding significant differences via the global F-test, significant differences were evaluated with a multiple t-test (Fisher´s least significant differnence test) at significance level of 5%. A letter display was used to present results of multiple comparisons [28]. Additionally, simple means were calculated for all traits for presentation purposes only.

Statistical analyses were performed using SAS Software, version 9.4 (SAS Institute Inc., Cary, NC, USA). Figures were generated using SigmaPlot, version 13.0 (Systat Software Inc., CA, USA) and Excel 2013 (Microsoft Corporation, WA, USA).

3. Results

3.1. Tuber Yield

Fresh-matter (FM) tuber yield (t ha^{-1}) and dry-matter (DM) tuber yield (t ha^{-1}) were significantly affected by year-by-genotype and year-by-fertilizer interaction effects. Therefore, the two experimental years are presented separately (Table 3). For fresh-matter tuber yield, genotype means were significantly different from each other in 2017 only (Table A2). In 2016, 0 kg N ha^{-1} yielded significantly higher tuber yield values (22.05 t ha^{-1}) compared to 80 kg N ha^{-1} (16.44 t ha^{-1}) (Table A4). Both genotypes achieved lowest tuber yields in the highest fertilization level. In 2017, the average yield level increased with fertilization. Tuber yields reached from 42.81 t ha^{-1} (B40) up to 67.32 t ha^{-1} (R80). Both genotypes achieved highest tuber yields in the highest fertilization level of 80 kg N ha^{-1}.

Tuber dry matter showed significant fertilization-by-genotype interaction effects, but no interactions with year was found (Table 3, Table A5). Tuber DM ranged from 10.4 (B40) to 17.7% (R40) in 2016. Across both years, RG had significantly higher DM in all fertilization levels. Within the genotypes, R40 had significantly higher DM than R0 and R80. Within BG, no significant differences between the fertilization levels were determined.

Dry-matter (DM) tuber yield (t ha^{-1}) was significantly affected by year-by-genotype and year-by-fertilizer (Tables 3, A2 and A4). In 2016, DM tuber yield ranged from 1.95 (B80) to 3.90 (R40) t ha^{-1}. Significantly higher DM tuber yield were reached for both genotypes in 2017, and ranged from 4.51 (B40) to 11.40 (R80) t ha^{-1}. Furthermore, in both experimental years, RG reached significantly higher DM tuber yield than BG. With regard to the fertilization level, in 2016, 0 and 40 kg N ha^{-1} reached significant higher tuber yields than 80 kg N ha^{-1}. In 2017, a reverse picture was shown, where the highest fertilization level reached significantly higher DM tuber yield than the other two fertilization levels.

Table 3. Tuber yield (t ha^{-1} FM), tuber dry matter (DM in %), and tuber yield (t ha^{-1} DM) for the two years (2016 and 2017) of the six treatments (B0, B40, B80, R0, R40, and R80) at harvest as mean value ± standard error.

Treatment		**Tuber Yield**		
		Fresh Matter [t ha^{-1} FM]	**DM [%]**	**Dry Matter [t ha^{-1} DM]**
2016				
B0		24.06 ± 2.45	11.83 ± 0.67	2.81 ± 0.3
B40		19.57 ± 2.45	10.36 ± 0.67	2.04 ± 0.3
B80		17.62 ± 2.45	11.28 ± 0.67	1.95 ± 0.3
R0		20.04 ± 2.45	15.03 ± 0.67	3.01 ± 0.3
R40		21.97 ± 2.45	17.68 ± 0.67	3.90 ± 0.3
R80		15.26 ± 2.45	16.25 ± 0.67	2.47 ± 0.3
2017				
B0		45.38 ± 3.55	10.58 ± 0.47	4.72 ± 0.5
B40		42.81 ± 3.67	10.45 ± 0.47	4.51 ± 0.5
B80		50.25 ± 3.55	11.31 ± 0.47	5.67 ± 0.5
R0		60.44 ± 3.66	17.04 ± 0.47	10.35 ± 0.5
R40		61.93 ± 3.55	17.00 ± 0.47	10.50 ± 0.5
R80		67.32 ± 3.55	17.00 ± 0.47	11.40 ± 0.5
Results of statistical analysis				
Factor	DF		*p*-Value	
Year × Rep	4	<0.0001	0.1060	0.0048
Year	1	<0.0001	0.6375	<0.0001
G	1	<0.0001	<0.0001	<0.0001
Year × G	1	<0.0001	0.1272	<0.0001
F	2	0.8731	0.6895	0.8622
Year × F	2	0.0137	0.6356	0.0057
G × F	2	0.4782	0.0486	0.2412
Year × G × F	2	0.9438	0.0698	0.5333

ANOVA table (factor (replication = REP; genotype = G; fertilizer = F), degree of freedom (DF) and *p*-value) carried out for tuber yield (t ha^{-1} FM), tuber DM (%) and tuber yield (kg ha^{-1} DM).

3.2. Sugar Composition

The fractions GF_4, GF_3, GF_2, sucrose, total FOS (GF_4, GF_3, and GF_2), and total sugar content (sum of all sugar fractions) were significantly affected by year-by-genotype-by-fertilizer interactions (Table 4). Fructose was significantly affected by year-by-genotype interactions. Only glucose was significantly affected by year and genotype, and therefore showed no interactions with the year. For this reason, the two experimental years, 2016 and 2017, were presented separately.

In 2016, all sugar components except GF_4 B40 showed the highest concentration. In 2017, B80 was best for all sugar components, except for monosaccharides (B0) and sucrose (B40). In general, concentrations in 2017 tended to be lower compared to 2016.

In 2016, GF_4 ranged from 10.5 to 18.6%. B0 (12.2%) and R0 (18.6%), as well as B80 (13.5%) and R80 (11.6%) were significantly different from each other. The other fertilization levels did not differ significantly between the genotypes. B80 reached the highest amounts of GF_4 (13.5%) and differed significantly from B0 and B40. Contrary results were shown for RG. The highest amounts of GF_4 were reached by R0 (18.6%), which were significantly different to R40 and R80. In 2017, GF_4 ranged from 9.9 to 14%. All fertilization levels differed significantly between the genotypes. Within the genotypes in each case with increasing fertilization, the amount of GF_4 increased. B80 (11.4%) differed significantly to B40 and B0. In addition, R40 and R0 differed significantly to R80 (14%).

The amount of GF_3 in 2016 ranged from 12 to 20.9%. Except for B0 (19.0%) and R0 (20.8%), all fertilization levels differed significantly between the genotypes. Estimates for fertilizer levels of BG did not differ significantly between each other. Within RG, R0 (20.8%) reached significantly higher amounts of GF_3 than R40 and R80. In 2017, the amount of GF_3 ranged between 12.2 and 15.5%. Again, for all fertilizer levels, genotypes were significantly different from each other except B0 (13.5%) and R0 (12.2%). Within the genotypes, there were significant differences between fertilization levels similar to GF_4. In each case, the amount of GF_3 increased with increasing fertilization levels. An exception was R0 (20.8%) in 2016, which was significantly higher than R40 (12.0%) and R80 (12.4%). In 2017, B80 (15.5%) and R80 (13.7%) had significantly higher amounts of GF_3 than the other fertilization levels.

In 2016, the amount of GF_2 ranged between 7.4 and 25.1%. GF_2 values of the two genotypes differed for all fertilization levels, with BG showing higher values. Within BG, there were non-significant differences between the fertilization levels. Within RG, R0 achieved a significantly increased amount of GF_2 (14.6%) compared to R40 and R80. In 2017, the amount of GF_2 ranged from 6.0 (R0) to 15.1% (B80). In 2017, GF_2 values of genotypes differed for all fertilization levels, with BG again showing higher values. Within a genotype, no differences between fertilizer levels were found. However, an increase in fertilization was found to lead to an increase in the amount of GF_2.

In 2016, sucrose ranged from 1.8 (R40) to 7.1% (B40). In all fertilization levels, RG reached significantly lower amounts of sucrose than BG. R0 reached 4.2%, and therefore significantly higher amounts than R40 and R80. Within BG, there were no significant differences between the fertilization levels. In 2017, the sucrose amount ranged from 2.3 (R0) to 5.0% (B40). Again, for all fertilization levels, the estimates differed significantly between the genotypes. Within the genotypes, there were no significant differences between the fertilization levels, nor in the BG and in the RG.

The amount of fructose ranged from not detectable (coded as zero) (R0, R40, and R80) to 4.0% (B0). In both years, BG reached significantly higher amounts of fructose than RG. Furthermore, both genotypes reached significantly higher amounts of fructose in 2017 than in 2016.

The amount of glucose ranged from 1.7 (R40 in 2016) to 10.7% (B0 in 2017). For glucose, BG generally indicated significantly higher amounts than RG.

The total FOS amount in 2016 ranged from 30.8 (R40) to 58.2% (B80). Except B0 and R0, the other fertilization levels differed significantly between the genotypes. Within BG, there were no significant differences between the fertilization levels. R0 (54.0%) reached the highest amount and was significantly different to R40 and R80. In 2017, the content of total FOS ranged from 30.5 (R0) to 42.0% (B80). All fertilization levels were significantly different between the genotypes. Within the genotypes, there was a similar trend. B0 (36.2%) and R0 (30.5%) reached the lowest amounts of FOS and differed significantly to B80 (42.0%) and R80 (34.8%). B40 and R80 were not significantly different to the other two fertilization levels in the corresponding genotype.

The total sugar content was significantly affected by year. In 2016, the sugar content ranged from 34.3 (R40) to 73.7% (B40). Fertilization levels 40 and 80 kg N ha^{-1} of BG reached significantly higher sugar contents than the same fertilizer levels in RG. Also within the genotypes, there were significant differences between the fertilization levels. BG had the highest sugar content in B40 (73.7%) and lowest in B0 (66.6%). B80 did not differ significantly to B0 or B40. Within the RG, R0 reached the highest sugar content of 60.7% and differed significantly to R40 (34.3%) and R80 (35.3%). B0, B40, B80, and R0 reached significantly higher sugar contents in 2016 than in 2017. Only R40 and R80 reached similar (R40) or higher sugar contents in 2017.

In 2017, the sugar content ranged from 36.2 (R0) to 58.8% DM (B40). In all fertilization levels, BG reached significantly higher sugar contents than RG. Within the genotypes, there were no significant differences between the fertilization levels for the sugar content of BG. Within RG, R80 had significantly higher sugar contents of 41.8% than R0 with 36.2% DM. R40 did not differ significantly to R0 or R80.

Table 4. Fructose, glucose, sucrose, GF_2, GF_3, GF_4, total fructooligosaccharides (FOS), and total sugar content in % of dry matter (DM) for the two years (2016 and 2017) of the six treatments (B0, B40, B80, R0, R40, and R80) at harvest, notated as the mean value ± standard error.

Treatment	Fructose	Glucose	Sucrose	GF_2	GF_3	GF_4	Total FOS	Total Sugar
2016								
B0	1.38 ± 0.6	4.67 ± 1.2	6.15^{aA} ± 0.4	23.16^{aA} ± 1.0	19.04^{aA} ± 0.6	12.22^{bAB} ± 0.5	54.42^{aA} ± 1.8	66.62^{aB} ± 2.16
B40	2.63 ± 0.6	7.87 ± 1.2	7.09^{aA} ± 0.4	25.07^{aA} ± 1.0	19.30^{aA} ± 0.6	11.77^{aB} ± 0.5	56.15^{aA} ± 1.8	73.74^{aA} ± 2.16
B80	1.60 ± 0.6	5.44 ± 1.2	6.58^{aA} ± 0.4	23.85^{aA} ± 1.0	20.85^{aA} ± 0.6	13.52^{aA} ± 0.5	58.22^{aA} ± 1.8	71.84^{aAB} ± 2.16
R0	n.d.	2.48 ± 1.2	4.22^{bA} ± 0.4	14.59^{bA} ± 1.0	20.75^{aA} ± 0.6	18.64^{aA} ± 0.5	53.99^{aA} ± 1.8	60.69^{aA} ± 2.16
R40	n.d.	1.68 ± 1.2	1.84^{bB} ± 0.4	8.20^{bB} ± 1.0	12.05^{bB} ± 0.6	10.50^{aB} ± 0.5	30.75^{bB} ± 1.8	34.27^{bB} ± 2.16
R80	n.d.	2.01 ± 1.2	1.94^{bB} ± 0.4	7.38^{bB} ± 1.0	12.43^{bB} ± 0.6	11.55^{bB} ± 0.5	31.36^{bB} ± 1.8	35.31^{bB} ± 2.16
2017								
B0	4.01 ± 0.4	10.66 ± 0.9	4.78^{aA} ± 0.2	12.89^{aA} ± 1.0	13.45^{aB} ± 0.6	9.86^{bB} ± 0.4	36.21^{aB} ± 1.2	55.65^{aA} ± 1.70
B40	3.92 ± 0.4	10.50 ± 0.9	5.02^{aA} ± 0.2	14.22^{aA} ± 1.0	14.49^{aAB} ± 0.6	10.64^{bAB} ± 0.4	39.35^{aAB} ± 1.2	58.80^{aA} ± 1.70
B80	3.18 ± 0.4	8.00 ± 0.9	4.37^{aA} ± 0.2	15.09^{aA} ± 1.0	15.54^{aA} ± 0.6	11.39^{bA} ± 0.4	42.02^{aA} ± 1.2	57.56^{aA} ± 1.70
R0	0.08 ± 0.4	3.28 ± 0.9	2.32^{bA} ± 0.2	6.05^{bA} ± 1.0	12.23^{aB} ± 0.6	12.22^{aB} ± 0.4	30.50^{bB} ± 1.2	36.18^{bB} ± 1.70
R40	0.17 ± 0.4	3.85 ± 0.9	2.68^{bA} ± 0.2	6.87^{bA} ± 1.0	13.12^{bAB} ± 0.6	13.24^{aAB} ± 0.4	33.23^{bAB} ± 1.2	39.92^{bAB} ± 1.70
R80	0.15 ± 0.4	4.16 ± 0.9	2.63^{bA} ± 0.2	7.10^{bA} ± 1.0	13.72^{bA} ± 0.6	13.99^{aA} ± 0.4	34.81^{bA} ± 1.2	41.75^{bA} ± 1.70

Results of statistical analysis

Factor	DF	*p*-Value							
Year × Rep	4	0.2147	0.3612	0.0594	0.1646	0.1028	0.0843	0.1656	0.2596
Year	1	0.0064	0.0003	<0.0001	<0.0001	<0.0001	0.0003	<0.0001	<0.0001
G	1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Year × G	1	0.0156	0.1196	0.0003	<0.0001	<0.0001	0.0104	<0.0001	0.0006
F	2	0.5143	0.3753	0.1348	0.3982	0.0010	0.0001	0.0085	0.0523
Year × F	2	0.7009	0.7453	0.0834	0.0025	<0.0001	<0.0001	<0.0001	<0.0001
G × F	2	0.5364	0.2099	0.0100	0.0019	<0.0001	<0.0001	<0.0001	<0.0001
Year × G × F	2	0.6348	0.2230	0.0021	0.0095	<0.0001	<0.0001	<0.0001	<0.0001

ANOVA table (factor (replication = REP; genotype = G; fertilizer = F), degree of freedom (DF) and *p*-value) carried out for the sugar fractions GF_4, GF_3, GF_2, sucrose, fructose, glucose, total FOS and total sugar content in % of DM. Within the years, the same lowercase letter in one column indicates no significant differences between genotypes with the same fertilization level at $p < 0.05$. Within the years, the same capital letters in one column indicates no significant differences between fertilization levels of one genotype at $p < 0.05$.

3.2.1. Nitrogen Concentration and Nitrogen Uptake

Nitrogen concentration (% of DM) was significantly affected by year and genotype in the two plant parts, rhizome and tuber (Table 5). For rhizome, differences between fertilizer levels were found. In the case of aboveground biomass, there were significant effects by all two-way interactions of year, genotype, and fertilizer.

Table 5. Nitrogen concentration (%) in the aboveground biomass of rhizome and tuber at the last destructive measurement (161 and 165 DAP) immediately before harvest for two years (2016 and 2017) of the six treatments (B0, B40, B80, R0, R40, and R80), notated as the mean value ± standard error.

Treatment		% N in Different Plant Parts		
		Aboveground Biomass	**Rhizome**	**Tuber**
2016				
B0		3.35 ± 0.11	1.46 ± 0.15	0.95 ± 0.07
B40		3.06 ± 0.11	1.43 ± 0.15	0.96 ± 0.07
B80		4.01 ± 0.11	1.75 ± 0.15	1.07 ±0.07
R0		3.19 ± 0.11	1.25 ± 0.15	0.82 ± 0.07
R40		3.31 ± 0.11	1.64 ± 0.15	0.73 ± 0.07
R80		3.52 ± 0.11	1.47 ± 0.15	0.91 ± 0.07
2017				
B0		3.21 ± 0.12	1.45 ± 0.05	0.91 ± 0.03
B40		3.18 ± 0.12	1.52 ± 0.05	0.75 ± 0.03
B80		3.19 ± 0.12	1.50 ± 0.05	0.78 ± 0.03
R0		2.14 ± 0.12	0.98 ± 0.05	0.61 ± 0.03
R40		2.31 ± 0.12	1.27 ± 0.05	0.77 ± 0.03
R80		2.10 ± 0.12	1.34 ± 0.05	0.71 ± 0.03
Results of statistical analysis				
Factor	DF	*p*-Value		
Year × Rep	4	0.0275	0.3944	0.2193
Year	1	<0.0001	0.0297	0.0002
G	1	<0.0001	0.0088	0.0018
Year × G	1	<0.0001	0.1362	0.2133
F	2	0.0097	0.0262	0.1710
Year × F	2	0.0010	0.9263	0.1677
G × F	2	0.0233	0.1500	0.7892
Year × G × F	2	0.2954	0.2032	0.1834

ANOVA table (factor (replication = REP; genotype = G; fertilizer = F), degree of freedom (DF) and *p*-value) for nitrogen concentration in different plant parts: aboveground biomass, rhizome and tuber.

In 2016, N concentration in aboveground biomass ranged from 3.1 (B40) to 4.0% (B80). Fertilization level 80 kg N ha^{-1} differed significantly to the fertilization levels 0 and 40 kg N ha^{-1} (Table A4). The two genotypes did differ significantly (Table A2). In 2017, the N concentration in the aboveground biomass ranged from 2.1 (R80) to 3.2% (B0) and did not differ significantly between the genotypes. There were also no significant differences between the fertilization levels.

The N concentration of the rhizomes ranged from 1.0 (R0) to 1.8% (B80). Across both experimental years, BG reached significantly higher N concentrations than RG. With regard to fertilization level, 40 and 80 kg N ha^{-1} reached significantly higher N concentrations than 0 kg N ha^{-1} (Table A3).

The N concentration of tubers ranged from 0.6 (R0 in 2017) to 1.0% (B80 in 2016) and, across both years, were significantly higher in BG than in RG (A1).

The N uptake (kg N ha^{-1}) of the aboveground and total plant were significantly affected by genotype and fertilizer (Table 6). The N uptake of the tuber was significantly different between genotypes-by-years combinations (Table 6, Table A1). For the N uptake of rhizomes, no significant effects were found. The RG had a significantly higher N uptake in aboveground biomass and total plant compared to BG. The N uptake of aboveground biomass differed significantly between 0 and 40 kg N ha^{-1}, whereas 80 kg N ha^{-1} did not differ significantly to both other fertilizer levels. Within the total plant, the N uptake of fertilization level 0 kg N ha^{-1} was significantly lower than fertilization levels 40 and 80 kg N ha^{-1}.

The N uptake of aboveground biomass ranged from 88.6 (B0 in 2016) up to 226.0 kg ha^{-1} (R80 in 2017). Across both years, RG reached significantly higher N uptakes than BG. Furthermore, the fertilization level of 40 kg N ha^{-1} reached significantly higher N uptake than 0 kg N ha^{-1}. The fertilization level 80 kg N ha^{-1} did not differ significantly to the other two fertilization levels.

The N uptake of rhizomes ranged from 9.3 (R0) to 29.3 kg ha^{-1} (B80). No significant differences could be detected.

The N uptake in tubers ranged from 19.1 (B0) to 31.4 kg N ha^{-1} (R0) and from 29.5 (B40) to 84.2 kg N ha^{-1} (R80) in 2016 and 2017, respectively. In general, the N uptake of tubers increased with increasing fertilization.

The N uptake of the total plant ranged from 121.0 (B0 in 2016) 330.3 kg ha^{-1} (R80 in 2017) and was significantly highest for RG and for fertilization levels 40 and 80 kg N ha^{-1}.

Table 6. Nitrogen uptake (kg N ha^{-1}) of different plant parts, and sum of total plant N uptake at the last destructive measurement (161 and 165 DAP, respectively) immediately before harvest for two years (2016 and 2017) of the six treatments (B0, B40, B80, R0, R40, and R80) notated as the mean value ± standard error.

Treatment		N Uptake (kg ha^{-1}) of Different Plant Parts			
		Aboveground Biomass	**Rhizome**	**Tuber**	**Total Plant**
2016					
B0		88.60 ± 28.6	13.31 ± 4.8	19.06 ± 6.7	120.98 ± 32.3
B40		169.42 ± 28.6	22.35 ± 4.8	18.77 ± 6.7	210.56 ± 32.3
B80		110.19 ± 28.6	12.20 ± 4.8	29.80 ± 6.7	152.18 ± 32.3
R0		118.81 ± 28.6	10.84 ± 4.8	31.41 ± 6.7	161.07 ± 32.3
R40		200.64 ± 28.6	20.46 ± 4.8	15.33 ± 6.7	236.42 ± 32.3
R80		152.62 ± 28.6	17.03 ± 4.8	30.08 ± 6.7	199.73 ± 32.3
2017					
B0		131.00 ± 18.3	12.74 ± 6.6	33.36 ± 8.7	177.10 ± 26.3
B40		130.30 ± 18.3	22.66 ± 6.6	29.52 ± 8.7	182.48 ± 26.3
B80		128.81 ± 18.3	29.32 ± 6.6	38.53 ± 8.7	196.66 ± 26.3
R0		151.14 ± 18.3	9.30 ± 6.6	50.88 ± 8.7	211.31 ± 26.3
R40		193.38 ± 18.3	15.07 ± 6.6	72.25 ± 8.7	280.71 ± 26.3
R80		226.03 ± 18.3	20.03 ± 6.6	84.19 ± 8.7	330.25 ± 26.3
Results of statistical analysis					
Factor	DF	*p*-Value			
Year × Rep	4	0.4321	0.4120	0.0149	0.1587
Year	1	0.1666	0.5236	<0.0001	0.0087
G	1	0.0033	0.3313	0.0004	0.0014
Year × G	1	0.3708	0.3095	0.0019	0.1509
F	2	0.0252	0.0856	0.0683	0.0191
Year × F	2	0.1153	0.2629	0.2708	0.1873
G × F	2	0.4400	0.9508	0.7648	0.4534
Year × G × F	2	0.6343	0.7186	0.1287	0.5043

ANOVA table (factor (replication = REP; genotype = G; fertilizer = F), degree of freedom (DF) and *p*-value) carried out for nitrogen uptake in different plant parts and total plant.

3.2.2. Indicators for Plant Efficiency

The three different indicators show the efficiency of different treatments related to N use and sugar production. All indicators were calculated as mentioned in 2.4. Therefore, in the following text, no units for indicators are given.

For $TNUtE_D$, no significant differences could be detected (Table 7). $TNUtE_D$ ranged from 35.3 (B80) to 185.0 (R40).

$PNUtE_S$ ranged from 6.1 (R80) to 13.4 (B0) and from 13.7 (B40) to 17.3 (R0) in 2016 and 2017, respectively. Across both experimental years and genotypes, efficiency of fertilization levels 0 kg N ha^{-1} was significantly higher than of the other two fertilization levels (Table A3).

For $TNUtE_S$, no significant differences could be detected. $TNUtE_S$ ranged from 37.8 (R80) to 96.3 (B0). The general trend was decreasing efficiency with an increasing amount of N fertilization.

Table 7. Indicator for tuber N utilization efficiency for tuber dry-matter yield ($TNUtE_D$), total plant N utilization efficiency for sugar (PNUtES), and tuber N utilization efficiency for sugar ($TNUtE_S$) at the last destructive measurement (161 and 165 DAP) immediately before harvest for the two years (2016 and 2017) of the six treatments (B0, B40, B80, R0, R40, and R80), notated as the mean value ± standard error.

Treatment		$TNUtE_D$	$PNUtE_S$	$TNUtE_S$
2016				
B0		80.33 ± 40.3	13.38 ± 1.7	96.32 ± 20.9
B40		114.69 ± 40.3	5.68 ± 1.7	75.14 ± 20.9
B80		35.29 ± 40.3	6.74 ± 1.7	73.74 ± 20.9
R0		105.48 ± 40.3	9.56 ± 1.7	50.96 ± 20.9
R40		184.95 ± 40.3	7.25 ± 1.7	95.19 ± 20.9
R80		103.48 ± 40.3	6.11 ± 1.7	37.77 ± 20.9
2017				
B0		83.96 ± 7.0	14.88 ± 1.8	78.54 ± 3.6
B40		134.16 ± 7.0	13.70 ± 1.8	84.41 ± 3.6
B80		129.35 ± 7.0	15.71 ± 1.8	80.68 ± 3.6
R0		164.51 ± 7.0	17.26 ± 1.8	72.29 ± 3.6
R40		131.23 ± 7.0	14.41 ± 1.8	56.32 ± 3.6
R80		85.43 ± 7.0	15.17 ± 1.8	60.59 ± 3.6
Results of statistical analysis				
Factor	DF	*p*-Value		
Year × Rep	4	0.2726	0.9535	0.0789
Year	1	0.3445	<0.0001	0.9472
G	1	0.0912	0.9606	0.0605
Year × G	1	0.2456	0.3926	0.9026
F	2	0.1022	0.0281	0.4142
Year × F	2	0.4356	0.2328	0.4548
G × F	2	0.6241	0.7200	0.5396
Year × G × F	2	0.1571	0.3422	0.1979

ANOVA table (factor (replication = REP; genotype = G; fertilizer = F), degree of freedom (DF) and *p*-value) carried out for the indicators $TNUtE_D$, $PNUtE_S$ and $TNUtE_S$.

4. Discussion

4.1. Tuber Yield

Tuber yields were affected by year, and were significantly higher in 2017 than in 2016. The tuber yields were comparable to other studies. Under similar climatic conditions in the Czech Republic, tuber yield ranged from 21 to 29 t ha^{-1} [29,30]. In 2016, tuber yields of this study (except B80) were in a similar range, and in 2017 were noticeably higher. However, plant density in the present study (12,531 plants ha^{-1}) was noticeably lower than the commonly used plant densities ranging between 23,000 to 30,000 plants ha^{-1} [31]. Therefore, the tuber yields reached were remarkably higher, considering the plant density. Yacon plants were conceivably able to compensate for the lower plant densities through a higher single-plant tuber yield [31]. Douglas et al. showed noticeable differences in tuber yields, which ranged from 11 to 81 t ha^{-1}, depending on location and, associated therewith, precipitation [31]. Also, Fernández et al. reported a very high impact of precipitation on tuber yield formation [29]. This is also true for the present study, where significantly higher tuber yields were reached in 2017, the year with higher precipitation (70 mm more than 2016) and a lower average temperature (1.5 °C lower than 2016). In particular, precipitation in 2017 was higher in July and August, the months where tuberous root formation started. Similarly, water stress is also one of the most important factors for tuber yield formation of chicory and Jerusalem artichoke [32,33]. In general, for yacon, 550 mm was sufficient for tuberous root production, even if higher precipitation could lead to higher yields [29].

With regard to the fertilization level, the two experimental years showed contrary results. In 2016, tuber yield decreased with increasing fertilization level, and the genotypes were not significantly different; whereas in 2017, a reverse picture was shown. In Jerusalem artichoke, the effect of N fertilization was more pronounced under non-water-limited conditions [34]. That could also explain the more pronounced effects of N fertilization in 2017 on yield, as the overall precipitation was higher. This would mean that the water requirement is perhaps different for optimum tuber yield formation and N utilization. The effects of fertilization level on tuber yield in 2017 were not significant. The tuber yield increased with increasing N fertilization, but no maximum could be achieved in both genotypes. Fernandes et al. reported that under high N rates, tuber yield by sweet potato were similar in all treatments. Losavio et al. also reported no significant effect of N fertilization on tuber yield by Jerusalem artichoke [16,35]. This is also in accordance with Maltas et al., who reported increasing tuber yields of potatoes with increasing N fertilization, but no significant differences in the higher N rates of about 120 kg N ha^{-1} under comparable climatic conditions [21]. In general, the expected mineralization in the soil of the present study was quite high. Due to the formation of ridges, mineralization was stimulated because of oxygen supply and fast heating [36]. Furthermore, the long growing period leads to higher N mineralization [37]. As mineralization decreases with increasing N supply (N_{min} + additional fertilization) [37], no significant effects of higher N fertilization levels on tuber yield were obtained.

Significant differences between the genotypes may indicate that the RG had a higher yield potential in general, or better N-use efficiency, which is confirmed by the data shown in Table 7 where $TNUtE_D$ showed higher values for RG. Also, several other studies reported significant differences between different yacon genotypes with regard to tuber yield [29,38]. As significant differences between the genotypes were only observed in 2017, it can be assumed that tuber yield formation did not reach its maximum in 2016. Tuber DM of BG was similar to DM reported in other studies and ranged from 10.3 to 14% [39–41]. The significantly higher DM of RG was similar to the findings of Campos et al., who reported DM up to 18.6% [42]. In accordance with the present study, Hermann et al. showed that tuber DM differed significantly between the genotypes [40,43].

4.2. Sugar Composition

Contrary to the obtained tuber yields, the sugar content, on average, was higher in 2016 than in 2017. That could be justified by the higher precipitation in 2017 than 2016. In the case of Jerusalem artichoke, sugar content increased in dry years, and vice versa [44]. With regard to the monosaccharides, fructose achieved rather low amounts, and could not be detected in RG in 2016. This is in contrast to the results of other studies where fructose represented the highest proportion of monosaccharides and carbohydrates in yacon tubers [7,40,45–47]. However, some of these investigations were carried out on stored tubers. Due to the reduction of FOS and sucrose, the amount of fructose was highest in tubers [45–47]. Contrary to that are the findings of Valentova et al., who also reported highest amounts of fructose, but without the storage of tubers [7]. Herman et al. showed both, depending on the investigated genotype [40]. Similarly, Fukai et al. and Khajehei et al. detected the lowest amounts of fructose [48,49]. Therefore, the amount of fructose depends on genotype, but also on the post-harvest conditions of tubers. With increasing storage time, the amount of fructose increases [45]. In general, amounts of FOS decreased during storage, and sucrose, fructose, and glucose increased due to hydrolyzation of FOS [15,50]. Fructose amounts in Jerusalem artichoke decreased with later harvest dates, and therefore prolonged plant growth [51]. As RG started flowering, in contrast to BG, it might have been closer to physiological maturity than BG, leading to changes in sugar profiles.

In general, it is striking that the monosaccharides fructose and glucose were only affected by the year-by-genotype or genotype interactions, respectively. This indicates that the amount of monosaccharides were not influenced by N fertilization. Also, the fructose content in Jerusalem artichoke was not influenced by N fertilization, but by genotype [51,52]. In general, a reaction similar to that of Jerusalem artichoke or potato would have been expected, where higher amounts of N fertilizer delayed maturity [51,53]. This would lead to a decrease in DM content, as well as a decrease in carbohydrates [16,21]. Furthermore, a difference in sugar composition would be expected. In sugar-containing crops like sugar beet, or starch-containing crops like potatoes, sugar or starch content decreases with increasing fertilization, and the composition changes [54]. As no changes in yacon were observed, this might be related to either the date of application [51] or the N fertilizer used. In contrast to the studies on potatoes, all N was applied at planting. In addition, a slow-release fertilizer was used, which might have affected the N availability during the season not negatively affecting carbohydrate formation.

The amount of sucrose was significantly higher in BG in all fertilization levels and both years. It is reported in the literature that higher amounts of sucrose can lead to higher amounts of FOS [7,46,55]. This was confirmed in the present study, where the BG in all treatments reached significantly higher amounts of FOS than RG, except for R0 in 2016. This exception is due to significantly higher amounts of sucrose in R0 than in other treatments of RG, which led to significantly higher amounts of FOS. In addition, R0 (2016) was the only treatment which differed significantly to other fertilization levels within the genotype. All other treatments showed no significant influence of N fertilization.

The amount of total FOS ranged over both experimental years from 30.5% to 58.2% in DM. This is in the range of findings in other studies, which showed a wide range from 6.4 to 70% [8,40,48]. This wide range is due to a strong influence of year (climatic conditions) and genotype [5,45]. Furthermore, this wide range is due to different post-harvest conditions like those mentioned above. The FOS in yacon tubers are extremely sensitive to temperature and storage conditions [15,50]. Compared to the FOS content of Jerusalem artichoke, which ranged from 24.7 to 67%, it was quite similar [56–58]. Similar to yacon, tubers of Jerusalem artichoke were sensitive to different post-harvest conditions, which indicates that storage duration and storage temperature can have a high impact on FOS content.

If compared to other FOS-containing vegetables, such as artichoke and chicory (up to 2%), the amount in yacon tubers is really high [26]. In general, RG achieved lower amounts of FOS, which corresponded to the findings of Graefe et al. who also showed higher FOS amounts in a light-colored genotype, due to significant differences between genotypes [8]. Furthermore, it was reported that the total amount of FOS and degree of polymerization (DP) correlated. Tubers containing highest amounts of total FOS had higher amounts of FOS with lower DP. Tubers containing lower amounts of total FOS had higher amounts of FOS with higher DP [46–48]. This corresponds to findings in the present study, where BG had higher amounts of FOS and mainly the highest amount of GF_2. All treatments in 2017 had, on average, a higher DP than in 2016, which led to lower amounts of total FOS in nearly all treatments. Different climatic conditions, like those mentioned above and higher total N supply in both years could have led to delayed maturity [51]. Jerusalem artichoke and chicory, as the two other mayor crops containing FOS, generally had higher chain length of DP >10 [26]. A lower DP <10, as in yacon, is preferable because of higher bifidogenic effects [39,57].

Due to there being few or no significant differences between fertilization levels regarding FOS amounts in general, a higher influence of average DP on the total FOS amount when compared to the

N fertilization level is assumed. This hypothesis is supported by no significant differences between treatments across the years in spite of higher N availability in 2017.

The total sugar content of all treatments in the present study were below or equal to the normal range of 70–80% of DM [13,45]. Compared to the sugar content of Jerusalem artichoke (71% of DM), chicory (74% of DM), and artichoke (78–80% of DM), the sugar content in the present study were comparatively lower [33,35,59]. It has been reported that an increase of N leads to a decrease of sugar content for sugar beet and artichoke [19,35,60]. Besides the amount of applied N is, decisively, the date of application for sugar content by Jerusalem artichoke. Divided rates could lead to higher sugar yields, because of slow development of seedlings [19,51,61]. Furthermore, high N supply could have been the reason why the total sugar content was lower in 2017 [51]. Higher amounts of N supply lead to a delay in maturity [61], which would lead to a higher percentage of sugar in tubers without delayed maturity [51]. In general, sugar content was highly variable and differed significantly due to the impact of several parameters, such as origin, nutrient content, and cultivation conditions, wherefore it might be difficult to compare total sugar content in general. [5,6,41]. Overall, determination of the optimal N fertilization level for sugar production is not merely. It is necessary to maximize both tuber yields and sugar content. Certainly, the effect of climatic conditions and genotype were greater than the impact of N fertilization level.

4.3. Nitrogen Concentration and Uptake

N concentration of aboveground biomass was significantly influenced by the genotype-by-fertilizer interaction. This is similar to the findings of Sah et al., who reported a significant influence of N level on N concentration in the vegetative parts of Jerusalem artichoke and chicory, amongst others. N concentration ranged from 0.3 to 1.0 and 1.5 to 2.0%, respectively [20]. N concentrations in the present study were noticeably higher and comparable to those of fodder beet, which ranged from 1.7 to 3.3% [20]. Similar to these are findings of N concentration in leaves of sweet potatoes, which ranged from 2.9 to 4.2%, also influenced by fertilizer [16]. RG had significantly lower N concentrations in aboveground biomass, while overall N uptake was significantly higher. This was due to bigger plants of RG, and therefore more biomass in general (data not shown). Furthermore, Hermann et al. reported that yacon leaves had noticeably higher N concentrations than the stems [40]. Comparing the two tested genotypes, BG had a lower plant height and bigger leaves, whereas that of RG was higher and had smaller leaves. Both genotypes were comparable in their N uptake of aboveground biomass to sugar beet (up to 238 kg N ha^{-1}) [19].

The nitrogen concentration of tubers was significantly higher for BG than for RG, and higher than the N concentration reported by Lebeda et al., which ranged between 0.6 and 0.7% [55]. Compared to the N concentration of potato tubers, which ranged approximately between 0.9 to 1.2%, the N concentration of RG was slightly lower, and the N concentrations of BG were similar [62,63]. Bélanger et al. also showed significant differences in N concentration between two potato genotypes [63]. Similarly, in tubers of Jerusalem artichoke, N concentration differed significantly between genotypes and ranged from 1.2 to 2.1% of DM [64]. In general, the N concentration of storage parts of chicory ranged between 0.7 and 1.1%, which is similar to that in yacon [20]. Regarding the fertilization level, there were no significant effects on tuber N concentration. In the case of potatoes, there were similar findings. It is reported that the fertilization level had no effect, but that it did for the time of application and possible splitting. An increase in N concentration with increasing fertilization could also be detected [65]. The decrease in N concentration in 2017 was probably due to a dilution effect. The N uptake of tubers in 2017 was significantly higher in RG when compared to BG, resulting in significantly higher tuber yields, although the amount of N on a percentage basis was significantly higher in BG across the years. Hermann et al. reported that the N uptake of tubers ranged between 0.4 and 0.8 kg N per t FM [40]. Nitrogen uptake in the present study was slightly higher and ranged between 0.8 and 1.2 kg N per t FM. Zotarelli et al. reported an N uptake in potato tubers between 90 to 148 kg ha^{-1} at different fertilization levels without any significant differences [59]. These results are similar to findings in the present study, where the N uptake was lower, but no differences between the fertilization levels could be detected.

The N concentration of the rhizomes was significantly influenced by N fertilizer level. With increasing fertilization, N concentration in rhizomes increased, too. Therefore, N storage in rhizomes did not increase in all cases with increasing fertilization level. The highest amount of N was obtained in each case (except BG in 2016) in the treatment with the highest N uptake of the total plant. This shows an increase of translocation of N into the rhizomes with an increasing N uptake of the plant. Similar to findings of Kleijn et al. regarding *V. album*, the amount of N in the whole plant was lowest in rhizomes. The amount of N was in decreasing order, being the highest in aboveground biomass, tubers, and lastly in rhizomes [66].

Total plant N uptake is composed of the N content of the three fractions—aboveground biomass, rhizome, and tuber. Similar to the N uptake of aboveground biomass, the genotype and fertilizer had a significant influence. Compared to the N uptake of sugar beet, which ranged from 58 to 285 kg N ha^{-1}, findings in the present study are in a comparable range [67,68]. The N uptake of fodder beet (150–370 kg N ha^{-1}) and Jerusalem artichoke (80–300 kg N ha^{-1}) confirmed that findings in the present study are in a normal range [20].

The significantly higher N uptake of RG can be explained by a significantly higher N uptake of aboveground biomass and tubers.

Overall, N uptakes exceeded N supply, which is due to a high mineralization rate that is common in soils high in organic matter [18]. Laufer et al. reported N uptakes of sugar beet roughly 130–180 kg above the given soil N_{min} content without any further fertilization, and attributed this to the preceding crops—winter wheat, or winter barley [67,69]. In addition, the effect of the previous crop in 2016 is decisive. The leaves of sugar beet have a N content of 20 to 30 mg N g^{-1}, and can be easily decomposed. The N content in soil is slightly higher with crop residues of sugar beet. The long-term effect is particularly remarkable [70].

4.4. Indicators for Plant Efficiency

The chosen indicators described relationships between tuber yield DM, N uptake, and sugar content for the different treatments. They are useful indicators for comparing the treatments and genotypes with each other, and with other appropriate crops as well.

The indicators $TNUtE_D$ and $TNUtE_S$ performed quite similarly. With increasing fertilization level, the efficiency of tubers for accumulating DM or sugar decreased in general. This is similar to the findings of Fernandes et al. who reported a decreasing N uptake efficiency under high N levels above 120 kg N ha^{-1} for sweet potatoes [16]. Also, Maltas et al. reported decreasing N utilization and uptake efficiency with increasing N fertilizer (above 120 kg N ha^{-1}) in potatoes [21]. This is explainable by a stronger sink effect of aboveground biomass [20]. Higher N fertilization mostly affects the vegetative growth of the plant [19,22]. $TNUtE_D$ showed differences between the genotypes. Both in 2016 and 2017, the highest BG efficiency was obtained at 40kg N ha^{-1}. In 2016, RG efficiency was higher when the level of fertilization was 40kg N ha^{-1}, and in 2017 when there was no fertilization. TNUtES was higher under low N fertilization conditions (B0 and R40) only in 2016. This is similar to the findings in 4.2, which showed lower sugar content under a higher N supply.

PNUtES decreased with increasing fertilization level (except B80 in 2017) and is an indicator for significant differences between the fertilization levels. PNUtES was highest for the unfertilized treatment, 0 kg N ha^{-1}. This is similar to several studies, which showed a decreasing amount of carbohydrates in potatoes, sugar beet, and Jerusalem artichoke [21,51,54]. Hence, the aboveground biomass seems to be particularly decisive for plant efficiency, because $TNUtE_D$ and $TNUtE_S$ did not show any significant differences.

Compared to the PNUtES of sugar beet and fodder beet under comparable climatic conditions in Germany and the Netherlands which ranged from 48 to 110, the determined efficiency of yacon can be seen to be quite low [69]. Possible reasons for this can be the high amounts of aboveground biomass up to 54 t ha^{-1}, and thus the high N uptakes of yacon [3]. With increasing amounts of aboveground biomass, the overall efficiency of a plant decreases. This is similar to findings of Sah et al., who reported higher efficiency of chicory than for Jerusalem artichoke, due to noticeably higher amounts of aboveground biomass by Jerusalem artichoke [20].

Considering all three indicators, higher amounts of N did not inescapably lead to higher efficiency. Even though tuber yields were significantly higher in 2017 and lower fertilization amounts in 2017 were favorable for almost all indicators, the requirement of N is apparently covered by high N_{min} values, and no additional fertilization is needed. The difference between the genotypes is also noticeable—for RG, lower amounts of N fertilization were suitable for higher efficiency than for BG, due to different growth and development patterns, especially of aboveground biomass. Ojala et al. reported potatoes' optimum maturity when the DM content was highest and carbohydrate content was lowest [53]. Present findings would suggest that RG is closer to physiological maturity while BG still shows vegetative growth. Considering the desired aim of the farmer, to produce sugar contents as high as possible, BG might be a better option. However, overall tuber yields have to be considered.

5. Conclusions

This study tested the influence of N fertilization on the tuber yield, sugar composition, and N uptake of yacon in a two-year field study. In general, differences of determined traits between years and the two tested genotypes were considerably higher than differences between the N fertilization levels.

In general, tuber yield increased with increasing N fertilization in 2017, while the reverse effect was obtained in 2016. With increasing yields, sugar and FOS content slightly decreased. A decreasing amount of FOS led to a slight increase in the amount of FOS, with a higher degree of polymerization.

Overall, for an optimum efficient tuber yield production, an N fertilization level of 40 kg N ha^{-1} is recommended, depending on the N_{min} value. This optimum N amount might be different if the precipitation is significantly higher. As mentioned above, the amount of precipitation is one of the key factors for tuber yield formation of yacon, even though it proved to be sufficient in the present study. Nevertheless, it is conceivable that under inexhaustible water supplies, the N uptake can change. At this point, it is necessary to conduct further investigations about the N uptake of yacon under various water conditions. For the climatic conditions in Central Europe, the amount of precipitation in the present study reflected the average quantity. In general, the two tested genotypes differed in their N uptake due to differences in aboveground biomass and tuber yield.

In summary, yacon can cope with lower N fertilizer rates than other tuberous crops, such as potatoes and sugar beet, leading to high tuber and sugar yields overall on a hectare basis.

Author Contributions: Conceptualization, L.K. and S.G.-H.; methodology, B.M. and L.K.; formal analysis, L.K.; investigation, L.K.; resources L.K. and S.G.-H.; data curation, L.K.; software, J.H.; writing—original draft preparation, L.K.; writing—review and editing, S.G.-H.; visualization, L.K.; supervision, S.G.-H.; project administration, S.G.-H.; funding acquisition, S.G.-H.

Funding: This research was funded by the German Federal Ministry for Economic Affairs and Energy within the Central Innovation Program for SMEs, grant number 16KN050526

Acknowledgments: The authors would like to thank the technical staff of the Experimental Station Ihinger Hof of the University of Hohenheim. Furthermore the authors would like to thank Fabian Görzgen from the department of biochemical and chemical engineering, TU Dortmund, for answering one or two questions about sugar constructions and composition.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Appendix A

Table A1. Results of a multiple t-test at significance level of 5% after finding significant differences via global F-test for the factor genotype (brown and RG). Same lowercase letters indicate no significant differences between the genotypes.

Genotype	Glucose [% DM]	Total Monosaccharides [% DM]	Total Sugar Content [% DM]	N Uptake Aboveground Biomass	N Uptake Total Plant [kg ha^{-1}]	% N Rhizome	% N Tuber
B	7.86^{a} ± 0.4	16.31^{a} ± 0.7	64.03^{a} ± 0.8	126.39^{b} ± 9.8	173.33^{b} ± 12.0	1.52^{a} ± 0.04	0.89^{a} ± 0.02
R	2.91^{b} ± 0.4	5.38^{b} ± 0.7	41.35^{b} ± 0.8	173.77^{a} ± 9.8	236.58^{a} ± 12.0	1.32^{b} ± 0.04	0.76^{b} ± 0.02

Table A2. Results of a multiple t-test at significance level of 5% after finding significant differences via global F-test for the factor year × genotype. Same lowercase letters indicate no significant differences between the years and same genotype. Same capital letters indicate no significant differences between genotypes within one year.

Year × Genotype	Tuber Yield [t ha^{-1} FM]	Tuber Yield [t ha^{-1} DM)	Fructose [% DM]	N Uptake Tuber [kg ha^{-1}]	% N Aboveground Biomass
2016 × B	20.42^{bA} ± 1.4	2.26^{bB} ± 0.2	1.87^{bA} ± 0.4	22.55^{aA} ± 3.9	3.47^{aA} ± 0.06
2016 × R	19.08^{bA} ± 1.4	3.19^{bA} ± 0.2	n.d.	33.80^{bA} ± 5.0	3.19^{aB} ± 0.07
2017 × B	46.15^{aB} ± 2.0	4.93^{aB} ± 0.3	3.70^{aA} ± 0.3	25.61^{aB} ± 3.9	3.34^{aA} ± 0.06
2017 × R	63.23^{aA} ± 2.0	10.75^{aA} ± 0.3	0.13^{aB} ± 0.3	69.11^{aA} ± 5.0	2.19^{aA} ± 0.07

Table A3. Results of a multiple t-test at significance level of 5% after finding significant differences via global F-test for the factor fertilizer (0, 40 and 80 kg N ha^{-1}). Same lowercase letters indicate no significant differences between the fertilization levels.

Fertilizer	N Uptake Aboveground Biomass [kg ha^{-1}]	N Uptake Total Plant [kg ha^{-1}]	% N Rhizome	PNUtE$_S$
0	122.39^{b} ± 12.0	167.62^{b} ± 14.7	1.29^{b} ± 0.05	13.77^{a} ± 0.9
40	173.44^{a} ± 12.0	227.54^{a} ± 14.7	1.47^{a} ± 0.05	10.26^{b} ± 0.9
80	154.41^{ab} ± 12.0	219.71^{a} ± 14.7	1.52^{a} ± 0.05	10.93^{b} ± 0.9

Table A4. Results of a multiple t-test at significance level of 5% after finding significant differences via global F-test for the factor year × fertilizer. Same lowercase letters indicate no significant differences between the years and same fertilization level. Same capital letters indicate no significant differences between the fertilization levels within one year.

Year × Fertilizer	Tuber Yield [t ha^{-1} FM]	Tuber Yield [t ha^{-1} DM]	Total Sugar Content [% DM]	% N Aboveground Biomass
2016*0	22.05^{bA} ± 1.7	2.89^{bA} ± 0.2	63.65^{aA} ± 1.5	3.27^{aB} ± 0.07
2016*40	20.77^{bAB} ± 1.8	3.08^{bA} ± 0.2	54.00^{aB} ± 1.5	3.19^{aB} ± 0.07
2016*80	16.44^{bB} ± 1.7	2.21^{bB} ± 0.2	53.57^{aB} ± 1.5	3.77^{aA} ± 0.07
2017*0	52.91^{aA} ± 2.6	7.48^{aB} ± 0.3	45.91^{bA} ± 1.2	2.68^{bA} ± 0.08
2017*40	52.37^{aA} ± 2.6	7.50^{aB} ± 0.3	49.36^{bA} ± 1.2	2.74^{bA} ± 0.08
2017*80	58.80^{aA} ± 2.5	8.54^{aA} ± 0.3	49.66^{aA} ± 1.2	2.65^{bA} ± 0.08

Table A5. Results of a multiple t-test at significance level of 5% after finding significant differences via global F-test for the factor genotype × fertilizer. Same lowercase letters indicate no significant differences between the genotypes and same fertilization level. Same capital letters indicate no significant differences between the fertilization levels within one genotype.

Genotype × Fertilizer	Tuber DM	% N Aboveground Biomass
B0	11.21^{bA} ± 0.41	3.28^{aB} ± 0.08
B40	10.41^{bA} ± 0.41	3.12^{aB} ± 0.08
B80	11.30^{bA} ± 0.41	3.59^{aA} ± 0.08
R0	16.04^{aB} ± 0.41	2.67^{bA} ± 0.08
R40	17.34^{aA} ± 0.41	2.81^{bA} ± 0.08
R80	16.63^{aAB} ± 0.41	2.81^{bA} ± 0.08

References

1. Ojansivu, I.; Ferreira, C.L.; Salminen, S. Yacon, a new source of prebiotic oligosaccharides with a history of safe use. *Trends Food Sci. Technol.* **2011**, *22*, 40–46. [CrossRef]
2. Bredemann, G. Über *Polymnia sonchifolia* Poepp. et Endl. (P. edulis Wedd.), die Yacon—Erdbirne. *Bot. Oeconomie* **1948**, *1*, 65–85.
3. Fernández, E.C.; Viehmannova, I.; Bechyne, M.; Lachman, J.; Milella, L. The cultication and phenological growth stage of yacon [*Smallanthus sonchifolius* (Poepp. et Endl.) H. Robinson]. *Agric. Trop. Subtrop.* **2007**, *40*, 71–77.
4. Zardini, E. Ethnobotanical notes on "Yacon" *Polymnia sonchifolia* (*Asteraceae*). *Econ. Bot.* **1991**, *45*, 72–85. [CrossRef]
5. Delgado, G.T.C.; da Silva Cunha Tamashiro, W.M.; Marostica, M.R., Jr.; Pastore, G.M. Yacon (*Smallanthus sonchifolius*): A functional food. *Plant Foods Hum. Nutr.* **2013**, *68*, 222–228. [CrossRef]
6. Douglas, J.A.; Follett, J.M.; Douglas, M.H.; Deo, B.; Scheffer, J.J.C.; Littler, R.A.; Manley-Harris, M. Effect of environment and time of planting on the production and quality of yacon (*Smallanthus sonchifolius*) storage roots. *N. Z. J. Crop Hortic. Sci.* **2007**, *35*, 107–116. [CrossRef]
7. Valentova, K.; Lebeda, A.; Dolezalova, I.; Jirovsky, D.; Simonovska, B.; Vovk, I.; Kosina, P.; Gasmanova, N.; Dziechciarkova, M.; Ulrichova, J. The biological and chemical variability of yacon. *J. Agric. Food Chem.* **2006**, *54*, 1347–1352. [CrossRef]
8. Graefe, S.; Hermann, M.; Manrique, I.; Golombek, S.; Buerkert, A. Effects of post-harvest treatments on the carbohydrate composition of yacon roots in the Peruvian Andes. *Field Crop. Res.* **2004**, *86*, 157–165. [CrossRef]
9. Manrique, I.; Parraga, A.; Hermann, M. *Yacon Syrup: Principles and Processing*; Centro International de la Papa: Lima, Peru, 2005.
10. Lachman, J.; Fernández, E.C.; Orsák, M. Yacon [*Smallanthus sonchifolia* (Poepp. et Endl.) H. Robinson] chemical composition and use—A review. *Plant Soil Environ.* **2003**, *6*, 283–290. [CrossRef]
11. Goto, K.; Fukai, K.; Hikida, J.; Nanjo, F.; Hara, Y. Isolation and structural analysis of oligosaccharides from yacon (*Polymnia sonchifolia*). *Biosci. Biotechnol. Biochem.* **2014**, *59*, 2346–2347. [CrossRef]
12. Mokrani, K.; Hamdi, K.; Tarchoun, N. Potato (*Solanum Tuberosum* L.) response to nitrogen, phosphorus and potassium fertilization rates. *Commun. Soil Sci. Plant Anal.* **2018**, *49*, 1314–1330. [CrossRef]
13. Sumiyanto, J.; Dayan, F.E.; Cerdeira, A.L.; Wang, Y.-H.; Khan, I.A.; Moraes, R.M. Oligofructans content and yield of yacon (*Smallanthus sonchifolius*) cultivated in Mississippi. *Sci. Hortic.* **2012**, *148*, 83–88. [CrossRef]
14. Doo, H.S. Changes in sugar contents and storability of yacon under different storage conditions. *Korean J. Crop Sci.* **2000**, *45*, 300–304.
15. Doo, H.S. Changes of chemical composition in tuberous root of yacon by different curing conditions. *Korean J. Crop Sci.* **2000**, *45*, 79–82.
16. Fernandes, A.M.; Campos, L.G.; Senna, M.S.; da Silva, C.L.; Assunção, N.S. Yield and nitrogen use efficiency of sweet potato in response to cover crop and nitrogen management. *Agron. J.* **2018**, *110*, 2004. [CrossRef]
17. Märländer, B.; Hoffmann, C.; Koch, H.-J.; Ladewig, E.; Merkes, R.; Petersen, J.; Stockfisch, N. Environmental situation and yield performance of the sugar beet crop in Germany: Heading for sustainable development. *J. Agron. Crop Sci.* **2003**, *11*, 201–226. [CrossRef]
18. Pocock, T.O.; Milford, G.F.J.; Armstrong, M.J. Storage root quality in sugarbeet in relation to nitrogen uptake. *J. Agric. Sci.* **1990**, *115*, 355. [CrossRef]
19. Carter, J.N.; Traveller, D.J. Effect of time and amount of nitrogen uptake on sugarbeet growth and yield. *Agron. J.* **1981**, *73*, 665–671. [CrossRef]
20. Sah, R.N.; Geng, S.; Puri, Y.P.; Rubatzky, V.E. Evaluation of four crops for nitrogen utilization and carbohydrate yield. *Fertil. Res.* **1987**, *13*, 55–70. [CrossRef]
21. Maltas, A.; Dupuis, B.; Sinaj, S. Yield and quality response of two potato cultivars to nitrogen fertilization. *Potato Res.* **2018**, *61*, 97–114. [CrossRef]
22. Gastal, F.; Lemaire, G. N uptake and distribution in crops: An agronomical and ecophysiological perspective. *J. Exp. Bot.* **2002**, *53*, 789–799. [CrossRef]
23. Goulding, K. Nitrate leaching from arable and horticultural land. *Soil Use Manag.* **2000**, *16*, 145–151. [CrossRef]

24. IUSS Working Group WRB. *World Reference Base for Soil Resources 2006. Ein Rahmen für Internationale Klassifikation*, Korrelation und Kommunikation. Erstes Update 2007. Deutsche Ausgabe; BGR: Hannover, Germany, 2008.
25. VDLUFA. *Methodenbuch Band II.1. Die Untersuchung von Bo den*; VDLUFA-Verlag: Darmstadt, Germany, 2004. Available online: https://www.vdlufa.de/Methodenbuch/index.php?option=com_content&view=article&id=9&Itemid=115&lang=de (accessed on 15 January 2019).
26. Campbell, J.M.; Bauer, L.L.; Fahey, G.C.; Hogarth, A.J.C.L.; Wolf, B.W.; Hunter, D.E. Selected fructooligosaccharide (1-kestose, nystose, and 1 F-β-fructofuranosylnystose) composition of foods and feeds. *J. Agric. Food Chem.* **1997**, *45*, 3076–3082. [CrossRef]
27. Wolfinger, R. Covariance structure selection in general mixed models. *Commun. Stat. Simul. Comput.* **1993**, *22*, 1079–1106. [CrossRef]
28. Piepho, H.P. An algorithm for a letter-based representation of all-pairwise comparisons. *Biometrical J.* **2004**, *13*, 456–466. [CrossRef]
29. Fernández, E.C.; Viehmannová, I.; Bechyne, M.; Lachman, J.; Milella, L. Yacon [*Smallanthus sonchifolius* (Poeppig & Endlicher) H. Robinson]: A new crop in the Central Europe. *Plant Soil Environ.* **2006**, *12*, 564–570.
30. Leemans, R.; Cramer, W.P. The IIASA database for mean monthly values of temperature, precipitation, and cloudiness on a global terrestrial grid. *IIASA Res. Rep.* **1991**, *91*.
31. Douglas, J.A. Research and development of yacon production in New Zealand. *Acta Hortic.* **2005**, *670*, 79–85. [CrossRef]
32. De Mastro, G.; Manolio, G.; Marzi, V. Jerusalem artichoke (*Helianthus tuberosus* L.) and chicory (*Chicorium intybus* L.): Potential crops for inulin production in the mediterranean area. *Acta Hortic.* **2004**, *629*, 365–374. [CrossRef]
33. Meijer, W.J.M.; Mathijssen, E.W.J.M.; Borm, G.E.L. Crop characteristics and inulin production of Jerusalem artichoke and chicory. *Stud. Plant Sci.* **1993**, *3*, 29–38.
34. Kai, G.; Tie-Xia, Z.; Qi-Bing, W. Nitrogen fertilization, irrigation, and harvest times affect biomass and energy value of *Helianthus tuberosus* L. *J. Plant Nutr.* **2016**, *39*, 1906–1914. [CrossRef]
35. Losavio, N.; Lamascese, N.; Vonella, A.V. Water requirements and nitrogen fertilization in Jerusalem artichoke (*Helianthus tuberosus* L.) grown under mediterranean conditions. *Acta Hortic.* **1997**, *1*, 205–209. [CrossRef]
36. Stahr, K.; Kandeler, E.; Herrmann, L.; Streck, T. *Bodenkunde und Standortlehre*, 2nd ed.; Eugen Ulmar KG: Stuttgart, Germany, 2012.
37. Engels, T.; Kuhlmann, H. Effect of the rate of N fertilizer on apparent net mineralization of N during and after cultivation of cereal and sugar beet crops. *J. Plant Nutr. Soil. Sci.* **1993**, *156*, 149–154. [CrossRef]
38. Manrique, I.; Hermann, M.; Bernet, T. *Yacon Fact Sheet*; International Potato Center (CIP): Lima, Peru, 2004.
39. Douglas, J.A. Maximising fructo-oligosacharide production in yacon. *Agron. N. Z.* **2002**, *32*, 49–55.
40. Hermann, M.; Freire, I.; Pazos, C. Compositional diversity of the yacon storage root. *CIP Program Rep.* **1997**, *98*, 425–432.
41. Leidi, E.O.; Altamirano, A.M.; Mercado, G.; Rodriguez, J.P.; Ramos, A.; Alandia, G.; Sørensen, M.; Jacobsen, S.-E. Andean roots and tubers crops as sources of functional foods. *J. Funct. Foods* **2018**, *51*, 86–93. [CrossRef]
42. Campos, D.; Betalleluz-Pallardel, I.; Chirinos, R.; Aguilar-Galvez, A.; Noratto, G.; Pedreschi, R. Prebiotic effects of yacon (*Smallanthus sonchifolius* Poepp. & Endl), a source of fructooligosaccharides and phenolic compounds with antioxidant activity. *Food Chem.* **2012**, *135*, 1592–1599. [CrossRef]
43. Hermann, M. *Andean Roots and Tubers: Ahipa, Arracacha, Maca and Yacon*; International Plant Genetic Resources Institute: Rome, Italy, 1997; pp. 191–243.
44. Sprague, H.B.; Farris, N.F.; Colby, W.G. Effect of soil conditions and treatment on yields of tubers and sugar from the American artichoke (*Helianthus tuberosus*). *J. Am. Soc. Agron.* **1935**, *27*, 392–399. [CrossRef]
45. Lachman, J.; Havrland, B.; Fernandez, E.C.; Dudjak, J. Saccharides of yacon [*Smallanthus sonchifolius* (Poepp. et Endl.) H. Robinson] tubers and rhizomes and factors affecting their content. *Plant Soil Environ.* **2004**, *50*, 383–390. [CrossRef]
46. Ohyama, T.; Ito, O.; Yasuyoshi, S.; Ikarashi, T.; Minamisawa, K.; Kubota, M.; Tsukihashi, T.; Asami, T. Composition of storage carbohydrate in tubers of yacon (*Polymnia sonchifolia*). *Soil Sci. Plant Nutr.* **1990**, *36*, 167–171. [CrossRef]

47. Delgado, G.T.C.; Thomé, R.; Gabriel, D.L.; Tamashiro, W.M.; Pastore, G.M. Yacon (*Smallanthus sonchifolius*)-derived fructooligosaccharides improves the immune parameters in the mouse. *Nutr. Res.* **2012**, *32*, 884–892. [CrossRef] [PubMed]
48. Fukai, K.; Miyazaki, S.; Nanjo, F.; Hara, Y. Distribution of carbohydrates and related enzyme activities in yacon (*polymnia sonchifolia*). *Soil Sci. Plant Nutr.* **1993**, *39*, 567–571. [CrossRef]
49. Khajehei, F.; Merkt, N.; Claupein, W.; Graeff-Hoenninger, S. Yacon (*Smallanthus sonchifolius* Poepp. & Endl.) as a novel source of health promoting compounds: Antioxidant activity, phytochemicals and sugar content in flesh, peel, and whole tubers of seven cultivars. *Molecules* **2018**, *23*, 278. [CrossRef]
50. Minamisawa, K.; Ohyama, T. Fluctuations of oligofructan contents in tubers of yacon (*Polymnia. sonchifolia*) during growth and storage. *Jpn. Soc. Soil Sci. Plant Nutr.* **1991**, *62*, 621–627.
51. Dorrell, D.G.; Chubey, B.B. Irrigation, fertilizer, harvest dates and storage effects on the reducing sugar and fructose concentrations of Jerusalem artichoke tubers. *Can. J. Plant Sci.* **1997**, *57*, 591–596. [CrossRef]
52. Soja, G.; Dersch, G.; Praznik, W. Harvest dates, fertilizer and varietal effects on yield, concentration and molecular distribution of fructan in Jerusalem artichoke (*Helianthus tuberosus* L.). *J. Agron. Crop Sci.* **1990**, *165*, 181–189. [CrossRef]
53. Ojala, J.C.; Stark, J.C.; Kleinkopf, G.E. Influence of irrigation and nitrogen management on potato yield and quality. *Am. Potato J.* **1990**, *67*, 29–43. [CrossRef]
54. Richter, C. *Agrikulturchemie und Pflanzenernährung*; Margraf Publishers GmbH: Weikersheim, Germany, 2005.
55. Lebeda, A.; Dolezalova, I.; Valentova, K.; Gasmanova, N.; Dziechciarkova, M.; Ulrichova, J. Yacon (*Smallanthus sonchifolius*)—A traditional crop of the Andean Indians as a challenge for the future—The news about biological variation and chemical substances content. *Acta Hortic.* **2008**, 127–136. [CrossRef]
56. Ana, R.; Snezana, C.; Marina, T.; Viorica, T.; Gabriel, I.; Demetra, S.; Carmen, G.; Slobodan, J. Comparative analysis of the chemical composition of *Heliantus tuberosus* L. growing in Serbia and Romania. *Serb. J. Exp. Clin. Res.* **2013**, *14*, 9–12. [CrossRef]
57. Slimestad, R.; Seljaasen, R.; Meijer, K.; Skar, S.L. Norwegian-grown Jerusalem artichoke (*Helianthus tuberosus* L.): Morphology and content of sugars and fructo-oligosaccharides in stems and tubers. *J. Sci. Food Agric.* **2010**, *90*, 956–964. [CrossRef]
58. Puangbut, D.; Jogloy, S.; Vorasoot, N.; Srijaranai, S.; Kesmala, T.; Holbrook, C.C.; Patanothai, A. Influence of planting date and temperature on inulin content in Jerusalem artichoke (*Helianthus tuberosus* L.). *Aust. J. Crop Sci.* **2012**, *6*, 1159–1165.
59. Zotarelli, L.; Rens, L.R.; Cantliffe, D.J.; Stoffella, P.J.; Gergela, D.; Burhans, D. Rate and timing of nitrogen fertilizer application on potato 'FL1867'. Part I: Plant nitrogen uptake and soil nitrogen availability. *Field Crop. Res.* **2015**, *183*, 246–256. [CrossRef]
60. Märländer, B. Influence of nitrogen supply on yield and quality of sugar beet. *J. Plant Soil Sci.* **1990**, *153*, 327–332. [CrossRef]
61. Landwirtschaftliches Technologiezentrum Augustenberg. *Merkblätter für die Umweltgerechte Landbewirtschaftung: Kartoffeln, Anbau, Düngung, Pflanzenschutz*; Landwirtschaftliches Technologiezentrum Augustenberg: Karlsruhe, Germany, 2011; pp. 1–12.
62. Battilani, A.; Plauborg, F.L.; Hansen, S.; Dolezal, F.; Mazurczyk, W.; Bizik, J.; Coutinho, J. Nitrogen uptake and nitrogen use efficiency of fertigated potatoes. *Acta Hortic.* **2008**, 61–67. [CrossRef]
63. Bélanger, G.; Walsh, J.R.; Richards, J.E.; Milburn, P.H.; Ziadi, N. Nitrogen fertilization and irrigation affects tuber characteristics of two potato cultivars. *Am. J. Potato Res.* **2002**, *79*, 269–279. [CrossRef]
64. Seiler, G.J. Protein and mineral concentrations in tubers of selected genotypes of wild and cultivated Jerusalem-artichoke (*Helianthus tuberosus, asteraceae*). *Econ. Bot.* **1990**, *44*, 322–335. [CrossRef]
65. Joern, B.C.; Vitosh, M.L. Influence of applied nitrogen on potato part 1: Yield, quality, and nitrogen uptake. *Am. Potato J.* **1995**, *72*, 51–63. [CrossRef]
66. Kleijn, D.; Treier, U.A.; Müller-Schärer, H. The importance of nitrogen and carbohydrate storage for plant growth of the alpine herb Veratrum album. *New Phytol.* **2005**, *166*, 565–575. [CrossRef] [PubMed]
67. Laufer, D.; Koch, H.-J. Growth and yield formation of sugar beet (*Beta vulgaris* L.) under strip tillage compared to full width tillage on silt loam soil in Central Europe. *Eur. J. Agron.* **2017**, *82*, 182–189. [CrossRef]
68. Houba, V.J.G.; Huijbregts, A.W.M.; Wilting, P.; Novozamsky, I.; Gort, G. Sugar yield, nitrogen uptake by sugar beet and optimal nitrogen fertilization in relation to nitrogen soil analyses and several additional factors. *Biol. Fertil. Soils* **1995**, *19*, 55–59. [CrossRef]

69. Laufer, D.; Nielsen, O.; Wilting, P.; Koch, H.-J.; Märländer, B. Yield and nitrogen use efficiency of fodder and sugar beet (*Beta vulgaris* L.) in contrasting environments of northwestern Europe. *Eur. J. Agron.* **2016**, *73*, 124–132. [CrossRef]
70. Mengel, K. Turnover of organic nitrogen in soils and its availability to crops. *Plant Soil* **1996**, *181*, 83–93. [CrossRef]

6. Chapter IV: Environmental and economic performance of yacon (*Smallanthus sonchifolius*) cultivated for fructooligosaccharide production

Publication IV:

Wagner, M., Kamp, L., Graeff-Hönninger, S., Lewandowski, I. (2019): Environmental and economic performance of yacon (*Smallanthus sonchifolius*) cultivated for fructooligosaccharide production. Sustainability 2019, 11, 4581.

Chapter IV combined the results of publication I – III in order to assess the environmental and economic performance of yacon-based FOS production. In this study several practical oriented yacon cultivation systems were investigated. Hereby the cultivation of two genotypes - brown-shelled and red-shelled - with three different nitrogen fertilization levels and two propagation methods were assessed. In particular, the focus was on the holistic assessment and optimization of the costs and the environmental impact of yacon cultivation for FOS production. As demonstrated there are considerable differences between the cultivations systems investigated, mainly depending on genotype and propagation method. In conclusion chapter IV showed, that there is a considerable potential for producing FOS out of yacon while simultaneously optimizing the economic and environmental performance.

sustainability

MDPI

Article

Environmental and Economic Performance of Yacon (*Smallanthus sonchifolius*) Cultivated for Fructooligosaccharide Production

Moritz Wagner [1,*], Larissa Kamp [2], Simone Graeff-Hönninger [2] and Iris Lewandowski [1]

[1] Department Biobased Products and Energy Crops, Institute of Crop Science, University of Hohenheim, 70599 Stuttgart, Germany

[2] Institute of Crop Science, University of Hohenheim, 70599 Stuttgart, Germany

* Correspondence: moritz.wagner@uni-hohenheim.de; Tel.: +49-0711-459-23557

Received: 21 July 2019; Accepted: 21 August 2019; Published: 23 August 2019

check for updates

Abstract: As the prevalence of diabetes is predicted to rise globally in the coming decades, the demand for sugar substitutes is expected to increase significantly. In this context, natural sweeteners have been receiving particular attention, as artificial sweeteners have been associated with obesity and cardiovascular disease. One natural sweetener is yacon (*Smallanthus sonchifolius*) ((Poepp. and Endl.) H. Robinson), which could play a prominent role due to its high fructooligosaccharides yield. Yacon is currently only a minor crop in Europe and there is little information available on the environmental and economic impacts of its various cultivation systems. These are especially affected by nitrogen fertilization levels and genotype selection. Thus, before the crop is introduced on a larger scale, it is expedient to identify the most sustainable cultivation system. The life-cycle assessment (LCA) and life-cycle costing (LCC) analysis of yacon cultivation systems conducted in this study revealed significant differences between yacon genotypes and found that a nitrogen fertilization level of 80 kg N ha^{-1} significantly decreased production costs and simultaneously led to a comparatively good environmental performance. The results indicated that, for the holistic evaluation of agricultural systems, it is crucial to assess both the economic and environmental performance of new crops.

Keywords: yacon; fructooligosaccharides; environmental performance; LCA; production cost; LCC

1. Introduction

Yacon (*Smallanthus sonchifolius*) ((Poepp. And Endl.) H. Robinson) is a tuberous root plant belonging to the family *Asteraceae*. It is a herbaceous perennial plant with a height of up to 2.5 m that originates from the Andean region [1], where it is cultivated as a staple food for local consumption and as a cash crop [2,3]. In addition to its region of origin, yacon is also cultivated in Brazil, Czech Republic, Italy, Japan, and New Zealand [4,5]. It can achieve tuber yields of up to 67 t fresh matter (FM) ha^{-1} [6]. The tuberous roots, which have a dry matter content of between 10% and 18%, act as storage organs for the plant [6–9]. Similar to Jerusalem artichoke and chicory, yacon stores carbohydrates primarily as fructan, in particular as fructooligosaccharides (FOS), with FOS accounting for up to 70% of the dry matter content [10]. The FOSs in yacon consist mainly of kestose, nystose, and fructofuranosylnystose [7]. The high fructooligosaccharide content makes yacon an interesting resource for the food processing industry. FOSs cannot be digested by the human intestinal tract and therefore do not lead to an increase in blood glucose level. For this reason, yacon can be used as a natural sweetener for diabetics [11]. Due to its high tuber yield and interesting properties, yacon could offer European farmers a promising opportunity to increase crop diversity.

In recent years, several publications have assessed the influence of genotype selection and cultivation practice on yacon tuber yields and composition [6,8,12–15]. Kamp et al., for example, showed that nitrogen fertilization had an influence not only on the tuber yield but also on the fructooligosaccharide content of the tubers [6]. An increase in nitrogen fertilization levels led to an increase in both tuber yields and the FOS content of the tubers, and therefore also to an increase in total FOS yield per hectare. However, an increase in nitrogen fertilization was also accompanied by an increase in environmental impact, for example through nitrate leaching, and additional costs for the farmer. Furthermore, it has been shown that different propagation techniques lead to considerable differences in both propagations costs and tuber yields [14].

Thus, before this novel food crop is introduced on a larger scale, it is necessary to consider which yacon cultivation system is the most beneficial from both an environmental and economic point of view. Despite the growing importance of FOS-producing crops, there are currently no studies on the environmental performance of yacon cultivation. With regard to its economic performance, only the economic feasibility of the different propagation methods has been analysed to date [14]. For this reason, the current paper assesses the economic and environmental performance of entire yacon cultivation systems. In line with the sustainable intensification approach, the aim is to find cultivation systems which increase the yacon tuber yield and quality, while minimizing negative environmental impacts and production costs [16]. In addition, it identifies possible trade-offs between environmental and economic factors and discusses possible mitigation options.

The environmental performance of yacon-based FOS production was assessed by conducting a life-cycle assessment (LCA), according to the ISO standards 14040 and 14040 [17,18], and applying the life-cycle impact assessment methodology ReCiPe [19]. The selection of the relevant environmental impact categories was based on Wagner et al. [20], who analysed the relevance of various impact categories in the assessment of the environmental performance of agricultural production systems. Their study recommended including the impact categories climate change (CC)—which corresponds to global warming potential—agricultural land occupation (ALO), marine (ME) and freshwater eutrophication (FE), human toxicity (HT), as well as marine (MET) and freshwater ecotoxicity (FET) [20]. The economic performance was analysed in a complementary life-cycle cost (LCC) assessment, in accordance with Swarr et al. [21]. The data for the yacon cultivation were based on a field trial at Ihinger Hof, a research station of the University of Hohenheim, as described in Kamp et al. [6]. The FOS content of the yacon tubers was analysed by high performance liquid chromatography (HPLC). Background data on emissions and costs associated with input substrates (e.g., fertilizer), machine use, and transport processes were taken from the ecoinvent database 3.5 [22] and from the KTBL database [23].

2. Materials and Methods

2.1. Scope and Boundaries

The functional unit chosen was 1 kg of fructooligosaccharide contained in the yacon tubers at the farm gate. The further FOS extraction process was not included here.

The system assessed in this study is displayed in Figure 1. The system boundaries included the production and transport of the input substrates used, such as mineral fertilizers and herbicides, the production of the propagation material, and the agricultural management (soil cultivation, ridging, planting, fertilization, herbicide spraying, harvesting), including diesel consumption of the respective process steps. After soil cultivation and fertilizer application, ridges were formed, into which the yacon plantlets were then transplanted. Chemical weed control was performed twice, once before planting and once during the growth period. After the harvest, which was performed using a modified potato harvester, the tubers and rhizomes were separated by hand. The rhizomes were stored until the next year to be used for propagation of new plantlets in the greenhouse.

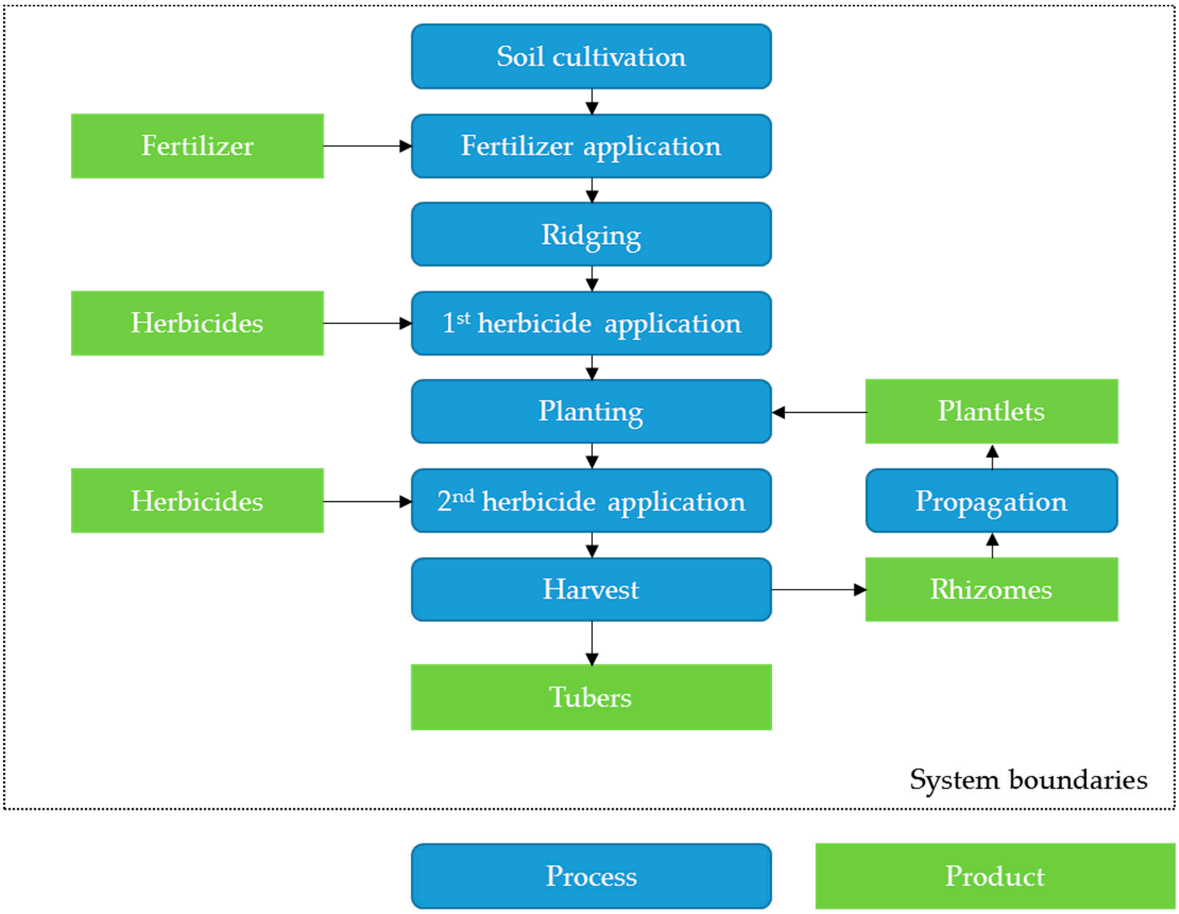


Figure 1. System description and boundaries for yacon cultivation.

2.2. Life-Cycle Inventory

The study was based on the results of a field trial where yacon was cultivated under three nitrogen fertilizer regimes at the Ihinger Hof, a research station of the University of Hohenheim (48°44′ N, 8°55′ E and 475 a.s.l.) in southwest Germany [6]. Before planting, soil preparation was performed once with a plough and twice with a tine cultivator. At the beginning of May, the yacon plantlets were transplanted by hand into the ridges (height × width: 60 × 45 cm; 44 cm between ridges) with a plant density of 12,531 plants ha^{-1}. Plantlets were obtained from rhizome pieces pre-cultivated for six to eight weeks in the greenhouse before being planted. The field trial evaluated the tuber yield formation of two yacon genotypes: a brown-shelled (BG) and a red-shelled genotype (RG). The yacon genotypes are described more in detail in Kamp et al. [6]. In addition, three nitrogen fertilization levels were investigated: 0, 40, and 80 kg N ha^{-1}. In the field trial of Kamp et al. [6], ENTEC 26 was applied as nitrogen fertilizer. ENTEC 26 (EuroChem Agro GmbH, Mannheim, Germany) is a stabilized fertilizer consisting of 26% total nitrogen (18% ammonium nitrogen, 7.5% nitrate nitrogen) and 13% hydro soluble sulphur, with nitrification inhibiter 3,4-dimethyl-1H-pyrazole phosphate (DMPP). The N_{min} in the soil prior to planting was 119 kg NO_3 ha^{-1} [6]. The life-cycle inventory also included the application of 100 kg potassium in form of potassium sulphate, according to the fertilization recommendation of Singh [24]. It has been shown that potassium fertilization has positive effects on the yield and quality of tuberous root plants [25]. The potassium fertilization was the same for all nitrogen fertilisation levels analysed in this assessment. In yacon, weed control has to be applied [26]. The current study made the assumption that chemical weed control was applied using 1.25 l ha^{-1} Dual Gold (Syngenta, active ingredient 960 g l^{-1} S Metolachlor) as a pre-emergence herbicide before planting and 3.5 l ha^{-1} Stomp Aqua (BASF, active ingredient 455 g l^{-1} Pendimethalin) as a post-emergence herbicide. Furthermore, it was assumed that all input substrates were transported 150 km from their production sites to the farm by truck and 2 km to the field by tractor. In practice, yacon is harvested in October with a modified potato or carrot harvester. The results of the field trial showed significant differences in yield between the two genotypes and the three nitrogen levels [6]. The dry matter yield, FOS content, and FOS yield for the different fertilization levels are displayed in Table 1. The data used in the current study resulted from the year 2017. In Kamp et al. [6], the results for the field trials are displayed for 2016 and 2017. However, in 2016 a different propagation system was used, therefore the current assessment includes only the yield data and yacon tuber characteristics from the year 2017.

Table 1. Dry matter yield, fructooligosaccharide (FOS) content, and FOS yield of the yacon genotypes, with three different nitrogen fertilization levels. Establishment was carried out using standard procedure, i.e., planting of pre-cultivated plantlets. Data from Kamp et al. [6].

Input/Output	Red-Shelled Genotype			Brown-Shelled Genotype		
Fertilization level in kg N ha^{-1}	0	40	80	0	40	80
Tuber yield in kg DM ha^{-1}	10,350	10,496	11,405	4716	4515	5672
FOS content in %	30.50	33.23	34.81	36.21	39.35	42.02
FOS yield in kg FOS ha^{-1}	3157	3488	3970	1708	1777	2383

In the harvesting process, both the yacon tubers and rhizomes are harvested. As a consequence, there is no risk of yacon re-sprouting in the follow-on crop. In addition, the cold winter temperatures in southwest Germany would destroy any plant material left, as yacon is a non-frost tolerant crop [1]. After the harvest, the tubers have to be manually separated from the rhizomes. The rhizomes are wrapped in perforated bags and stored in lightproof boxes, filled with a mixture of sand and sawdust to absorb humidity. The following year, the rhizomes are sliced into smaller pieces, which are then propagated in the greenhouse, as described in Kamp et al. [14]. This procedure is referred to as "standard procedure" in the following text. It results in a yield of 15 pieces per rhizome. Therefore approximately 836 rhizomes are required to obtain the necessary planting density of 12,531 plants ha^{-1}. In the current study, it was assumed that the farmer buys new rhizomes every 10 years to acquire novel yacon genotypes and keep up with breeding progress. The costs of purchasing 836 rhizomes were allocated to the 10 years in which the genotype was used.

Fertilizer-induced emissions during the cultivation process were estimated as described below. Direct N_2O and NO emissions from nitrogen fertilizer were calculated according to Bouwman et al. [27]. Indirect N_2O emissions from nitrogen fertilizer and N_2O emissions from harvest residues were calculated based on emission factors taken from Intergovernmental Panel on Climate Change (IPCC) [28]. Nitrogen-fertilizer-induced ammonia emissions were estimated according to EMEP/CORINAIR emission inventory guidebook [29]. Phosphate and phosphorus emissions to surface and ground water were estimated based on Nemecek and Kägi [30]. Nitrate leaching to ground water was calculated according to the emission factors taken from IPCC [28]. All pesticides applied were modelled completely as emissions to agricultural soil, in accordance with Nemecek and Schnetzer [31]. The ecotoxicity values for the herbicides applied were taken from the ecoinvent database [22]. In the field trials, a fertilizer with nitrification inhibitors was used (ENTEC 26). The resulting emission reductions were calculated for direct N_2O and NO emissions according to Akiyama et al. [32] and for nitrate leaching according to Díez López and Hernaiz [33].

The costs of machinery and diesel used in the agricultural operations were based on the KTBL database [23]. The related labour costs were calculated using the working time requirements for each agricultural operation specified by KTBL [23]. Hourly wages of €17 were assumed based on calculations by the North Rhine-Westphalia chamber of agriculture and the German agricultural labour agreement [34]. These labour costs included incidental wage costs. An annual land rent of €328 per hectare was applied. This was based on the average cost of leasing agricultural land in Germany in the year 2016 [35]. Background data associated with the transport of the input substrates, transport costs for the yacon tubers, and herbicide costs were taken from the ecoinvent database 3.5 [22]. Potassium and ENTEC 26 fertilizer costs were based on market prices [36,37]. The cost assumptions used are described more in detail in the supplementary material. The costs of the agricultural operations are given in Table S1 and those of the input substrates in Table S2. The costs of biomass transport are shown in Table S3 and details of costs associated with the propagation process are given in Table S4.

2.3. Scenario Analysis

In the standard procedure, plantlets are obtained from rhizome pieces pre-cultivated for six to eight weeks in the greenhouse before being planted. This pre-cultivation step is quite labour- and energy-intensive. It has been demonstrated that the direct planting of rhizomes can potentially decrease propagation process costs substantially, but that the tuber yield is also considerably lower [14]. According to Kamp et al. [14], a yield reduction of up to 30% can occur. For this reason, the influence of direct rhizome planting on the economic and environmental performance of yacon cultivation was assessed in a scenario analysis. In this scenario (direct planting), the rhizomes were planted directly into the soil with a modified potato planter and the FOS yield was reduced by 30% compared to the standard procedure (as displayed in Table 1).

3. Results

The results of the life-cycle cost analysis are presented first, followed by the life-cycle assessment.

3.1. Life-Cycle Cost Analysis

The life-cycle costs of the red-shelled (RG) and brown-shelled genotypes (BG) are given in Euro per kg FOS (Figure 2). In addition, in Table S5 in the supplementary, they are given per tonne FM. There are considerable differences between the two genotypes. The production costs of the brown-shelled genotype are almost twice as high as for the red-shelled genotype. This is caused by the significantly lower FOS yield of the brown-shelled genotype. A comparison of the different treatments showed that the increase in FOS yield caused by additional nitrogen fertilizer led to a significant decrease in costs. In addition, despite the lower yield, direct planting was associated with lower production costs. This is true for both genotypes (see Figure 2). However, the differences between the standard procedure and direct planting were quite small.

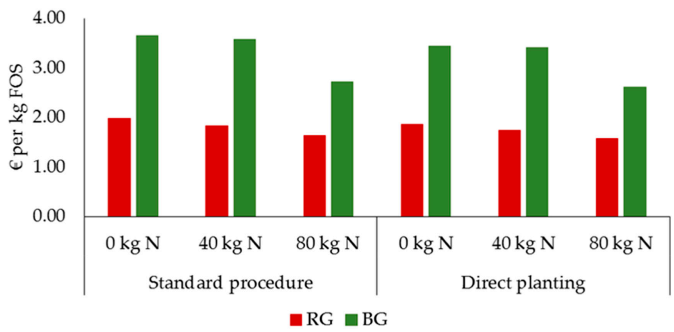


Figure 2. Yacon production costs in Euro per kg FOS for the red-shelled (RG) and the brown-shelled genotype (BG).

Figure 3 shows the distribution of the costs for the standard procedure and direct planting. For both treatments, the results are displayed for the red-shelled genotype and the fertilization level 40 kg N ha^{-1}. Here, "production input material" includes the production of all fertilizers and pesticides. "Agricultural operations" incorporates all steps from soil cultivation through to harvest, including the separation of tubers and rhizomes. "Propagation" includes the storage of the rhizomes and propagation in the greenhouse. "Transport biomass" incorporates the transport of the yacon tubers and rhizomes from the field to the farm.

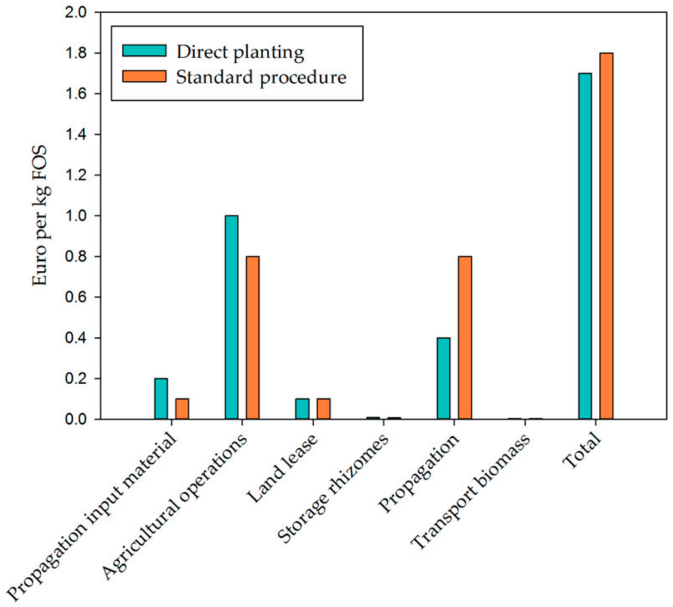


Figure 3. Distribution of yacon production costs in Euro per kg FOS (here shown only for the red-shelled genotype and the 40 kg N ha^{-1} fertilization level).

The yacon production costs are dominated mainly by the costs of agricultural operations and propagation (Figure 3). The agricultural operations costs are incurred to a large extent from the yacon planting and harvest. There are considerable differences between the two treatments. The most pronounced difference can be seen in the step "propagation". Propagation costs are dominated by labour costs (e.g., due to the slicing of the rhizomes) as well as by costs for greenhouse infrastructure and operation, which are not incurred in direct planting.

3.2. Life-Cycle Assessment

For the seven impact categories assessed, the environmental impacts are expressed per functional unit (FU) of 1 kg FOS (Figures 4–6). In addition, in Table S5 in the supplementary materials they are given per tonne FM. In the category marine eutrophication, the environmental impact increased with an increase in nitrogen fertilization. The standard procedure showed lower results than for direct planting and thus had a more favourable environmental performance (Figure 4).

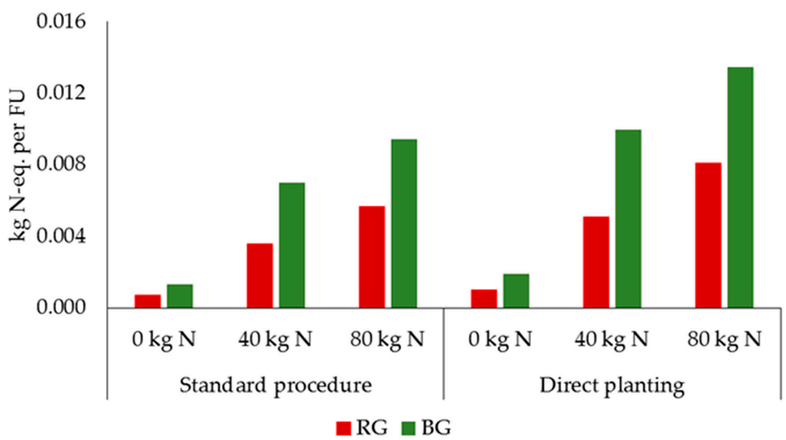


Figure 4. Marine eutrophication (kg N-eq.) per kg FOS for the red-shelled (RG) and the brown-shelled genotype (BG).

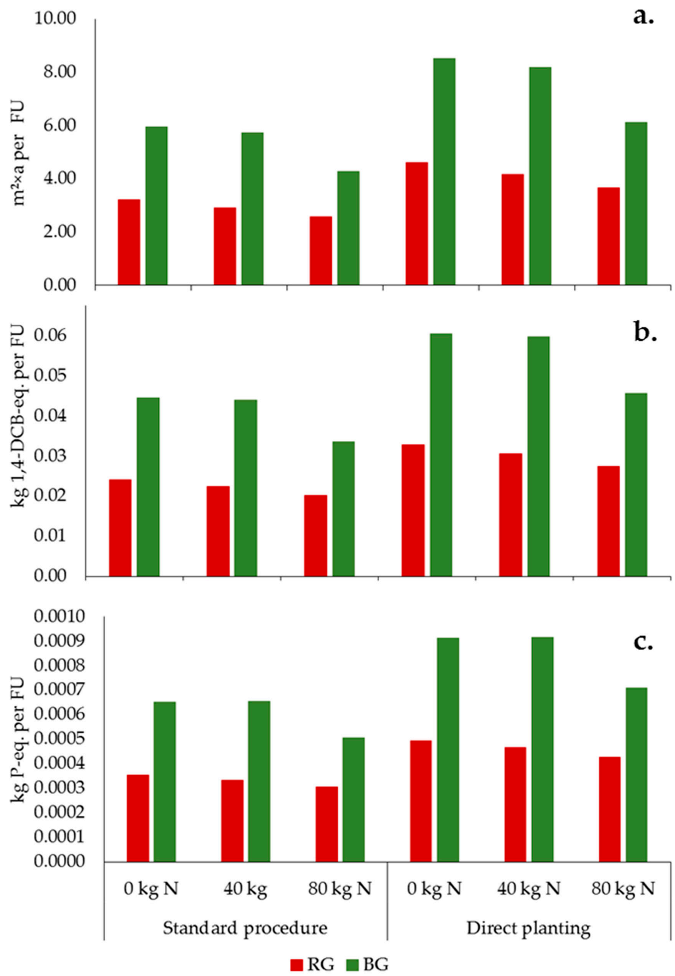


Figure 5. (**a**) Agricultural land occupation ($m^2 \times a$), (**b**) freshwater ecotoxicity (kg 1,4-DCB-eq.), (**c**) freshwater eutrophication potential (kg P-eq.) per kg FOS for the red-shelled (RG) and the brown shelled genotype (BG).

By contrast, in the impact categories agricultural land occupation, freshwater ecotoxicity, and freshwater eutrophication, an increase in nitrogen fertilization level led to a decrease in the respective environmental impacts per FU. This was true for both propagation methods, the standard procedure and direct planting (Figure 5).

The life-cycle impact assessment results for the impact categories climate change, human toxicity, and marine ecotoxicity are shown in Figure 6. For the brown-shelled genotype, the 40 kg N ha^{-1} fertilization level resulted in the highest environmental impacts per kg FOS in all three categories. The differences in the environmental performance between the 0 and 80 kg N ha^{-1} fertilization levels were comparatively small (Figure 6). For the red-shelled genotype, the assessment showed a slight increase in the impact categories climate change and human toxicity with increasing nitrogen fertilization. In the category marine ecotoxicity, the 40 kg N ha^{-1} fertilization level showed the highest impacts for the red-shelled genotype. The 0 and 80 kg N ha^{-1} levels are comparable.

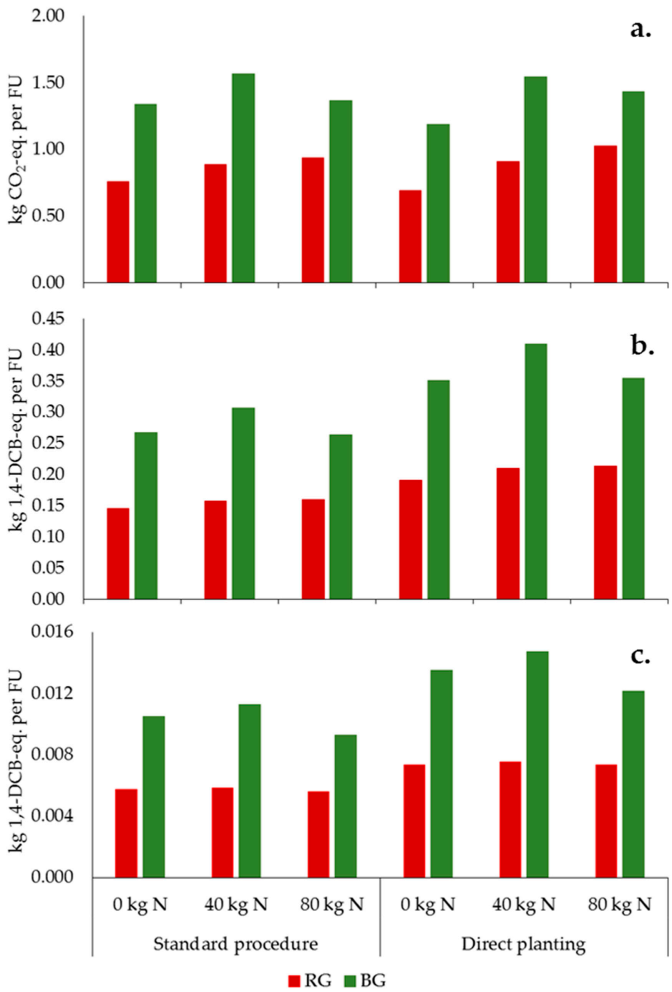


Figure 6. (**a**) Climate change (kg CO_2-eq.), (**b**) human toxicity (kg 1,4-DCB-eq.), (**c**) marine ecotoxicity (kg 1,4-DCB-eq.) per kg FOS for the red-shelled (RG) and the brown shelled genotype (BG).

3.3. Hotspot Aanalysis

A hotspot analysis of the economic and environmental performance of yacon cultivation for FOS production is displayed in Figure 7. Results are shown for the 40 kg N ha^{-1} fertilization level for the red-shelled genotype planted in the standard procedure. Here, "production input material" includes the production of all fertilizers and pesticides. "Agricultural operations" incorporates all steps from soil cultivation through to harvest, including the separation of tubers and rhizomes. The "agricultural system" includes the land use of the yacon cultivation as well as all fertilizer-induced emissions. "Propagation" refers to the storage of the rhizomes and the propagation in the greenhouse. "Other" includes land rent and all costs and environmental impacts associated with the transport of the biomass from the field to the farm.

There are considerable differences between the major contributors to the costs and environmental impacts. Whereas the life-cycle costs of FOS production are dominated by costs for propagation and agricultural operations, the environmental impacts are strongly influenced by the agricultural system (Figure 7). ALO is almost exclusively dominated by the agricultural system, i.e., the land used for cultivation. By contrast, the impact of the agricultural system in the category climate change is mainly caused by nitrogen fertilizer production (contained in production input material) and nitrogen-fertilizer-induced emissions, such as N_2O. Fertilizer-induced emissions are also main contributors to the impact categories ME (nitrate emissions to ground water), FE (phosphate and phosphorus emissions to surface and ground water), and FET (phosphorus emissions to surface water).

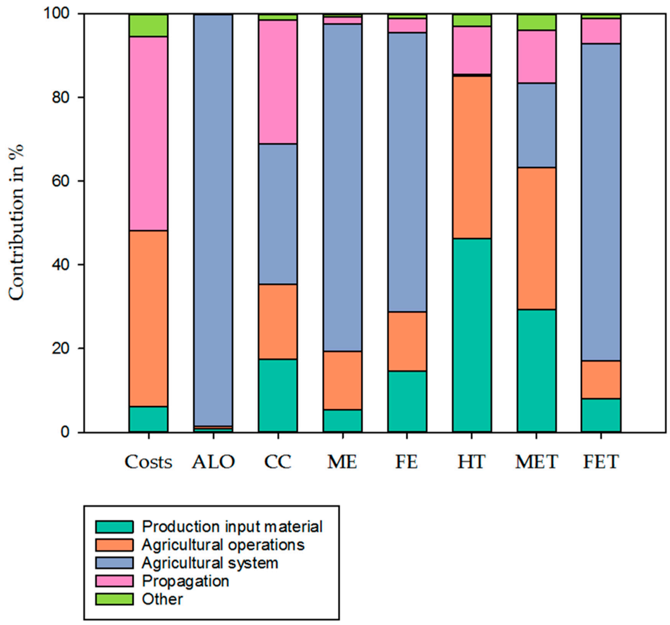


Figure 7. Hotspot analysis of the economic and environmental performance of yacon cultivation for FOS production (results are shown for the 40 kg N ha^{-1} fertilization level of the red-shelled genotype planted in the standard procedure). ALO = Agricultural land occupation; CC = Climate Change; ME = Marine eutrophication; FE = Freshwater eutrophication; HT = Human toxicity; MET = Marine ecotoxicity; FET = Freshwater ecotoxicity.

4. Discussion

The first part of the discussion provides a critical analysis of the environmental and economic performance of yacon-based FOS production. Here, possible trade-offs are identified between life-cycle costs and environmental impact categories, as well as between the environmental impacts themselves, the main hotspots are highlighted, and potential improvements suggested. The second section focuses on the question of which yacon cultivation system makes the most sense from an environmental and economic point of view and can be recommended for introduction into agricultural practice in Europe.

4.1. Environmental and Economic Performance of Yacon-Based FOS Production

The results of the environmental and economic assessment of the different yacon production procedures revealed that a high FOS yield is the key to low negative environmental impacts with simultaneous low costs.

It is this higher FOS yield that led to both lower environmental impacts and life-cycle costs per kg FOS in the red-shelled rather than the brown-shelled genotype, independent of treatment and propagation method. Although the brown-shelled genotype had a higher percentage FOS content, the lower tuber yields resulted in considerably lower FOS yields per hectare compared to the red-shelled genotype. As the vast majority of costs and environmental impacts remained the same per hectare regardless of the FOS yield, the red-shelled genotype had a superior economic and environmental performance per kg FOS.

The study showed that there were only relatively small differences in production costs per kg FOS between the two propagation methods "standard procedure" and "direct planting". In "standard procedure", significantly higher propagation costs for the greenhouse cultivation of plantlets were incurred. These were avoided to a large extent in "direct planting", leading to slightly lower production costs per kg FOS, despite the 30% yield gap. However, with regard to the environmental performance, direct planting led to considerably higher impacts in all categories assessed. This is because, although the propagation method had a huge influence on production costs (as explained above), it had only minor impacts on the environmental performance in most impact categories. It was shown that the cost-intensive manual labour involved in the propagation method standard procedure did not lead to environmental impacts. Therefore, the two propagation methods had comparable environmental impacts per hectare, but these impacts had to be allocated to considerably different yield levels. As a result, the standard procedure had a better environmental performance per kg FOS produced. This study assumed a 30% yield reduction for direct planting, in accordance with Kamp et al. [14]. However in other field trials, the recorded yield reduction was considerably smaller. In a study conducted by Doo et al. [38], the yield for the direct planting of yacon rhizomes was only 5% lower than for the greenhouse pre-cultivation treatment. A decrease in yield reduction of this magnitude through adapted genotypes and agricultural management would offer the opportunity of significantly improving the environmental and economic performance of the direct planting of yacon. The production costs per kg FOS, for example, would decrease by 26%.

In addition to the differences in environmental performance between the two propagation methods, there were also considerable differences in both environmental and economic performance between the different nitrogen fertilization levels. Marine eutrophication is mainly caused by nitrate leaching as a result of nitrogen fertilizer application. Thus, the impact in this category was found to increase with an increase in fertilization level, despite higher yields. This has also been shown in other studies assessing the influence of nitrogen fertilization levels on agricultural production systems [39]. As the use of nitrogen fertilizer had no significant influence on the impact categories agricultural land occupation, freshwater eutrophication, and freshwater ecotoxicity, the increase in FOS yield led to a decrease in the environmental impact in these categories from the 0 to 80 kg N ha^{-1} level. For the impact categories climate change, human toxicity, and marine ecotoxicity, the picture was more complex. In these categories, the environmental impact per kg FOS of the brown-shelled genotype was comparable in the two fertilization levels 0 and 80 kg N ha^{-1}. The environmental impact of the fertilization level 40 N ha^{-1} was significantly higher. This was caused by the only small increase in FOS yield from 0 to 40 N ha^{-1} (in the case of the brown-shelled genotype), which led to a less favourable environmental performance of the 40 N ha^{-1} treatment per kg FOS produced. The advantage of the 80 N ha^{-1} level was related to the fact that not only the tuber yield but also the FOS content increased, resulting in the highest FOS yields. For the red-shelled genotype, there was a slight increase in the categories climate change and human toxicity from the 0 to the 80 kg N ha^{-1} fertilization level. In the case of human toxicity, the impact was due to nitrogen fertilizer production, and in particular to heavy metals, such as Cd, Zn, Co, Se, Hg, contained in the fertilizer [40]. In addition to fertilizer production, the impact in the category climate change was caused to a large extent by fertilizer-induced N_2O emissions and N_2O emissions resulting from the decomposition of the yacon leaves. In intensive systems with high inputs (e.g., fertilizer), it is quite common that, in the category climate change, the impact per kg output increases despite significant increases in yield [41].

The hotspots of the impacts varied significantly between the environmental impact categories and the life-cycle costs. As demonstrated above, the environmental performance was mainly influenced by fertilizer production and fertilizer-induced emissions. By contrast, the life-cycle costs were dominated by the costs of propagation and of agricultural management. This means there is no easy way to improve the environmental and economic performance simultaneously. As already mentioned, yield increase is one important variable in improving the economic and environmental sustainability. An increase in yield at constant inputs decreased both the environmental impacts [42] and the costs [43] per kg output produced (e.g., kg FOS). Here, the focus should be on the propagation method direct planting, as there is a considerable yield gap between this and the standard procedure.

Another important factor in the environmental performance of the yacon-based FOS production, in addition to fertilizer-induced emissions, was the release of emissions by the decomposition of harvest residues. In the 80 kg N ha^{-1} treatment, the yacon leaves of the red-shelled genotype contained up to 226 kg N per ha [6] and, according to the IPCC calculation guidelines [28], their decomposition may lead to considerable N_2O emissions. One way of avoiding these emissions would be to harvest the leaves as a by-product. Yacon leaves could be ensiled to be used as biogas substrate, as has already been demonstrated for sugar beet leaves [44]. In addition, yacon leaves contain valuable phytochemicals, such as phenolic and flavonoid compounds [45], which can have anti-microbial and anti-inflammatory properties [46]. Khajehei et al. [47] demonstrated that old leaves of the red-shelled yacon genotypes exhibited a high antioxidant activity level as well as high amounts of certain valuable phytochemicals. It is assumed that the harvest of the leaves should take place as late as possible in order to avoid an adverse effect on tuber formation and thus also tuber yield. Field trials with other root and tuber crops that also store carbohydrates as FOS, such as Jerusalem artichoke, showed that a late harvest is advantageous, as it enables the plant to recirculate macro- and micronutrients from the aboveground back to the underground biomass [48,49]. Using the leaves for the production of valuable by-products would also offer an opportunity to significantly improve the economic performance of yacon production.

4.2. Guidelines for an Economically and Environmentally Sustainable Yacon-Based FOS Production

Based on the results of this study, it might be concluded that from both an economic and environmental perspective the red-shelled genotype fertilized with the highest rate of 80 kg N ha^{-1} and propagated in the standard procedure is the most sustainable cultivation system of those analysed. This cultivation system achieved the highest FOS yields per hectare, lowest FOS production costs, and lowest environmental impacts in five of the seven categories assessed. However, future research should focus on the propagation method direct planting, in particular on closing the yield gap to the standard procedure. One method of achieving higher yields in direct planting could be the use of larger rhizomes pieces. Another possibility would be the cultivation of genotypes more suitable for direct planting, for example, those which yield stronger rhizomes or have a faster crop development. Genotype selection also has a significant influence on the environmental and economic sustainability of yacon cultivation, as there are significant differences between genotypes in tuber yield [6,50], sugar content [15,51], as well as phenolic content and antioxidant activity [52]. Therefore, the future success of yacon cultivation is dependent on breeding and cultivating genotypes that are adapted to direct planting and that exhibit both high tuber yield and high FOS content. In addition, for these genotypes more long-term field trials are necessary. The environmental and economic performance assessed in the current study was based on yield data from one year. The data used, however, are comparable to field trials with similar tuber crops such as Jerusalem artichoke, which demonstrated that an increase in nitrogen fertilization leads to an increase in tuber yields [53,54], even though there is more information needed as annual climatic effects, such as changes in precipitation, can have a significant impact on yacon tuber yield formation [6].

Experience with other root and tuber crops, such as Jerusalem artichoke, has shown that, to be economically viable, various parts of the plant need to be used [55]. As discussed above, not only the tubers, but also the leaves should be utilized for the production of high-value products [45,46]. The impact of the harvest of leaves as a by-product was not included in this study. However, the cultivation of yacon as a double-use crop with the utilization of these valuable by-products offers an opportunity to significantly improve the economic and environmental performance of yacon cultivation.

With the worldwide prevalence of diabetes likely to rise considerably in coming decades [56], the demand for natural sweeteners that do not lead to an increase in blood glucose level will increase. Yacon, currently a minor crop in Europe, could play a prominent role here, due to its high FOS yield. The results of this study demonstrated that it is possible to select agricultural production systems with comparatively low production costs and impacts on the environment. In addition, they emphasized the importance of an ex ante assessment before a new crop is introduced on a wider scale, and the necessity of including both economic and environmental performance in such assessments.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/17/4581/s1, Table S1: Costs of agricultural operations, Table S2: Costs of input substrates, Table S3: Biomass transport costs, Table S4: Propagation costs, Table S5: Environmental impacts and production costs per t FM yacon tubers.

Author Contributions: Conceptualization: M.W. and L.K.; methodology: M.W.; investigation: M.W.; writing—original draft preparation: M.W. and L.K.; writing—review and editing: I.L. and S.G.-H.

Funding: This study was partly supported by the Bio-Based Industries Joint Undertaking under the European Union's Horizon 2020 Research and Innovation Programme, grant agreement No 745012, and by the German Federal Ministry for Economic Affairs and Energy within the Central Innovation Program for SMEs, grant number 16KN050526.

Acknowledgments: The authors are grateful to Nicole Gaudet for proofreading the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zardini, E. Ethnobotanical notes on "Yacon," *Polymnia sonchifolia* (*Asteraceae*). *Econ. Bot.* **1991**, *45*, 72–85. [CrossRef]
2. Pedreschi, R.; Campos, D.; Noratto, G.; Chirinos, R.; Cisneros-Zevallos, L. Andean Yacon Root (*Smallanthus sonchifolius* Poepp. Endl) Fructooligosaccharides as a Potential Novel Source of Prebiotics. *J. Agric. Food Chem.* **2003**, *51*, 5278–5284. [CrossRef] [PubMed]
3. Valentová, K.; Ulrichová, J. *Smallanthus sonchifolius* and lepidium meyenii–prospective andean crops for the prevention of chronic diseases. *Biomed. Pap.* **2003**, *147*, 119–130. [CrossRef]
4. Bredemann, G. Über *Polymnia sonchifolia* Poepp. & Endl. (*Polymnia edulis* Wedd.), die Yacon—Erdbirne. *Bot. Oeconomie.* **1948**, *1*, 65–85.
5. Ojansivu, I.; Ferreira, C.L.; Salminen, S. Yacon, a new source of prebiotic oligosaccharides with a history of safe use. *Trends Food Sci. Technol.* **2011**, *22*, 40–46. [CrossRef]
6. Kamp, L.; Hartung, J.; Mast, B.; Graeff-Hönninger, S. Impact of Nitrogen Fertilization on Tuber Yield, Sugar Composition and Nitrogen Uptake of Two Yacon (*Smallanthus sonchifolius* Poepp. & Endl.) Genotypes. *Agronomy* **2019**, *9*, 151.
7. Choque Delgado, G.T.; da Silva Cunha Tamashiro, W.M.; Maróstica Junior, M.R.; Pastore, G.M. Yacon (*Smallanthus sonchifolius*): A Functional Food. *Plant Foods Hum. Nutr.* **2013**, *68*, 222–228. [CrossRef] [PubMed]
8. Douglas, J.A.; Follett, J.M.; Douglas, M.H.; Deo, B.; Scheffer, J.J.C.; Littler, R.A.; Manley-Harris, M. Effect of environment and time of planting on the production and quality of yacon (*Smallanthus sonchifolius*) storage roots. *N. Z. J. Crop Hortic. Sci.* **2007**, *35*, 107–116. [CrossRef]
9. Valentová, K.; Lebeda, A.; Doležalová, I.; Jirovský, D.; Simonovska, B.; Vovk, I.; Kosina, P.; Gasmanová, N.; Dziechciarková, M.; Ulrichová, J. The Biological and Chemical Variability of Yacon. *J. Agric. Food Chem.* **2006**, *54*, 1347–1352. [CrossRef]
10. Graefe, S.; Hermann, M.; Manrique, I.; Golombek, S.; Buerkert, A. Effects of post-harvest treatments on the carbohydrate composition of yacon roots in the Peruvian Andes. *Field Crops Res.* **2004**, *86*, 157–165. [CrossRef]
11. Lachman, J.; Fernández, E.C.; Orsák, M. Yacon [*Smallanthus sonchifolia* (Poepp. et Endl.) H. Robinson] chemical composition and use—A review. *Plant Soil Environ.* **2003**, *49*, 283–290. [CrossRef]
12. Campos, D.; Betalleluz-Pallardel, I.; Chirinos, R.; Aguilar-Galvez, A.; Noratto, G.; Pedreschi, R. Prebiotic effects of yacon (*Smallanthus sonchifolius* Poepp. & Endl), a source of fructooligosaccharides and phenolic compounds with antioxidant activity. *Food Chem.* **2012**, *135*, 1592–1599. [PubMed]
13. Fernández, E.C.; Rajchl, A.; Lachman, J.; Čížková, H.; Kvasnička, F.; Kotíková, Z.; Milella, L.; Voldřich, M. Impact of yacon landraces cultivated in the Czech Republic and their ploidy on the short- and long-chain fructooligosaccharides content in tuberous roots. *LWT Food Sci. Technol.* **2013**, *54*, 80–86. [CrossRef]
14. Kamp, L.; Hartung, J.; Mast, B.; Graeff-Hönninger, S. Plant growth, tuber yield formation and costs of three different propagation methods of yacon (*Smallanthus sonchifolius*). *Ind. Crops Prod.* **2019**, *132*, 1–11. [CrossRef]
15. Kamp, L.; Hartung, J.; Mast, B.; Graeff-Hönninger, S. Tuber Yield Formation and Sugar Composition of Yacon Genotypes Grown in Central Europe. *Agronomy* **2019**, *9*, 301. [CrossRef]
16. Garnett, T.; Appleby, M.C.; Balmford, A.; Bateman, I.J.; Benton, T.G.; Bloomer, P.; Burlingame, B.; Dawkins, M.; Dolan, L.; Fraser, D.; et al. Sustainable Intensification in Agriculture: Premises and Policies. *Science* **2013**, *341*, 33–34. [CrossRef] [PubMed]
17. *ISO Environmental Management—Life Cycle Assessment—Principles and Framework*; ISO 14040:2006; ISO: Geneva, Switzerland, 2006.

18. *ISO Environmental Management—Life cycle Assessment—Requirements and Guidelines*; ISO 14044:2006; ISO: Geneva, Switzerland, 2006.
19. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; van Zelm, R. ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147. [CrossRef]
20. Wagner, M.; Kiesel, A.; Hastings, A.; Iqbal, Y.; Lewandowski, I. Novel Miscanthus Germplasm-Based Value Chains: A Life Cycle Assessment. *Front. Plant Sci.* **2017**, *8*, 990. [CrossRef]
21. Swarr, T.E.; Hunkeler, D.; Klopffer, W.; Pesonen, H.-L.; Ciroth, A.; Brent, A.C.; Pagan, R. *Environmental Life Cycle Costing: A Code of Practice*; Society of Environmental Toxicology and Chemistry: Pensacola, FL, USA, 2011; ISBN 978-1-880611-87-6.
22. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. The ecoinvent database version 3 (part I): Overview and methodology. *Int. J. Life Cycle Assess.* **2016**, *21*, 1218–1230. [CrossRef]
23. KTBL. *KTBL-Feldarbeitsrechner*; Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V. (KTBL): Darmstadt, Germany, 2018.
24. Lebeda, A.; Dolezalová, I.; Fernández, E.; Viehmannová, I. *Genetic Resources, Chromosome Engineering, and Crop Improvement. Medicinal Plants*; Singh, R.J., Ed.; Taylor & Francis: Boca Raton, FL, USA; New York, NY, USA, 2012; Volume 6, ISBN 978-1-4200-7384-3.
25. Zhang, W.; Liu, X.; Wang, Q.; Zhang, H.; Li, M.; Song, B.; Zhao, Z. Effects of potassium fertilization on potato starch physicochemical properties. *Int. J. Biol. Macromol.* **2018**, *117*, 467–472. [CrossRef]
26. Scheffer, J.J.C.; Douglas, J.A.; Triggs, C.M. Evaluation of some pre- and post-emergence herbicides for weed control in yacon. *N. Z. Plant Prot.* **2002**, *55*, 228–234.
27. Bouwman, A.F.; Boumans, L.J.M.; Batjes, N.H. Modeling global annual N_2O and NO emissions from fertilized fields. *Glob. Biogeochem. Cycles* **2002**, *16*, 28-1–28-9. [CrossRef]
28. IPCC. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Eds.; Prepared by the National Greenhouse Gas Inventories Programme; IPCC: Hayama, Japan, 2006; ISBN 978-4-88788-032-0.
29. EMEP/CORINAIR. *Joint EMEP/CORINAIR Atmospheric Emission Inventory Guidebook*, 3rd ed.; European Environment Agency: Copenhagen, Denmark, 2001.
30. Nemecek, T.; Kägi, T. *Life Cycle Inventories of Swiss and European Agricultural Production Systems*; Final report ecoinvent V2.0 No. 15a; Ecoinvent: Zürich, Switzerland; Dübendorf, Switzerland, 2007.
31. Nemecek, T.; Schnetzer, J. *Methods of Assessment of Direct Field Emissions for LCIs of Agricultural Production Systems: Data v3.0 2011*; Agroscope Reckenholz-Tänikon Research Station (ART): Zürich, Switzerland, 2011.
32. Akiyama, H.; Yan, X.; Yagi, K. Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N_2O and NO emissions from agricultural soils: Meta-analysis: Mitigation options for n_2o and no emissions. *Glob. Chang. Biol.* **2010**, *16*, 1837–1846. [CrossRef]
33. Díez López, J.A.; Hernaiz, P. Effect of a nitrification inhibitor (DMPP) [3,4-dimethylpyrazole phosphate] on nitrate leaching and maize yield during two growing seasons. *Span. J. Agric. Res.* **2008**, *6*, 294. [CrossRef]
34. Landwirtschaftskammer Nordrhein-Westfalen; RLV e.V. *Erfahrungssätze für überbetriebliche Maschinenarbeiten im Rheinland 2017*; Landwirtschaftskammer Nordrhein-Westfalen: Münster, Germany, 2017.
35. Statistisches Bundesamt. *Statistisches Jahrbuch Deutschland 2017*; Statistisches Bundesamt: Wiesbaden, Germany, 2017; ISBN 978-3-8246-1057-0.
36. Agrarheute.com Düngerpreise. Available online: https://www.agrarheute.com/tag/duengerpreise (accessed on 22 August 2019).
37. Raiffeise. Available online: https://www.raiffeisen-duengershop.de/produkt/obstbau/entec-26/ (accessed on 13 June 2019).
38. Doo, H.S.; Ryo, J.H.; Lee, K.S.; Choi, S.Y.; Cheong, Y.K.; Park, K.H. Response of Different Seedlings to Growth and Yield in Yacon. *Korean J. Crop Sci* **2002**, *47*, 356–360.
39. Wagner, M.; Lewandowski, I. Relevance of environmental impact categories for perennial biomass production. *GCB Bioenergy* **2017**, *9*, 215–228. [CrossRef]
40. Charles, R.; Jolliet, O.; Gaillard, G.; Pellet, D. Environmental analysis of intensity level in wheat crop production using life cycle assessment. *Agric. Ecosyst. Environ.* **2006**, *113*, 216–225. [CrossRef]
41. Goglio, P.; Bonari, E.; Mazzoncini, M. LCA of cropping systems with different external input levels for energetic purposes. *Biomass Bioenergy* **2012**, *42*, 33–42. [CrossRef]

42. Meyer, F.; Wagner, M.; Lewandowski, I. Optimizing GHG emission and energy-saving performance of miscanthus-based value chains. *Biomass Convers. Biorefinery* **2017**, *7*, 139–152. [CrossRef]
43. Wagner, M.; Mangold, A.; Lask, J.; Petig, E.; Kiesel, A.; Lewandowski, I. Economic and environmental performance of miscanthus cultivated on marginal land for biogas production. *GCB Bioenergy* **2019**, *11*, 34–49. [CrossRef]
44. Parawira, W.; Murto, M.; Zvauya, R.; Mattiasson, B. Anaerobic batch digestion of solid potato waste alone and in combination with sugar beet leaves. *Renew. Energy* **2004**, *29*, 1811–1823. [CrossRef]
45. Honoré, S.M.; Genta, S.B.; Sánchez, S.S. *Smallanthus sonchifolius* (Yacon) leaves: An emerging source of compounds for diabetes management. *J. Biol. Res.* **2015**, *5*, 21–42.
46. Oliveira, R.B.; Chagas-Paula, D.A.; Secatto, A.; Gasparoto, T.H.; Faccioli, L.H.; Campanelli, A.P.; Da Costa, F.B. Topical anti-inflammatory activity of yacon leaf extracts. *Rev. Bras. Farmacogn.* **2013**, *23*, 497–505. [CrossRef]
47. Khajehei, F.; Niakousari, M.; Seidi Damyeh, M.; Merkt, N.; Claupein, W.; Graeff-Hoenninger, S. Impact of Ohmic-Assisted Decoction on Bioactive Components Extracted from Yacon (*Smallanthus sonchifolius* Poepp.) Leaves: Comparison with Conventional Decoction. *Molecules* **2017**, *22*, 2043. [CrossRef] [PubMed]
48. Somda, Z.C.; McLaurin, W.J.; Kays, S.J. Jerusalem artichoke growth, development, and field storage. II. Carbon and nutrient element allocation and redistribution. *J. Plant. Nutr.* **1999**, *22*, 1315–1334. [CrossRef]
49. Swanton, C.J.; Cavers, P.B. Biomass and nutrient allocation patterns in Jerusalem artichoke (*Helianthus tuberosus*). *Can. J. Bot.* **1989**, *67*, 2880–2887. [CrossRef]
50. Fernández, E.C.; Viehmannov, I.; Lachman, J.; Milella, L. Yacon [*Smallanthus sonchifolius* (Poeppig & Endlicher) H. Robinson]: A new crop in the Central Europe. *Plant Soil Environ.* **2006**, *52*, 564–570.
51. Khajehei, F.; Merkt, N.; Claupein, W.; Graeff-Hoenninger, S. Yacon (*Smallanthus sonchifolius* Poepp. & Endl.) as a Novel Source of Health Promoting Compounds: Antioxidant Activity, Phytochemicals and Sugar Content in Flesh, Peel, and Whole Tubers of Seven Cultivars. *Molecules* **2018**, *23*, 278.
52. Khajehei, F.; Hartung, J.; Graeff-Hönninger, S. Total Phenolic Content and Antioxidant Activity of Yacon (*Smallanthus Sonchifolius* Poepp. and Endl.) Chips: Effect of Cultivar, Pre-Treatment and Drying. *Agriculture* **2018**, *8*, 183. [CrossRef]
53. Izsáki, Z.; Kádi, G.N. Biomass Accumulation and Nutrient Uptake of Jerusalem Artichoke (*Helianthus tuberosus* L.). *Am. J. Plant Sci.* **2013**, *4*, 1629–1640. [CrossRef]
54. Rodrigues, M.A.; Sousa, L.; Cabanas, J.E.; Arrobas, M. Tuber yield and leaf mineral composition of Jerusalem artichoke (*Helianthus tuberosus* L.) grown under different cropping practices. *Span. J. Agric. Res.* **2007**, *5*, 545–553. [CrossRef]
55. Johansson, E.; Prade, T.; Angelidaki, I.; Svensson, S.-E.; Newson, W.; Gunnarsson, I.; Hovmalm, H. Economically Viable Components from Jerusalem Artichoke (*Helianthus tuberosus* L.) in a Biorefinery Concept. *Int. J. Mol. Sci.* **2015**, *16*, 8997–9016. [CrossRef] [PubMed]
56. Ogurtsova, K.; da Rocha Fernandes, J.D.; Huang, Y.; Linnenkamp, U.; Guariguata, L.; Cho, N.H.; Cavan, D.; Shaw, J.E.; Makaroff, L.E. IDF Diabetes Atlas: Global estimates for the prevalence of diabetes for 2015 and 2040. *Diabetes Res. Clin. Pract.* **2017**, *128*, 40–50. [CrossRef] [PubMed]

7. General discussion

The main target of the present study was to develop a cropping system for yacon, which can be adapted for Europe. Therefore, it was of particular importance to establish a system, which is suitable for this region, as it may be different in some major agronomic aspects from the cropping systems established in the countries of yacon’s origin. Furthermore, at the moment predominant knowledge about the small holder cultivation is available whereby large-scale cultivation is not conceivable through missing agronomical standards for cultivation.

Each publication focused on one major topic. **Publication I** covered the topic of propagation methods and compared three different propagation methods according to tuber yield formation and incurring costs to identify the most profitable and best practice method for the farmer. To identify the most suitable genotypes for cultivation in Europe in **publication II**, nine different genotypes were examined regarding tuber yield formation and sugar content as well as their composition. **Publication III** investigated the influence of nitrogen fertilization on the nitrogen uptake as well as tuber yield formation and sugar composition. **Publication IV** examined the production costs and environmental impact of different yacon cultivation systems to determine the most suitable cultivation system for a practice oriented implementation. These different aspects were identified and discussed in each publication separately and will not be repeated in this chapter. The general discussion will merge the explored information of all publications with the objective to outline the opportunities, chances and risks of yacon cultivation in Europe. Besides the cultivation, also the market chances and processing opportunities will be covered. Overall the discussion will come up with a final rating of emerging opportunities for agriculture in Europe out of the cultivation of yacon.

7.1 Propagation

A crop that is new to existing structures requires a strong focus due to various challenges associated with its cultivation. One major problem are the high propagation costs. To reduce costs for propagation, the direct planting of rhizome pieces is preferable and an option with a high potential for a future mechanization. However direct planting induces yield losses of about 30% compared to other propagation methods, which includes pre cultivation in the greenhouse (Kamp et al. 2019c). Due to lower tuber yields direct planting has considerably higher environmental impacts in nearly all categories than yacon cultivation with pre cultivation in greenhouse (Wagner et al. 2019). Increasing the tuber yield is therefore a decisive factor in the further development of direct planting. One possible improvement could be achieved by increasing the size and also the number of buds of the direct planted rhizome pieces. Unpublished results of a field trial carried out in the framework of the present thesis showed, that with increasing weight of planted rhizome pieces the tuber yield also increased (Figure 1). However, no significant difference between rhizome weights could be detected due to inhomogeneous development of the plant stock and therewith a wide range of tuber yield. Nevertheless, the trend of an increasing yield was noticeable. Additionally to accelerate the sprouting process a fleece was used that covered the whole trial. No positive effect of the fleece regarding the sprouting time was determined. However, the study indicated that with an increasing rhizome weight also the tuber yield increased, but further examinations are needed for homogenous development and faster emergence.

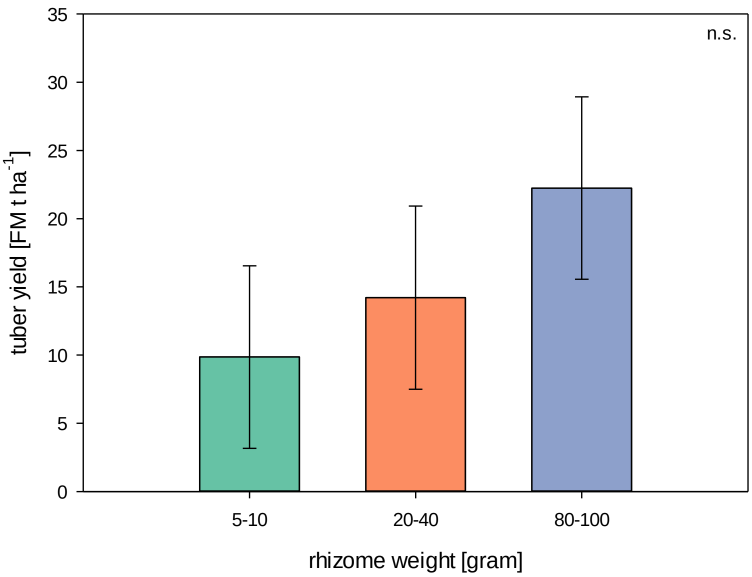


Figure 1: Tuber yield of three different direct planted rhizome weights across the experimental years 2017 and 2018. ANOVA carried out for the three different weights in FM t ha^{-1}. No significant differences between the three different weights could be detected for $p<0.05$ (year: 0.1518; year*rep: 0.5389; rhizome weight: 0.5336)

Besides the relevance of rhizome size and number of buds per rhizome piece, further improvements could be achieved, if similar to potatoes, pre-sprouting methodologies would be developed. Besides a better and faster field emergence, homogenous plant stands and also increased tuber yields might be expected. Pre-sprouting of potatoes is controlled by temperature, light and water. Four to six weeks before planting, potatoes are placed in a box or a mesh bag. Temperatures up to 15 to 20 °C are normally used to induce the growth of a light shoot of

1 to 1.5 cm (Haase et al. 2007). This pre-sprouting caused in general an earlier field emergence between eight to 14 days compared to non-pre-sprouted potatoes (Karalus and Rauber 1997; Moll 1985). This is advantageous due to faster competitiveness against weed pressure and longer growth periods, which could lead to higher tuber yields (Möller and Reents 2007). This is also shown by Doo et al., who reported 1.8% higher tuber yields with pre-sprouted rhizomes of yacon (Doo et al. 2002). Moreover it would be possible to grade the rhizomes after pre-sprouting to enhance the homogenous development of the plant stock. The combination of higher rhizome weights and pre-sprouting could increase the tuber yield significantly and makes direct planting a promising method. The similarity to potatoes in case of planting and harvesting makes it possible to use common potato planters with some modifications in regard to height of ridges and planting depth (Douglas et al. 2005a). The process step of separating the tubers and the rhizomes at harvest must be done manually, independently of propagation method. This is also common in other vegetables crops. The harvest of leek and cauliflower need due to manual process steps 11.43 and 71.21 h ha^{-1}, respectively (KTBL-Kuratorium für Technik und Bauwesen in der Landwirtschaft 2019). Also the fact, that pre-sprouting does not need a high input of technical equipment and the knowledge is already existing, turns it into a realistic opportunity for enhancing yacon tuber yields. Another side-effect of increasing tuber yields would be the related decrease of environmental impact and production costs of this cultivation method.

Another possible option to propagate yacon could be the development of *in-vitro* cultivation. Advantages of the propagation by *in-vitro* cultivation are homogenous plant material, low space requirement for propagation and, depending on the method, storage of the rhizomes would be no longer necessary. One option is to cultivate stem cuttings on nutrient medium (Estrella and Lazarte 1994). A disadvantage of cultivating stem cuttings is the need of plants for inducing *in-vitro* cultivation. To induce propagation in the winter month, plant material from the greenhouse is needed. Hence, a more preferable option is the propagation by somatic embryogenesis. For this purpose leaves are cultivated *in-vitro* to induce callus tissue and afterwards to gain somatic embryos from this callus (Corrêa et al. 2009). For the first initiation plants or plant are material needed, but if callus tissue is generated once, it could be used for further callus generation and *in-vitro* propagation (Verma et al. 2016). In this case, storage of rhizomes is no longer needed, because plant material for further propagation could be stored *in-vitr*o. This long term conversation of plant material is even possible under slow-growing conditions (Skalova et al. 2012). Several studies that investigated this topic so far showed that adaption of plants *in-vitro* culture is possible, but associated with high efforts (Trevisan et al. 2014; Corrêa et al. 2009). Therefore, there is a need for further studies to examine the field stability of *in-vitro* cultivated yacon plants. Due to the associated high costs, in-vitro cultivation is not used extensively (Xue et al. 2015).

7.2 Management practices – Implementation in existing cultivation systems

7.2.1 Crop rotation

One further sensitive point is the integration of yacon in existing crop rotations. Decisive for the successful implementation are for instance the aspects of length of vegetation period and besides that the characteristics of a crop like nutrient demand or nutrient content in crop residues.

Similar to sugar beet is the nitrogen content in the aboveground biomass of yacon, left after harvest quite high and reached up to 226 kg N ha^{-1} (Kamp et al. 2019a; Carter and Traveller 1981). The aboveground biomass of both crops exhibits a low C/N-ratio which ranged in average from eight to eleven for sugar beets and from eight to 15 for yacon. Therefore, a quick release of nitrogen through mineralization is anticipated (Rahn et al. 2003; Whitmore and Groot 1994) which increases the risk of nitrate leaching (Goulding 2000). To avoid the risk of nitrate leaching a subsequent crop with high nitrogen uptake potential is needed. One further opportunity to avoid risks of nitrate leaching during the winter month is the use of the aboveground biomass as well. Similar to the tubers also the aboveground biomass of yacon, which is rich in health promoting compounds like phenols and flavonoids, can be used for extract preparation (Khajehei et al. 2017). Besides the utilization for human diets, also the use for animal feed purpose or for energetic use as a silage could be imaginable (Koike et al. 2009). With such a full utilization of the whole plant, no plant residues will be left, and the environmental impact would be minimized. Besides the potential additional value of by-product usage, more flexibility in the crop rotation would result as the potential high nitrogen leftovers in the soil would no longer oppose a problem.

Since sugar beet and potato are comparable to yacon due to similar vegetation periods from April to October, solutions for embedding yacon in the crop rotation could follow the given guidelines of these two crops (Estrella et al. 2007; Freyer 2003). Due to the late harvest date of yacon, the possibilities for subsequent crops are limited at least in Germany. As yacon is cultivated on ridges, conventional soil cultivation or at least the use of a chisel plow is needed after harvest for the subsequent crop. One option for the subsequent crop could be the late establishment of winter wheat, as winter wheat is one of the latest sown crops in Germany and can be established also in frozen ground late in the year. All other cereals like winter rye, winter barley or triticale are not possible, because of the late harvest date of yacon in October or preferably November (Estrella et al. 2007). Another option could be the cultivation of catch crops. But also in this case the late harvest date is critical and only permits green rye (Komainda et al. 2016). Another possibility could be to use the system of conversation tillage. Leaving plant residues with a cover of >30% at the soil surface reduces the risk of wind and water erosion during the winter months (Prasuhn 2012; Kassam et al. 2011). Plant residues could be inserted after winter and nitrogen for the subsequent crop. This could also be a good option for organic farming, to increase the soil fertility and protect the soil against erosion at the same time.

Taking into account the climatic conditions in other European countries,higher average temperatures would allow earlier planting dates for yacon, which would lead to differences in harvest dates and the available vegetation period (Figure 2). Besides temperature, precipitation is also a decisive factor. Like shown in previous studies, precipitation is one of the major influencing factors for tuber yield (Kamp et al. 2019b; Douglas et al. 2007; Cabrera et al. 2005). As a result nearly the whole part of Italy, the south-west of France, major parts in Spain, Portugal, Slovenia and Croatia could offer suitable conditions for direct planting due to higher average temperatures and sufficient precipitation. Especially the north-west part of Spain and Portugal seems to be a promising area due to high average temperatures and high precipitation during planting and germination period. Even though Hungary also showed higher average temperatures than Germany, it is not suitable for yacon cultivation due to lower precipitation, except farmers would apply irrigation in the cropping system. All other countries are comparable to Germany with regard to temperature or lower like Scandinavian countries. As a result, there would be lower tuber yields in Scandinavia due to the later possible planting date, which makes yacon unsuitable for cultivation.

The cultivation of yacon in other parts of Europe and therewith the possible earlier planting date results in several options for its implementation in a suitable crop rotation as well as a longer vegetation period. In addition to the possible integration in crop rotation, a longer vegetation period can lead to higher tuber yields. By improving the propagation process through pre-sprouting, as discussed in chapter 7.1, new opportunities are also conceivable for Germany.

Besides the advantage of higher temperatures in March and therewith the possibility for an earlier planting date also the precipitation over the whole vegetation period must be considered. As mentioned in literature at least 550 mm precipitation are required for the production of yacon tubers (Cabrera et al. 2005). As shown in publication II, the impact of hot and dry climatic conditions is not equal for all genotypes and can be a determining factor in future. Therefore, further investigations are needed, in order to figure out which genotypes are suitable to different regions in Europe. On this occasion a few factors can be an issue such as specifications of genotypes and of the regions as well. Potentially some genotypes are better adapted to hot and dry conditions due to less aboveground biomass or other phenotypical characteristics. Also the given agronomic pre-conditions of a region are decisive. In some areas without sufficient precipitation there are perhaps well-developed irrigation structures, which make cultivation of yacon possible. Additionally so far, no investigations have been carried out with regard to temperature effects on tuber yield and sugar composition of yacon.

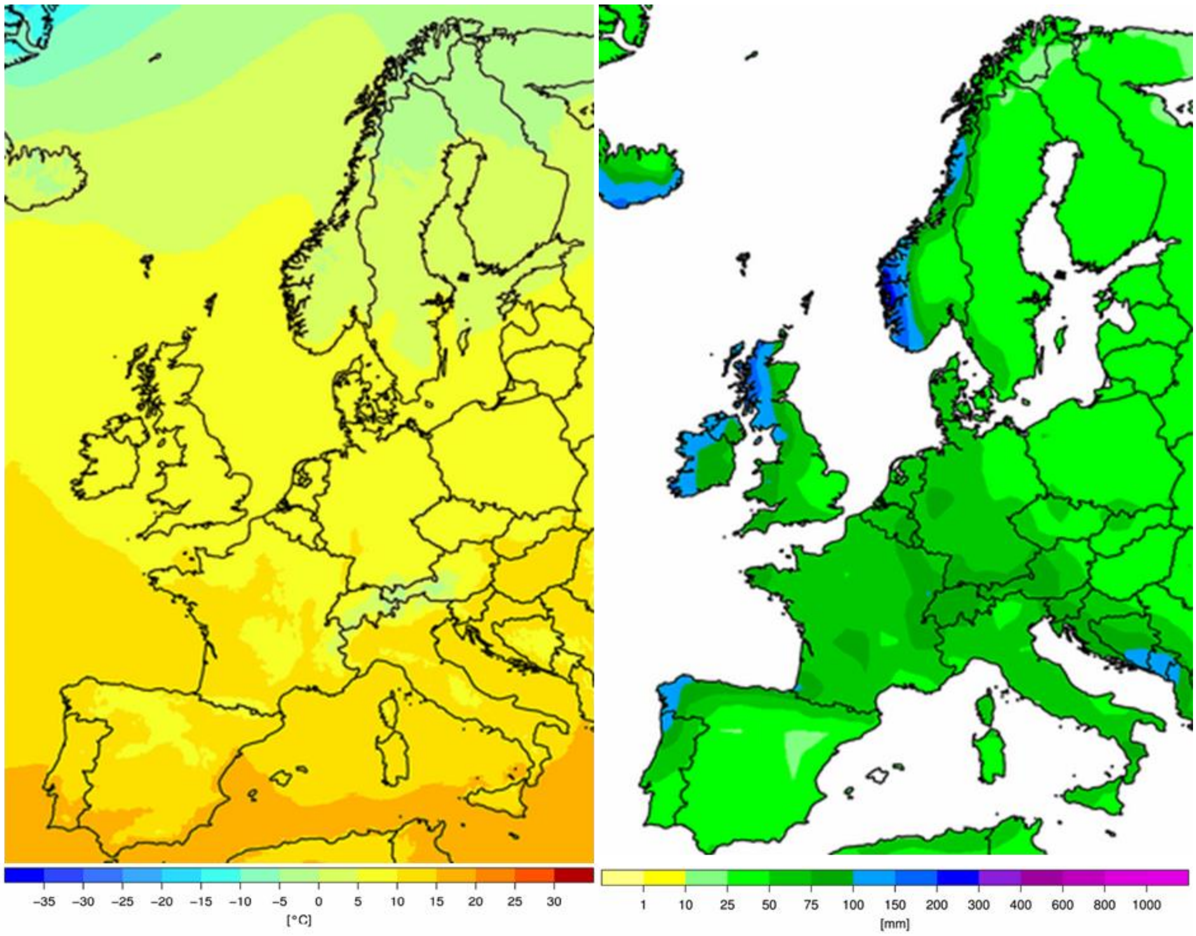


Figure 2: Map of Europe; on the left: long term average temperature in March in °C; on the right long term average precipitation in March in mm. Reference: Deutscher Wetter Dienst, 2019 (Deutscher Wetterdienst 2019).

Apart from the possibilities for subsequent crops, the requirements for the previous crop and the soil conditions for yacon cultivation are a critical point. Contrary to the high nitrogen contents in aboveground biomass, publication III showed, that the nitrogen demand of yacon is not very high and sufficiently covered with 40 kg N ha^{-1} (Kamp et al. 2019a). Nitrogen uptake is nevertheless high, due to mineralization. Mineralization is increased according to faster heating and better soil aeration through cultivation in ridges (Stahr et al. 2012). Also, the long vegetation period provides the high uptake rates. Consequently, the claim to the previous crop is not quite high. That offers the opportunity to cultivate yacon in organic farming systems, as there is no need for additional fertilizer if appropriate N_{min} values exist. In general, the importance of crop rotation in organic farming systems is higher than in conventional farming systems, as no mineral fertilizer can be used. Therefore, it is highly relevant to implement a meaningful crop rotation. On this occasion yacon offers a good alternative being a crop with low nitrogen demand.

7.2.2 Plant protection

The field trials,conducted in the frame of the present thesis, were not showing any pests or diseases, which was contrary to other studies whereas *Rhizoctonia, Scelortinia* and *Botrytis* occurred (Kwon et al. 2014; Fenille et al. 2005; Tomioka et al. 2002). It should be considered that yacon, like other tuber crops, is susceptible to certain diseases. According to this, further examinations with regard to the occurrence of diseases, their influence of growth, development and tuber yield as well as the possibilities for plant protection are necessary. It is important to figure out, if common plant protection treatments also work for yacon without causing significant yield losses.

According to the enormous weed pressure at the first development stages of yacon, either an herbicide treatment or a mechanical weed control is necessary, as yacon development is quite slow in the beginning. When reaching row cover after 50 to 60 days, no further weed control on the ridges is needed, but only between the ridges (Fernández et al. 2007). The use of pre-emergence herbicides is possible and does not cause a decrease in tuber yield (Douglas et al. 2007; Scheffer et al. 2002). If for direct planting a mulch fleece for ridge cover is used, pre-emergence herbicides are not mandatory. Contrary to the unproblematic pre-emergence herbicides, the application of some post-emergence herbicides can cause leaf necrosis and a decrease of tuber yield and only selected products are possible for application (Scheffer et al. 2002). If cultivation of yacon should be organic or farmers want to avoid the use of herbicides, mechanical weed control is indispensable. One option could be the use of common weed choppers used in potatoes in-between the ridges and, when no mulch fleece is used, for the flanks of the ridges. Also manual weed control is common in cultivation of vegetables and ranges from 7.16 to 52.08 h ha^{-1}, depending on procedures and vegetable (KTBL-Kuratorium für Technik und Bauwesen in der Landwirtschaft

2019). Another option could be sowing of winter wheat in-between the ridges to avoid weed pressure. Winter wheat can be easily mulched if required. This system was already partially established in the present study. In case of even stricter discussions on the use of herbicides, the option of mechanical weed control is important.

As elaborated in the previous paragraph, the implementation of yacon in existing cultivation systems is possible from an agronomic point of view. The implementation can offer advantages for the farmer in several points. With cultivation of yacon as a new plant, the crop diversity will increase and offers diversity for the landscape and also for the farmer, which means redistribution of work peaks as well as new possibilities for profit. Besides the advantages in case of workload and biodiversity, the farmer can also have a benefit of the new market for processing and selling yacon.

7.3 Market situation for yacon as a sugar substitutes

The high demand for sugar substitutes in the form of natural sweeteners increased steadily over the last years due to the intension of replacing sugar in food products (Max Rubner-Institut; Bundesforschungsinstitut für Ernährung und Lebensmittel 2018b). This recommendation from the Federal Research Institute for Nutrition and Food is already implemented by the food retail industry, but only partially done with natural sweeteners due to higher costs and caloric values (REWE Group Buying GmbH 2018; Neacsu and Madar 2014). Yacon, as a sugar substitute and as natural sweetener, offers several benefits compared to other natural sweeteners. Most of the other natural sweeteners contain high amounts of monosaccharides and provide a high caloric value, wherefore they are unsuitable for replacement of sugar (Neacsu and Madar 2014). The expectancy attitude of consumers is to decrease at the same time the amount of sugar and caloric value without losing the sweet taste (REWE Group Buying GmbH 2018; Chattopadhyay et al. 2014). Therefore, yacon, with high amounts of FOS up to 70% of DM is one of the most preferable natural sweeteners (Kamp et al. 2019b). Besides the combination of sweet taste and low caloric value, yacon also offers further health promoting benefits like bifidogenic effects (Caetano et al. 2016b; Del Castillo et al. 2012). In comparison with Jerusalem artichoke and chicory, yacon is preferable due to shorter DP. Products with a DP <10 provide a higher bifidogenic effect than Products with a DP >10 (Slimestad et al. 2010; Douglas et al. 2002; Campbell et al. 1997).

The use of yacon can be various, for example in dried form as chips, flakes or dried and milled as powder. After juicing it can also be used as a syrup or juice. If consumers buy it fresh, they can eat it raw like fruits or in cook the tubers as well (Leidi et al. 2018; de Almeida Paula et al. 2015). These multiple fields of application make yacon a favorable natural sugar substitute. Especially for the most relevant food products like dietary products and breakfast cereals, yacon offers further advantages due to its bifidogenic effect (Caetano et al. 2016a). For yoghurt it can be added as a powder, for breakfast cereals in form of dried flakes or as syrup to cover the cereals and also as a powder in instant soups (de Almeida Paula et al. 2015). For the production of a sugar substitute other regulations apply than for fresh market of tubers. Size and shape of tubers is not relevant for the processing industry, but the sugar yield and especially the sugar composition. Besides that color is a decisive factor for a sugar substitute as well as it influences the possibilities for replacement of sugar in food products (Khuenpet et al. 2017). As already mentioned, not only the taste, but also the appearance and feel of the products play a role in replacing sugar in food. There might be differences between the texture of yacon powder or syrup depending on the individual sugar composition of the genotypes. However, this has not been investigated, yet.

Apart from all requirements for direct marketing of tubers and processing performance the storage and post-harvest treatment of tubers has a major influence on quality of tubers, especially the sugar composition, and therewith the final product. As mentioned in chapter 1.3 the amount of FOS after harvest decreases rapidly and will be accelerated by warm temperatures. Investigations in the frame of this thesis showed, that the sugar composition of yacon tubers changed terrifically during storage (Figure 3A + B). Immediately after harvest 66% of total sugar were composted as FOS, this value declined to 19% after a storage period of four month at cold temperatures of 3 °C. FOS were degraded mainly to glucose, which can be seen in the noticeable increase of glucose from 22 to 64%. This change in sugar composition has the consequence that the health-promoting benefits of yacon and yacon products are no longer existing.

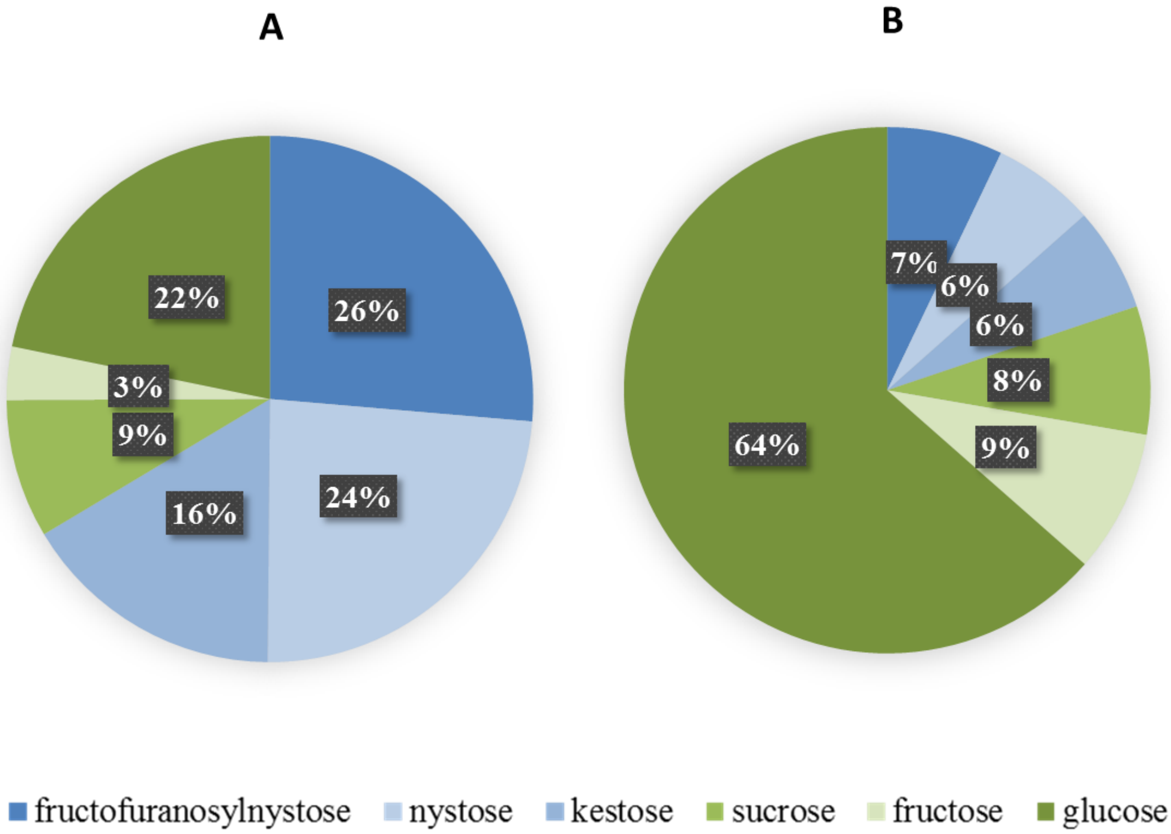


Figure 3A + B: Average sugar composition of 9 yacon genotypes (A) immediately after harvest and (B) after 4 month storage in soil-sandy mixture at 3 °C and 65% air humidity.

To keep the health-promoting benefits processing after harvest as soon as possible is mandatory. One possibility to keep the health-promoting benefits could be to freeze the tubers after harvest. The freezing of tubers will stop the degradation process of polysaccharides and offers a longer timeframe for processing. However, it has not been determined yet, if freezing of tubers has an influence on processing and final product quality. Therefore, further investigations are required.

7.4 Future potential

The present thesis fundamentally discussed relevant parts of a possible yacon cropping system in Europe. Even if some major parts for the implementation of yacon are already clarified to a satisfactory level, some major aspects still remain open and offer potential for further research. Besides some technical aspects like propagation (7.1.) and some open questions related to the management like implementation in crop rotation and use of aboveground biomass (7.2), the utilization as a sugar substitute and therewith the necessary post-harvest treatments (7.3) are important. As shown in 7.3 the demand for natural sweeteners as a sugar substitute is increasing. Extremely important are ongoing investigations according to the best storage conditions without losing the health-promoting benefits which could change the options for farmers and the processing industry.

Like shown in 7.1 direct planting offers a huge potential for further investigation like pre-sprouting. Besides that, also the possibility of *in-vitro* technique can be considered if more research efforts are directed towards this topic. As figured out in 7.2 the implementation of yacon in a crop rotation is a sensitive aspect and can be optimized related to the given possibilities of direct planting. If an earlier planting date can be realized e.g. in other regions in Europe this would increase the options for choosing a subsequent crop. In general, this thesis showed that cultivation of yacon is conceivable in Europe and also that other areas are also suitable for the aspect of direct planting. Additional influencing factors during vegetation like precipitation and temperature must be further examined for genotypes and areas individually.

Overall, the greatest necessity for further research can be seen in the field of human health studies and product development as well as the possibilities for replacement of sugar. Most studies which covered the health promoting benefit of consuming yacon products are implemented with animals (Baroni et al. 2016; Caetano et al. 2016a; Campos et al. 2012). Therefore, resilient studies with human volunteers are needed to confirm the effect of consuming yacon or yacon products. This goes along with further investigations regarding food technology and the replacement of sugar with yacon. As yacon is mainly used as syrup or in form of powder, examinations for the replacement of sugar have to be done. That includes the development of products as well as the replacement of sugar and artificial sweeteners with yacon products.

8. Summary

The demand of healthy food is constantly increasing in Germany, as well as in developed countries in general. Here "healthy" is not clearly defined but it is often associated with foods indicating a low caloric value and further health-promoting benefits such as a high proportions of dietary fiber, phenols or antioxidants. In contrast, the proportion of obese people and the number of chronic diseases such as diabetes type II and obesity are increasing. As a result, the European Commission recommended to reduce the sugar content and the caloric value of food products, especially in sweetened beverages, breakfast cereals and dairy products by 10%. In general, a distinction can be made between artificial and natural sweeteners. Natural sweeteners such as honey, agave nectar or rapadura occur naturally and do not have to be artificially produced or synthesized. Disadvantages here are the high production costs as well as the high calorie value which is similar to conventionally used sugar. Artificial sweeteners, on the other hand, which are also known as "high-intensity sweeteners", have been artificially produced or synthesized. Examples are aspartame, saccharin or sucralose. They often have a lower calorie value (except for sugar alcohols such as xylitol or sorbitol) and are more economical to produce, which makes them particularly attractive for food producers. However, artificial sweeteners are suspected of being harmful to health or even carcinogenic. As a result, the consumer acceptance of artificial sweeteners is decreasing and the demand for natural sweeteners as alternatives is increasing.

A possible alternative as a natural sweetener is yacon (*Smallanthus sonchifolius*). Yacon is a tuberous root crop native to the Andean region. The roots store carbohydrates mainly as fructooligosaccharides (FOS). These FOS cannot be digested by the human intestinal tract, and therefore do not cause a noticeable increase of blood glucose level. In addition, high amounts of fiber, phenols and antioxidants lead to further health promoting benefits. So far, yacon has been cultivated mainly in the Andean region in smallholder structures. Therefore, there are several open questions regarding the cultivation of yacon in Europe, especially in the area of propagation, choice of genotypes and adapted nitrogen fertilization. Especially the propagation is an important factor, as it is normally done by seedlings of mother plants or single rhizome pieces, both with pre-cultivation in the greenhouse. This is expensive and leads to a price of 3.60 € for young plants. In addition, the influence of genotype and amount of nitrogen fertilization on tuber yield and sugar composition has not been investigated yet. These open questions regarding the cultivation of yacon in Europe outline the following objectives:

- to evaluate differences between direct planting and pre cultivation of rhizomes in two ways with regard to yacon growth, development, tuber yield formation and cost distribution;
- to investigate the yield potential of different yacon genotypes with regard to tuber yield, sugar yield and tuber composition under the given climatic conditions of Europe;
- to determine the influence of different nitrogen levels on nitrogen uptake, tuber yield formation and amount of monosaccharides and polysaccharides as well as total sugar;
- to investigate the environmental impact and the production costs of different yacon cultivation systems to determine the most sustainable cultivation method.

To achieve the objectives, field trials were carried out a from 2016 to 2018. As a result, four scientific publications were developed, which formed the body of this thesis. **Publication I** focused on the differences between a propagation with pre-cultivation in the greenhouse (DSAB), rhizome pieces with pre-cultivation in the greenhouse (RP1) and a direct planting of rhizome pieces (RP2) in agronomic and economic terms. RP1 achieved the highest yield with 29.8 t ha $^{-1}$ FM and differed significantly from the other treatments with 21.3 and 17.8 t ha^{-1} FM (DSAB and RP2, respectively). With regard to the cost per kg of produced yacon, RP1 was also convincing, which can be explained by a high tuber yield and comparatively low propagation costs. DSAB was the most expensive treatment and is therefore not recommended. Contrary to that RP2 has a high potential for mechanization and yield increases.

Publication II investigated the differences between nine different genotypes with respect to tuber yield and sugar composition. The three genotypes red-shelled, brown-shelled and Morado achieved the significantly highest tuber yields with 46.6, 43.5 and 41.6 t FM ha^{-1}. Also the sugar contents were outstanding with up to 66% of the DM in the red-shelled genotype. As a result, the sugar yields of these three genotypes were highest with 2.2, 2.0 and 1.9 t ha^{-1} in the same order as the tuber yields.

In **Publication III** the influence of different amounts of nitrogen fertilizer (0, 40 and 80 kg ha^{-1}) on tuber yield, sugar composition and nitrogen uptake of the brown- and red-shelled genotype was investigated. Both genotypes reached highest tuber yields of 50 and 67 t FM ha^{-1} at the highest nitrogen fertilizer amount (brown- and red-shelled, respectively). Contrary to this responded the total amounts of sugar and FOS. Both decreased with increasing amounts of nitrogen. With decreasing amounts of FOS, the proportion of FOS with higher degree of polymerization (DP) increased. With regard to the nitrogen utilization efficiency of both, tubers and the entire plant, a nitrogen amount of 40 kg N ha^{-1} seems to be sufficient and recommendable.

8. Summary

Publication IV examined the ecological and economic sustainability of the cultivation of two genotypes (brown- and red-shelled), each with pre-cultivation in the greenhouse and as direct planting, with three different nitrogen fertilizer levels. The aim was to investigate the environmental impact and production costs of different yacon cultivation systems. Considering the costs, the highest fertilizer amount (80 kg N ha^{-1}) led to the lowest production costs and also to comparatively low environmental impacts per functional unit (1 kg FOS). The red-shelled genotype performed better, both in terms of cost and environmental impact. This was mainly due to higher tuber yields.

Overall, the preceding publications showed that the cultivation of yacon in Europe is possible and offers new possibilities for farmers. Embedding yacon successfully into existing cropping systems and crop rotations seems to be possible. The farmer has the opportunity to establish a promising new crop with great value potential on his farm in order to cover the increasing demand for raw materials for natural sweeteners.

9. Zusammenfassung

Die Nachfrage nach gesunden Lebensmitteln nimmt in Deutschland, sowie generell in Industriestaaten, stetig zu. Hierbei ist „gesund“ nicht eindeutig definiert, wird aber oft mit Lebensmitteln mit einem geringem Kalorienwert sowie weiteren gesundheitsfördernden Inhaltsstoffen wie zum Beispiel ein hoher Anteil an Ballaststoffen, Phenolen oder Antioxidantien assoziiert. Konträr dazu steigt der Anteil der übergewichtigen Personen und die Anzahl chronischer Erkrankungen wie Diabetes-Typ II und Adipositas stetig. Infolgedessen strebt die Europäische Kommission an, den Zuckergehalt in gesüßten Getränken, Frühstückscerealien und Molkereiprodukten um 10% zu reduzieren. Generell unterscheidet man zwischen künstlichen und natürlichen Süßungsmitteln. Natürlich vorkommende Süßungsmittel wie Honig, Agavennektar oder Rapadura müssen nicht künstlich hergestellt oder synthetisiert werden. Nachteile hierbei sind, die hohen Kosten für die Produktion, sowie der oftmals ähnlich hohe Kalorienwert wie bei herkömmlich verwendetem Zucker. Die künstlichen Süßungsmittel hingegen, welche auch als „hoch-intensive Süßungsmittel“ bezeichnet werden, sind künstlich hergestellt bzw. synthetisiert und günstiger in der Produktion. Beispiele hierfür sind Aspartame, Saccharin oder Sucralose. Jedoch stehen künstliche Süßungsmittel in Verdacht gesundheitsschädigend bis hin zu krebserregend zu sein. Infolgedessen sinkt die Akzeptanz der Verbraucher und die Nachfrage nach natürlichen Alternativen steigt.

Eine mögliche Alternative als natürliches Süßungsmittel ist Yacon (*Smallanthus sonchifolius*). Yacon stammt aus der Andenregion und bildet essbare Speicherorgane aus. Die Kohlenhydrate werden nicht in Form von Stärke, sondern überwiegend als Fructooligosaccharide (FOS) eingelagert. Diese FOS können vom menschlichen Darm nicht verdaut werden, wodurch der Blutzuckerspiegel nicht merkbar ansteigt. Zudem enthalten Yaconknollen weitere gesundheitsfördernde Inhaltsstoffe wie Phenole und Antioxidantien und zeichnen sich durch einen hohen Gehalt an Ballaststoffen aus. Bislang wird Yacon überwiegend in der Andenregion in kleinbäuerlichen Strukturen angebaut. Daher gibt es noch verschiedene offene Fragen bei der Kultivierung von Yacon in Europa, insbesondere im Bereich der Vermehrung der Jungpflanzen, der Sortenwahl, sowie der angepassten Stickstoffdüngung. Insbesondere die Vermehrung ist ein wichtiger Faktor, da die bisher übliche Vermehrung über Stecklinge zeit- und kostenintensiv ist und somit zu Jungpflanzenpreisen von 3,60 € führt. Zusätzlich ist der Einfluss von Genotyp und Höhe der Stickstoffdüngung auf Knollenertrag und Zuckerzusammensetzung noch nicht untersucht. Diese offenen Fragen in Bezug auf die Kultivierung von Yacon in Mitteleuropa wurden in der vorliegenden Dissertation bearbeitet und skizzierten folgende Zielsetzungen:

- Prüfung der Unterschiede zwischen Direktpflanzung und Vorkultivierung von Rhizomen in Bezug auf Wachstum, Entwicklung, Knollenertragsbildung und Kostenverteilung;
- Untersuchung des Ertragspotenzials verschiedener Genotypen in Bezug auf Zuckerertrag und -zusammensetzung unter den klimatischen Bedingungen Mitteleuropas;
- Bestimmung des Einflusses verschiedener Stickstoffdüngermengen auf die Stickstoffaufnahme, den Knollenertrag, sowie die Menge an Monosacchariden, Polysacchariden und den Gesamtzucker;
- Untersuchung der Umweltwirkung sowie der Produktionskosten verschiedener Yaconanbausysteme zur Ermittlung der nachhaltigsten Anbauvariante.

Für diese Zielsetzung wurden in den Jahren 2016 – 2018 Feldversuche durchgeführt. Resultierend aus den Feldversuchen entstanden vier wissenschaftliche Publikationen, die den Hauptteil dieser Dissertation darstellen. **Publikation I** arbeitete die Unterschiede zwischen einer Stecklingsvermehrung mit Vorkultivierung im Gewächshaus (DSAB), Rhizomstücke mit Vorkultivierung im Gewächshaus (RP1) sowie einer Direktpflanzung von Rhizomstücken (RP2) unter agronomischen und ökonomischen Aspekten heraus. RP1 erzielte mit 29,8 t ha^{-1} FM den höchsten Ertrag und unterschied sich deutlich von den anderen Varianten mit 21,3 und 17,8 t ha^{-1} FM (DSAB und RP2, entsprechend). In Bezug auf die Kosten pro produziertem kg Yacon konnte ebenfalls RP1 überzeugen, was durch einen hohen Knollenertrag und vergleichsweise geringe Vermehrungskosten zu erklären ist. DSAB war mit Abstand die kostenintensivste Variante und ist aufgrund dessen nicht zu empfehlen. Im Gegensatz dazu hat RP2 ein hohes Steigerungspotential durch mögliche Mechanisierung und weitere Ertragssteigerungen.

Publikation II untersuchte die Unterschiede zwischen neun verschiedenen Genotypen hinsichtlich Knollenertrag und Zuckerzusammensetzung. Die drei Genotypen rot-schalig, braun-schalig und Morado erzielten mit 46,6, 43,5 und 41,6 t FM ha^{-1} die signifikant höchsten Knollenerträge. Auch der Zuckergehalt war mit bis zu 66% der TM im rot-schaligen Genotype herausragend. Resultierend daraus waren auch die Zuckererträge dieser drei Genotypen in gleicher Reihenfolge wie die Knollenerträge mit 2,2, 2,0 und 1,9 t ha^{-1} am höchsten.

Im Rahmen von **Publikation III** wurde der Einfluss von unterschiedlichen Stickstoffdüngermengen (0, 40 und 80 kg ha^{-1}) auf Knollenertrag, Zuckerzusammensetzung und

Stickstoffaufnahme des braun- und rotschaligen Genotyp untersucht. Den höchsten Knollenertrag von 50 und 67 t FM ha^{-1} erzielten beide Genotypen bei der höchsten Stickstoffdüngermenge (braun- und rotschalig, entsprechend). Konträr dazu verhielten sich die Gesamtzuckermenge und der Anteil an FOS. Beides nahm mit zunehmender Stickstoffmenge ab. Mit abnehmender Menge FOS stieg der Anteil an FOS mit höheren Polymerisierungsgrad (DP) an. Unter Berücksichtigung der Stickstoffnutzungseffizienz, sowohl der Knollen und als auch der gesamten Pflanze, scheint eine Düngung von 40 kg N ha^{-1} ausreichend.

Publikation IV untersuchte die ökologische und ökonomische Nachhaltigkeit des Anbaus zweier Genotypen (braun- und rotschalig), jeweils mit Vorkultivierung im Gewächshaus und als Direktpflanzung, mit drei verschiedenen Stickstoffdüngerstufen. Ziel war es, die Umweltwirkung und Produktionskosten verschiedener praxisnaher Yaconanbausysteme zu untersuchen. Unter Betrachtung der Kosten führte die höchste Düngevariante (80 kg N ha^{-1}) zu den niedrigsten Produktionskosten und auch zu vergleichsweise geringen Umweltwirkungen pro funktioneller Einheit (1 kg FOS). Der rotschalige Genotyp schnitt sowohl bei den Kosten als auch der Umweltwirkung besser ab. Dies war vor allem durch die höheren Knollenerträge bedingt.

Insgesamt konnte die vorliegende Dissertation darstellen, dass ein Anbau von Yacon in Europa in der Praxis sowie eine Einbettung in bestehende Anbausysteme möglich ist. Basierend auf den Erkenntnissen dieser Arbeit bietet sich für den Landwirt die Möglichkeit eine vielversprechende neue Kultur mit großem Wertschöpfungspotential auf seinem Betrieb zu etablieren, um damit den steigenden Bedarf nach Rohstoffen für natürliche Süßungsmittel zu decken.

10. References

Andrade, E. F. de; Souza Leone, R. de; Ellendersen, L. N.; Masson, M. L. (2014): Phenolic profile and antioxidant activity of extracts of leaves and flowers of yacon (Smallanthus sonchifolius). In *Industrial Crops and Products* 62, pp. 499–506. DOI: 10.1016/j.indcrop.2014.09.025.

Ärztekammer Niedersachsen (2017): Presseinfos Detail. Thomas Spieker.

Baroni, S.; da Rocha, B. A.; Oliveira de Melo, J.; Comar, J. F.; Caparroz-Assef, S. M.; Bersani-Amado, C. A. (2016): Hydroethanolic extract of Smallanthus sonchifolius leaves improves hyperglycemia of streptozotocin induced neonatal diabetic rats. In *Asian Pacific journal of tropical medicine* 9 (5), pp. 432–436. DOI: 10.1016/j.apjtm.2016.03.033.

Bredemann, G. (1948): Über Polymnia sonchifolia Poepp. et Endl. (P. edulis Wedd.), die Yacon - Erdbirne. In *Botanische oeconomie* (1), pp. 65–85.

Cabrera, M. V.; Diaz, A.; Acero, A. (2005): Manual del cultivo de yacon. Edited by Pymagros - Convenio Cosude-Minag.

Caetano, B. F. R.; Moura, N. A. de; Almeida, A. P. S.; Dias, M. C.; Sivieri, K.; Barbisan, L. F. (2016a): Yacon (Smallanthus sonchifolius) as a Food Supplement: Health-Promoting Benefits of Fructooligosaccharides. In *Nutrients* 8 (7). DOI: 10.3390/nu8070436.

Caetano, B. F. R.; Moura, N. A. de; Almeida, A. P. S.; Dias, M. C.; Sivieri, K.; Barbisan, Luís F. (2016b): Yacon (Smallanthus sonchifolius) as a Food Supplement: Health-Promoting Benefits of Fructooligosaccharides. In *Nutrients* 8 (7). DOI: 10.3390/nu8070436.

Campbell, J. M.; Bauer, L. L.; Fahey, G. C.; Hogarth, A. J. C. L.; Wolf, B. W.; Hunter, D. E. (1997): Selected Fructooligosaccharide (1-Kestose, Nystose, and 1 F -β-Fructofuranosylnystose) Composition of Foods and Feeds. In *J. Agric. Food Chem.* 45 (8), pp. 3076–3082. DOI: 10.1021/jf970087g.

Campos, D.; Betalleluz-Pallardel, I.; Chirinos, R.; Aguilar-Galvez, A.; Noratto, G.; Pedreschi, R. (2012): Prebiotic effects of yacon (Smallanthus sonchifolius Poepp. & Endl), a source of fructooligosaccharides and phenolic compounds with antioxidant activity. In *Food chemistry* 135 (3), pp. 1592–1599. DOI: 10.1016/j.foodchem.2012.05.088.

Carter, J. N.; Traveller, D. J. (1981): Effect of Time and Amount of Nitrogen Uptake on Sugarbeet Growth and Yield. In *Agronomy Journal* 73, pp. 665–671.

Chattopadhyay, S.; Raychaudhuri, U.; Chakraborty, R. (2014): Artificial sweeteners - a review. In *Journal of food science and technology* 51 (4), pp. 611–621. DOI: 10.1007/s13197-011-0571-1.

Codex Alimentarius Commission (2017): Regional standards for yacon.

Corrêa, C. M.; Oliveira, G. N. de; Astarita, L. V.; Santarém, E. R. (2009): Plant regeneration through somatic embryogenesis of yacon [Smallanthus sonchifolius (Poepp. and Endl.) H. Robinson]. In *Brazilian archives of biology and technology* 52, pp. 549–554.

de Almeida Paula; H. A.; Abranches, M. V.; de Luces F. F.; Celia L. (2015): Yacon (Smallanthus sonchifolius): a food with multiple functions. In *Critical reviews in food science and nutrition* 55 (1), pp. 32–40. DOI: 10.1080/10408398.2011.645259.

Del Castillo, Valeria; Thomé, R.; Gabriel, D. L.; Tamashiro, W. M. S. C.; Pastore, G. M. (2012): Yacon (Smallanthus sonchifolius)-derived fructooligosaccharides improves the immune parameters in the mouse. In *Nutrition research (New York, N.Y.)* 32 (11), pp. 884–892. DOI: 10.1016/j.nutres.2012.09.012.

Delgado, G. T. C.; Tamashiro, W. M. S. C.; Marostica Junior, M. R.; Pastore, G. M. (2013): Yacon (Smallanthus sonchifolius): a functional food. In *Plant foods for human nutrition (Dordrecht, Netherlands)* 68 (3), pp. 222–228. DOI: 10.1007/s11130-013-0362-0.

Deutsche Adipositas-Gesellschaft; Deutsche Diabetes Gesellschaft; Deutsche Gesellschaft für Ernährung (2018): Konsensuspapier. Quantitative Empfehlung zur Zuckerzufuhr in Deutschland.

Deutscher Wetterdienst (2019): Klimakarten. Available online at https://www.dwd.de/DE/leistungen/rcccm/int/rcccm_int_rrr.html?nn=16102, checked on 7/20/2019.

Doo, H. S. (2000): Changes of chemical composition in tuberous root of yacon by different curing conditions. In *Korean Journal of Crop Science* 45 (2), pp. 79–82.

Doo, H. S.; Li, H. L.; Kwon, J.-H.; Ryu, J. H. (2000): Changes in sugar contents and storability of yacon under different storage conditions. In *Korean Journal of Crop Science* 45 (5), pp. 300–304.

Doo, H. S.; Ryu, J H.; Lee, K. S.; Choi, S. Y.; Cheong, Y. K.; Park, K. H. (2002): Response of Different Seedlings to Growth and Yield in Yacon. In *Korean Journal of Crop Science* (47), pp. 356–360.

Douglas, J. A.; Douglas, M. H.; Deo, B.; Follett, J. M.; Scheffer, J. J. C.; Sims, I. M.; Welch, R. A. S. (2005a): Research and Development of Yacon Production in New Zealand. In *Acta Hortic.* (670), pp. 79–85.

Douglas, J. A.; Follett, J. M.; Douglas, M. H.; Deo, B.; Scheffer, J. J. C.; Littler, R. A.; Manley-Harris, M. (2007): Effect of environment and time of planting on the production and quality of yacon (Smallanthus sonchifolius) storage roots. In *New Zealand Journal of Crop and Horticultural Science* 35 (1), pp. 107–116. DOI: 10.1080/01140670709510174.

Douglas, J. A.; Follett, J. M.; Waller, J. E. (2005b): Effect of propagule weight on production of yacon (Smallanthus sonchifolius). In *New Zealand Journal of Crop and Horticultural Science* 33 (2), pp. 143–148. DOI: 10.1080/01140671.2005.9514343.

Douglas, J. A.; Scheffer, J. J. C.; Sims, I. M.; Triggs, C. M. (2002): Maximising fructo-oligosacharide production in yacon. In *Agronomy New Zealand* (32), pp. 49–55.

Estrella, J. E.; Lazarte, J. E. (1994): In Vitro Propagation of Jicama (Polymnia sonchifolia Poeppig & Endlicher): A Neglected Andean Crop. In *Horticultural Science* 29 (4), p. 331.

Estrella, N.; SPARKS, T. H.I.M.; Menzel, A. (2007): Trends and temperature response in the phenology of crops in Germany. In *Global Change Biol* 13 (8), pp. 1737–1747. DOI: 10.1111/j.1365-2486.2007.01374.x.

FAO (2005): FAO Term Portal. Available online at http://www.fao.org/faoterm/viewentry/en/?entryId=170967, checked on 7/15/2019.

Fenille, R. C.; Ciampi, M. B.; Souza, N. L.; Nakatani, A. K.; Kuramae, E. E. (2005): Binucleate Rhizoctonia sp. AG G causing root rot in yacon (Smallanthus sonchifolius) in Brazil. In *Plant Pathology* 54 (3), pp. 325–330. DOI: 10.1111/j.1365-3059.2005.01161.x.

Fernandez, E. C.; Rajchl, A.; Lachman, J.; Čížková, H.; Kvasnička, F.; Kotíková, Z. et al. (2013): Impact of yacon landraces cultivated in the Czech Republic and their ploidy on the short- and long-chain fructooligosaccharides content in tuberous roots. In *LWT - Food Science and Technology* 54 (1), pp. 80–86. DOI: 10.1016/j.lwt.2013.05.013.

Fernández, E. C.; Viehmannova, Iva; Bechyne, M.; Lachman, J.; Milella, L. (2007): The cultivation and phenological growth stage of yacon [Smallanthus sonchifolius (Poepp. et Endl.) H. Robinson]. In *Agricultura tropica et subtropica* (40), pp. 71–77.

Fernández, E. C.; Viehmannová, I.; Bechyne, M.; Lachman, J.; Milella, L. (2006): Yacon [Smallanthus sonchifolius (Poeppig & Endlicher) H. Robinson]: a new crop in the Central Europe. In *Plant Soil Environment* (12), pp. 564–570.

forsa, Politik- und Sozialforschung GmbH (2017): So will Deutschland essen. forsa, Politik- und Sozialforschung GmbH.

Freyer, Bernhard (2003): Fruchtfolgen. Konventionell-Integriert-Biologisch. Stuttgart: Eugen Ulmar GmbH &Co.

Goto, K.; Fukai, K.; Hikida, J.; Nanjo, F.; Hara, Y. (2014): Isolation and Structural Analysis of Oligosaccharides from Yacon (Polymnia sonchifolia). In *Bioscience, Biotechnology, and Biochemistry* 59 (12), pp. 2346–2347. DOI: 10.1271/bbb.59.2346.

Goulding, K. (2000): Nitrate leaching from arable and horticultural land. In *Soil Use and Management* (16), pp. 145–151.

Graefe, S.; Hermann, M.; Manrique, I.; Golombek, S.; Buerkert, A. (2004): Effects of post-harvest treatments on the carbohydrate composition of yacon roots in the Peruvian Andes. In *Field Crops Research* 86 (2-3), pp. 157–165. DOI: 10.1016/j.fcr.2003.08.003.

Haase, T.; Schüler, C.; Piepho, H.-P.; Thöni, H.; Heß, J. (2007): The Effect of Preceding Crop and Pre-Sprouting on Crop Growth, N Use and Tuber Yield of Maincrop Potatoes for Processing Under Conditions of N Stress. In *J Agron Crop Sci* 193 (4), pp. 270–291. DOI: 10.1111/j.1439-037X.2007.00264.x.

Hermann, M.; Freire, I.; Pazos, C. (1997): Compositional Diversity of the Yacon Storage Root. Edited by CIP Program Report.

Kamp, L.; Hartung, J.; Mast, B.; Graeff-Hönninger, S. (2019a): Impact of Nitrogen Fertilization on Tuber Yield, Sugar Composition and Nitrogen Uptake of Two Yacon (Smallanthus sonchifolius Poepp. & Endl.) Genotypes. In *Agronomy* 9 (151).

Kamp, L.; Hartung, J.; Mast, B.; Graeff-Hönninger, S. (2019b): Tuber Yield Formation and Sugar Composition of Yacon Genotypes Grown in Central Europe. In *Agronomy* 9 (301). DOI: 10.3390/agronomy9060301.

Kamp, Larissa; Hartung, Jens; Mast, Benjamin; Graeff-Hönninger, Simone (2019c): Plant growth, tuber yield formation and costs of three different propagation methods of yacon (Smallanthus sonchifolius). In *Industrial Crops and Products* 132, pp. 1–11. DOI: 10.1016/j.indcrop.2019.02.006.

Karalus, W.; Rauber, R. (1997): Effect of Presprouting on Yield of Maincrop Potatoes (Solanum tuberosum L.) in Organic Farming. In *Journal of Agronomy and Crop Science* 179, pp. 241–249.

Kassam, A.; Friedrich, T.; Shaxson, F.; Pretty, J. (2011): The spread of Conservation Agriculture. Justification, sustainability and uptake. In *International Journal of Agricultural Sustainability* 7 (4), pp. 292–320. DOI: 10.3763/ijas.2009.0477.

Khajehei, F.; Merkt, N.; Claupein, W.; Graeff-Hoenninger, S. (2018): Yacon (Smallanthus sonchifolius Poepp. & Endl.) as a Novel Source of Health Promoting Compounds: Antioxidant Activity, Phytochemicals and Sugar Content in Flesh, Peel, and Whole Tubers of Seven Cultivars. In *Molecules (Basel, Switzerland)* 23 (2). DOI: 10.3390/molecules23020278.

Khajehei, F.; Niakousari, M.; Seidi D., M.; Merkt, N.; Claupein, W.; Graeff-Hoenninger, S. (2017): Impact of Ohmic-Assisted Decoction on Bioactive Components Extracted from Yacon (Smallanthus sonchifolius Poepp.) Leaves: Comparison with Conventional Decoction. In *Molecules (Basel, Switzerland)* 22 (12). DOI: 10.3390/molecules22122043.

Khuenpet, K.; Jittanit, W.; Sirisansaneeyakul, S.; Srichamnong, W. (2017): Inulin Powder Production from Jerusalem Artichoke (Helianthus tuberosus L.) Tuber Powder and Its Application to Commercial Food Products. In *Journal of Food Processing and Preservation* 41 (4), e13097. DOI: 10.1111/jfpp.13097.

Koike, A.; Murata, T.; Matsuda, Yy; Masuoka, C.; Okamoto, C.; Kabata, K. (2009): Cultivation and ensilage of yacon plants (Smallanthus sonchifolius [Poepp. & Endl.] H. Robinson) and the function of yacon silage. In *Grassland Science* 55 (1), pp. 6–10. DOI: 10.1111/j.1744-697X.2009.00130.x.

Komainda, M.; Taube, F.; Kluß, C.; Herrmann, A. (2016): Above- and belowground nitrogen uptake of winter catch crops sown after silage maize as affected by sowing date. In *European Journal of Agronomy* 79, pp. 31–42. DOI: 10.1016/j.eja.2016.05.007.

Kothari, D.; Patel, Ss; Goyal, A. (2014): Therapeutic spectrum of nondigestible oligosaccharides: overview of current state and prospect. In *Journal of food science* 79 (8), R1491-R1498. DOI: 10.1111/1750-3841.12536.

KTBL-Kuratorium für Technik und Bauwesen in der Landwirtschaft (2019): Feldarbeitsrechner: KTBL-Kuratorium für Technik und Bauwesen in der Landwirtschaft.

Kwon, J.-H.; Kang, D.-W.; Lee, S.-D.; Kim, J. (2014): First Report of Sclerotium Rot Caused by Sclerotium rolfsii on Yacón in South Korea. In *Plant Disease* 98 (10), p. 1443. DOI: 10.1094/PDIS-06-14-0616-PDN.

Lachman, J.; Fernández, E. C.; Orsák, M. (2003): Yacon [Smallanthus sonchifolia (Poepp. et Endl.) H. Robinson] chemical composition and use – a review. In *Plant Soil Environment* 49 (6), pp. 283–290.

Lachman, J.; Havrland, B.; Fernandez, E. C.; Dudjak, J. (2004): Saccharides of yacon [Smallanthus sonchifolius (Poepp. et Endl.) H. Robinson] tubers and rhizomes and factors affecting their content. In *Plant Soil Environment* 50 (9), pp. 383–390.

Leidi, E. O.; Altamirano, A. M.; Mercado, Geovana; Rodriguez, J. P.; Ramos, Alvaro; A., G. et al. (2018): Andean roots and tubers crops as sources of functional foods. In *Journal of Functional Foods* 51, pp. 86–93. DOI: 10.1016/j.jff.2018.10.007.

Manrique, I.; Hermann, M.; Bernet, T. (2004): Yacon Fact Sheet. Edited by International Potato Center (CIP). Lima, Peru.

Manrique, I.; Parraga, A.; Hermann, M. (Eds.) (2005): Conservación y uso de la biodiversidad de raíces y tubérculos andinos: Una década de investigación para el desarrollo (1993-2003). Centro International de la Papa. Lima, Peru.

Max Rubner-Institut; Bundesforschungsinstitut für Ernährung und Lebensmittel (2018a): Fett-, Zucker- und Salzgehalte von ausgewählten vorgefertigten Produkten: Differenzierung von Produktuntergruppen und Berechnung von Quartilen. Zusatzauswertung zum MRI-Bericht „Häufig im Lebensmitteleinzelhandel gekaufte industriell vorgefertigte Produkte und ihre Energie- und Nährwertgehalte, insbesondere Fett, Zucker, Salz.“.

Max Rubner-Institut; Bundesforschungsinstitut für Ernährung und Lebensmittel (2018b): Reformulierung von verarbeiteten Lebensmitteln. Bewertung und Empfehlung zur Reduktion des Zuckergehaltes.

Mensink, M. A.; Frijlink, H. W.; van der Voort Maarschalk, K; Hinrichs, W. L. J. (2015): Inulin, a flexible oligosaccharide I: Review of its physicochemical characteristics. In *Carbohydrate polymers* 130, pp. 405–419. DOI: 10.1016/j.carbpol.2015.05.026.

Mokrani, K.; Hamdi, K.; Tarchoun, N. (2018): Potato (Solanum Tuberosum L.) Response to Nitrogen, Phosphorus and Potassium Fertilization Rates. In *Communications in Soil Science and Plant Analysis* 49 (11), pp. 1314–1330. DOI: 10.1080/00103624.2018.1457159.

Moll, A. (1985): Der Einfluss des physiologischen Alters der Pflanzknollen auf die Ertragsbildung von Kartoffelsorten verschiedener Reifezeit. In *Potato Res* 28, pp. 233–250.

Möller, K.; Reents, H.-J. (2007): Impact of Agronomic Strategies (Seed Tuber Pre-sprouting, Cultivar Choice) to Control Late Blight (Phytophthora infestans) on Tuber Growth and Yield in Organic Potato (Solanum tuberosum L.) Crops. In *Potato Res.* 50 (1), pp. 15–29. DOI: 10.1007/s11540-007-9026-5.

Neacsu, N. A.; Madar, A. (2014): Artifical sweeteners versus natural sweeteners. In *Economic Sciences* 7 (56), pp. 59–64.

Ojansivu, I.; Ferreira, C. L.; Salminen, S. (2011): Yacon, a new source of prebiotic oligosaccharides with a history of safe use. In *Trends in Food Science & Technology* 22 (1), pp. 40–46. DOI: 10.1016/j.tifs.2010.11.005.

Panesar, P. S.; Bali V.; Kumari S.; Babbar N.; Oberoi H.S. (Eds.) (2014): Prebiotics. Biotransformation of Waste Biomass into High Value Biochemicals. With assistance of Brar S., Dhillon G., Soccol C. New York, NY: Springer.

Prasuhn, V. (2012): On-farm effects of tillage and crops on soil erosion measured over 10 years in Switzerland. In *Soil and Tillage Research* 120, pp. 137–146. DOI: 10.1016/j.still.2012.01.002.

Rahn, C. R.; Bending, G. D.; Turner, M. K.; Lillywhite, R. D. (2003): Management of N mineralization from crop residues of high N content using amendment materials of varying quality. In *Soil Use Manage* 19 (3), pp. 193–200. DOI: 10.1079/SUM2003188.

REWE Group Buying GmbH (2018): Strategiepapier-Zucker-Salz.

Scheffer, J. J. C.; Douglas, J. A.; Triggs, C. M. (2002): Evaluation of some pre- and post-emergence herbicides for weed control in yacon. In *New Zealand Plant Protection* (55), pp. 228–234.

Skalova, I.; Viehmannova, I.; Vitamvas, J. (2012): In vitro Conservation of Smallanthus sonchifolius under Slow-Growth Conditions. In *Agricultura tropica et subtropica* 45 (3), pp. 147–150. DOI: 10.2478/v10295-012-0024-5.

Slimestad, R.; Seljaasen, R.; Meijer, K.; Skar, Siv L. (2010): Norwegian-grown Jerusalem artichoke (Helianthus tuberosus L.): morphology and content of sugars and fructo-oligosaccharides in stems and tubers. In *Journal of the science of food and agriculture* 90 (6), pp. 956–964. DOI: 10.1002/jsfa.3903.

Stahr, K; Kandeler, E.; Herrmann, L.; Streck, T. (2012): Bodenkunde und Standortlehre. 2.th ed. Stuttgart: Eugen Ulmar KG.

Statista GmbH (2018): Mikrozensus-Körpermaße der Bevölkerung 2017. Available online at https://de.statista.com/statistik/daten/studie/256599/umfrage/bmi--anteil-der-uebergewichtigen-in-deutschland-nach-bundeslaendern/, checked on 7/20/2019.

Sumiyanto, J.; Dayan, F. E.; Cerdeira, A. L.; Wang, Y.-H.; Khan, I. A.; Moraes, R. M. (2012): Oligofructans content and yield of yacon (Smallanthus sonchifolius) cultivated in Mississippi. In *Scientia Horticulturae* 148, pp. 83–88. DOI: 10.1016/j.scienta.2012.09.020.

Tomioka, K.; Takeuchi, J.; Sato, T.; Nakanishi, T. (2002): Rhizoctonia Blight of Yacon Caused by Rhizoctonia AG-I (IB). In *Journal of General Plant Pathology* 68, pp. 103–104.

Trevisan, F.; Chu, E. P.; Gaspar, M.; Angela, M.; Carvalho, M. (2014): In vitro culture and fructan production by Vernonia herbacea (Asteraceae). In *Acta Physiol Plant* 36, pp. 2299–2307.

United States Department of Agriculture (2018): USDA Nutrient Database. Available online at https://ndb.nal.usda.gov/ndb/foods/show/09040?fgcd=&manu=&format=&count=&max=25&offset=&sort=default&order=asc&qlookup=Bananas%2C+raw&ds=&qt=&qp=&qa=&qn=&q=&ing=, checked on 6/8/2019.

Valentova, K.; Lebeda, A.; Dolezalova, I.; Jirovsky, D.; Simonovska, B.; Vovk, I. et al. (2006): The biological and chemical variability of yacon. In *Journal of agricultural and food chemistry* 54 (4), pp. 1347–1352. DOI: 10.1021/jf052645u.

Verma, S. K.; Das, A. K.; Cingoz, G. S.; Uslu, E.; Gurel, E. (2016): Influence of nutrient media on callus induction, somatic embryogenesis and plant regeneration in selected Turkish crocus species. In *Biotechnology Reports* 10, pp. 66–74. DOI: 10.1016/j.btre.2016.03.006.

Wagner, M.; Kamp, L.; Graeff-Hönninger, S.; Lewandowski, I. (2019): Environmental and economic performance of yacon (Smallanthus sonchifolius) cultivated for fructooligosaccharide production. In *Sustainability* 11 (4581)

Wersin, M.; gardening Helenion (2018): Price for yacon plantlets. E-Mail to Larissa Kamp, 2018.

10. References

Whitmore, A. P.; Groot, J.J.R. (1994): The mineralization of N from finely or coarsely chopped crop residues. Measurements and modelling. In *European Journal of Agronomy* 3 (4), pp. 367–373. DOI: 10.1016/S1161-0301(14)80168-8.

World Health Organization (2015): Guideline: sugars intake for adults and children. Genf. Available online at https://www.who.int/nutrition/publications/guidelines/sugars_intake/en/, checked on 7/14/2019.

Xue, S.; Kalinina, O.; Lewandowski, I. (2015): Present and future options for Miscanthus propagation and establishment. In *Renewable and Sustainable Energy Reviews* 49, pp. 1233–1246. DOI: 10.1016/j.rser.2015.04.168.

Zardini, E. (1991): Ethnobotanical notes on "Yacon" Polymnia sonchifolia (Asteraceae). In *Economic Botany* (45), pp. 72–85.

Appendix

Table A1: General overview about all publications or presentations in context of the dissertation.

Kamp, L., Mast, B., Claupein, W., Graeff-Hönninger, S.: Wachstumsverlauf und Ertrag verschiedener *Smallanthus sonchifolius* Genotypen; *Conference proceeding and poster presentation*: 14. Wissenschaftstagung Ökologischer Landbau, 07. – 10. März 2017, Weihenstephan-Triesdorf, pp.256 – 257.

Kamp, L., Mast, B., Übelhör, A., Claupein, W., Graeff-Hönninger, S.: Einfluss von Stickstoffdüngung auf Wachstumsverlauf, Entwicklung und Ertrag von Yacon (*Smallanthus sonchifolius*); *Conference proceeding and poster presentation*: Mitteilung der Gesellschaft für Pflanzenbauwissenschaften, Bd. 29, 60. Tagung der GPW, 26. – 28. September 2017, Witzenhausen, pp.164 – 165.

Kamp, L., Graeff-Hönninger, S., Claupein W.: Yacon – influence of genotype on tuber yield and sugar content; *Conference proceeding and poster presentation*: 5th International ISEKI_Food Conference, 3 – 5 July 2018, Stuttgart, pp. 226.

Kamp, L., Claupein, W., Graeff-Hönninger, S.: Einfluss von Rhizomstückgröße auf Auflaufrate und Knollenertrag von Yacon (*Smallanthus sonchifolius*); *Conference proceeding and poster presentation*: Mitteilung der Gesellschaft für Pflanzenbauwissenschaften, Bd. 30, 61. Tagung der GPW, 25. – 27. September 2018, Kiel, pp. 219 – 220.

Danksagungen

Ich möchte mich ganz herzlich bei **Prof. Dr. Simone Graeff-Hönninger** für die Betreuung und Überlassung des Forschungsthemas bedanken. Deine Unterstützung in den letzten drei Jahren und insbesondere in der Endphase der Dissertation war nicht immer selbstverständlich und hat auch von dir eine zeitliche Flexibilität abverlangt, für die ich dir sehr dankbar bin. Deine Türe stand immer offen und du hattest stets ein offenes Ohr und einen Ratschlag oder aufmunternde Worte parat. Zahlreiche Korrekturen, Vorschläge und Anregungen haben maßgeblich zu dieser Dissertation beigetragen. Ebenso möchte ich mich für die Freiheiten bei der Ausgestaltung meiner Arbeit bedanken.

Weiterhin möchte ich mich ganz herzlich bei meinem Zweitgutachter **PD Dr. Feng Yan** bedanken, sowie bei **Prof. Dr. Torsten Müller** für die Bereitschaft als Drittgutachter zu fungieren.

Auch dem Bundesministerium für Wirtschaft und Energie möchte ich danken, die im Rahmen des Zentralen Innovationsprogramm Mittelstand mein Projekt ermöglicht und gefördert haben.

Ebenso gilt mein Dank **Dr. Benjamin Mast,** der mich ermutigt hat den Weg der Promotion zu gehen. Ein weiteres Dankeschön geht an **Dr. Annegret Pflugfelder**, die besonders in der Anfangsphase immer mit Rat und Tat zur Seite stand. Ich weiß nicht wie oft ich dich mit Fragen gelöchert habe, ein Glück saßt du mir gegenüber und hattest immer die passende Antwort parat. **Dr. Jens Hartung** möchte ich für die zahlreichen Hilfestellungen rund um das Thema Statistik und Datenauswertung danken. Ohne deine Hilfe wäre ich so einige Male bei der Auswertung verzweifelt.

Ein ganz besonderer Dank gilt dem gesamten Team von Ihinger Hof, ohne welches die reibungslose Durchführung meiner Versuche nicht möglich gewesen wäre. Stellvertretend möchte ich mich besonders bei **Thomas Truckses** und **Martin Zahner** bedanken, die mir als Versuchstechniker und Laborleitung immer tatkräftig zur Seite standen.

Darüber hinaus geht ein ganz besonderer Dank an **Yasha Auer**, **Birgit Beierl, Martina Pertsch** und **Andrea Richter**. Ohne eure helfenden Hände wären viele Messungen und Untersuchungen nicht möglich gewesen. Besonders Yasha und Andrea; Für eure oft bis in die Abendstunden andauernde Ausdauer bei Blattflächenmessungen und Knollenwaschen möchte ich euch danken.

Auch meinen anderen Kolleginnen und Kollegen möchte ich recht herzlich für die netten Gespräche, die vielen Mensabesuche und die schöne Zeit danken. Ein ganz besonderer Dank geht dabei an die restlichen Doktoranden, mit denen ich wirklich eine schöne Zeit hatte. Auch außerhalb des Institutes haben wir so manche schöne Zeit zusammen verbracht und haben uns stets gegenseitig unterstützt und geholfen.

Zu guter Letzt geht ein ganz besonders großer Dank an meine Familie und meine Freunde. Ihr habt mich immer unterstützt und ermutigt, den für mich richtigen Weg zu gehen und nicht aufzugeben. Ihr habt Sorgen und Freuden mit mir geteilt und habt mir immer den liebevollen Rückhalt gegeben, den ich gebraucht habe.

Eidesstattliche Versicherung

gemäß § 18 Absatz 3 Satz 5 der Promotionsordnung der Universität Hohenheim für die Fakultät Agrar

1. Bei der eingereichten Dissertation zum Thema

A cropping system for yacon (Smallanthus sonchifolius Poepp. Endl.) – optimizing tuber formation, yield and sugar composition under European conditions

handelt es sich um meine eigenständig erbrachte Leistung.

2. Ich habe nur die angegebenen Quellen und Hilfsmittel benutzt und mich keiner unzulässigen Hilfe Dritter bedient. Insbesondere habe ich wörtlich oder sinngemäß aus anderen Werken übernommene Inhalte als solche kenntlich gemacht.

3. Ich habe nicht die Hilfe einer kommerziellen Promotionsvermittlung oder -beratung in Anspruch genommen.

4. Die Bedeutung der eidesstattlichen Versicherung und der strafrechtlichen Folgen einer unrichtigen oder unvollständigen eidesstattlichen Versicherung sind mir bekannt.

Die Richtigkeit der vorstehenden Erklärung bestätige ich. Ich versichere an Eides Statt, dass ich nach bestem Wissen die reine Wahrheit erklärt und nichts verschwiegen habe.

Ort, Datum

Unterschrift

Belehrung zur eidesstattlichen Versicherung

gemäß § 18 Absatz 3 Satz 6 der Promotionsordnung der Universität Hohenheim für die Fakultäten Agrar-, Natur- sowie Wirtschafts- und Sozialwissenschaften

Die Universität Hohenheim verlangt eine Eidesstattliche Versicherung über die Eigenständigkeit der erbrachten wissenschaftlichen Leistungen, um sich glaubhaft zu versichern, dass die oder der Promovierende die wissenschaftlichen Leistungen eigenständig erbracht hat.

Weil der Gesetzgeber der Eidesstattlichen Versicherung eine besondere Bedeutung beimisst und sie erhebliche Folgen haben kann, hat der Gesetzgeber die Abgabe einer falschen eidesstattlichen Versicherung unter Strafe gestellt. Bei vorsätzlicher (also wissentlicher) Abgabe einer falschen Erklärung droht eine Freiheitsstrafe bis zu drei Jahren oder eine Geldstrafe.

Eine fahrlässige Abgabe (also Abgabe, obwohl Sie hätten erkennen müssen, dass die Erklärung nicht den Tatsachen entspricht) kann eine Freiheitsstrafe bis zu einem Jahr oder eine Geldstrafe nach sich ziehen.

Die entsprechenden Strafvorschriften sind in § 156 StGB (falsche Versicherung an Eides Statt) und in § 161 StGB (Fahrlässiger Falscheid, fahrlässige falsche Versicherung an Eides Statt) wiedergegeben.

§ 156 StGB: Falsche Versicherung an Eides Statt

Wer vor einer zur Abnahme einer Versicherung an Eides Statt zuständigen Behörde eine solche Versicherung falsch abgibt oder unter Berufung auf eine solche Versicherung falsch aussagt, wird mit Freiheitsstrafe bis zu drei Jahren oder mit Geldstrafe bestraft.

§ 161 StGB: Fahrlässiger Falscheid, fahrlässige falsche Versicherung an Eides Statt

Abs. 1: Wenn eine der in den §§ 154 und 156 bezeichneten Handlungen aus Fahrlässigkeit begangen worden ist, so tritt Freiheitsstrafe bis zu einem Jahr oder Geldstrafe ein.

Abs. 2. Straflosigkeit tritt ein, wenn der Täter die falsche Angabe rechtzeitig berichtigt. Die Vorschriften des § 158 Absätze 2 und 3 gelten entsprechend.

Ich habe die Belehrung zur Eidesstattlichen Versicherung zur Kenntnis genommen.

____________________ ____________________

Ort, Datum Unterschrift

Curriculum vitae

Larissa Kamp

Born on 03rd of December 1990 in Radevormwald

Accurate operating personality with high personal and distinct abilities in agricultural research

- Implementation of several years research work with focus on vegetative propagation, genotype screening and analysis of ingredients
- Solution- and target-orientated working
- Excellent Communicator, confident manner and deep empathy

Professional Career

Since 04/2019 **Nunhems Netherlands BV (Vegetable seed division of BASF)**

Sales Specialist Carrots for Germany, Austria, Switzerland and Czech Republic

05/2016 – 03/2019 **University of Hohenheim, Stuttgart**

Faculty of Agricultural Science – Institute of Crop Science

Research employer

- Coordination and mentoring of a research project in the course of own PhD
- Planning, coordination and implementation of field-, greenhouse- and laboratory trials
- Data collection, sample preparation as well as analysis (HPLC, GC, NIRs, Photometer)
- Evaluation and publication of collected data and results
- Presentation of relevant research findings on specific conferences

Curriculum vitae

Education

05/2016 – 07/2019 **University of Hohenheim, Faculty of Agricultural Science, PhD**

PhD subject: „Development of cultivation and propagation methods for Yacon (*Smallanthus sonchifolius*) influencing tuber formation, yield and chemical composition"

10/2014 – 05/2016 **University of Hohenheim, Faculty of Agricultural Science**

Agricultural science – plant production systems

Degree: Master of Science (M.Sc.)

Masterthesis: „Kultivierung von *Salvia hispanica* L. in Mitteleuropa - Einfluss von Sorte, N-Düngung und Reihenweite auf Ertrag und Qualität "(Cultivation of *Salvia hispanica* L. in Central Europe – Impact of species, n-fertilization and row spacing on yield and quality)

10/2010 – 09/2014 **University of Hohenheim, Faculty of Agricultural Science**

Bio based products and bioenergy

Degree: Bachelor of Science (B.Sc.)

Bachelor thesis: „Photometrische Bestimmung von Zellmasse und Carotinoidproduktion am Beispiel von *Rhodotorula glutinis* "(Photometric determination of carotenoidproduction on the example of *Rhodotorula glutinis*)

08/2001 – 07/2010 **Leibniz (Secondary school), Remscheid-Lüttringhausen**

General education

Internship

06/2014 – 09/2014 **Study-related internship on the „Dehesa San Francisco“ (Fundación Monte Mediterráneo), Spain**

- Care and feeding of different animal herds (Iberian pigs, cows, merino sheep’s, goats, horses, donkeys, laying hens) in extensive free-ranged farming
- Assistant by veterinarian measures and investigations
- Cork harvest

Language skills

German:	Native
English:	Business fluent
Spanish:	Fluent

Ort, Datum Unterschrift