Performance of organic and conventional crop varieties and species mixtures under stress

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Table of contents

Prologue

This thesis is part of the collaborative research project *RightSeeds* by the Universities of Oldenburg and Göttingen with the Institute of Ecological Economy Research (IÖW) in Berlin. The project is funded by the Federal Ministry of Education and Research (grant number 01UU1602B). The objective of *RightSeeds* under the head of Prof. Stefanie Sievers-Glotzbach is to understand the impact of commons-based rights on seeds and crop varieties for a social-ecological transformation of plant cultivation. My work was conducted within the Department of Agroecology of the University of Göttingen under the leadership of Prof. Teja Tscharntke and the further supervision of Prof. Jacqueline Loos. I aimed to assess the role of traditional and organic, versus conventional crop varieties and species mixtures for sovereign food production and the promotion of resilient farming systems. As a cumulative dissertation my work consists of four chapters. Chapter ONE presents the currency of my research work leading to the research questions of this thesis. Followed by a systematic literature review in chapter TWO, providing details on provisioning, regulating, and cultural ecosystem services of traditional vs. modern crop varieties. Chapter THREE describes an empirical investigation of organic and conventional vegetable varieties within sub-optimal growing conditions like drought stress. Pursued in chapter FOUR, presenting the positive role of organic breeding for mixed-cropping with and without weed stress. The individual chapters of the dissertation highlight the relevance of a diverse variety portfolio for the sustainability and sovereignty of crop production, equally in the global South and North.

CHAPTER ONE: INTRODUCTION

Research Area and Central Questions

Terms used in this dissertation

Like in all subject areas with a wide body of literature, a portfolio of commonly used terms has developed around seeds and crop varieties. In order to structure and simplify the understanding of the terms used in this dissertation, a glossary is attached at the end of the thesis (page 120).

Research area and central questions

The conservation and promotion of (agro-)biodiversity is regarded as a priority for the maintenance of ecosystem services as well as for the sustainability and sovereignty of food production for the world's population under changing climatic and social-economic conditions (MEA, 2005; Zimmerer, 2013; Steffen et al., 2015). One of the "Sustainable Development Goals", developed by the United Nations as a "blueprint to achieve a better and more sustainable future for all" (UN, 2020), is therefore the in-situ conservation of a diversified crop variety portfolio in combination with improved and ecologically more sustainable agricultural cultivation systems (Tilman et al., 2002; FAO, 2018). In this context, significant value is attached to the diversity of plant genetic resources in the form of seeds and crop varieties (Kumar et al., 2015), and a high level of variety diversity is known to promote important provisioning, regulating, and cultural ecosystem services (Altieri, 1999; Tscharntke et al., 2005; Ficiciyan et al., 2018). However, it had also become clear that a major threat to agrobiodiversity and ecosystem services is the loss of traditional crop varieties (MEA, 2005). One of the reasons for this loss is their replacement with modern, improved varieties (MEA, 2005).

Through advanced plant breeding techniques (cross-breeding, hybrid breeding, mutation breeding, tissue culture, genetic engineering, smart breeding, genomic selection, genomic editing via CRISPR/Cas9) in recent decades, crop varieties have been greatly improved towards high yields and resistance to pests and diseases (Kingsbury, 2009). As a result of the successful adoption of these modern, improved varieties (in the following called *conventional varieties*) within intensified, monoculture farming systems, the demand for traditional varieties declined, so that today many of these traditional varieties have disappeared from the market (Van de Wouw et al., 2009; Casals et al., 2011; Olson et al., 2012).

Furthermore, the commercial plant breeding and seed market is dominated by four partly merged transnational seed and agrochemical companies (Bayer-Monsanto, DowDuPont/Corteva, ChemChina-Syngenta, BASF), controlling 50% of the market (ETC Group, 2017; OECD, 2018). This strong corporate market concentration means that these companies can dictate the global market availability of crop species and varieties, focussing mainly on those with the highest economic output and prevent their free use by intellectual property rights via plant variety protection and patents (ETC Group, 2017).

Moreover, the strict acceptance criteria of distinctness, uniformity and stability (DUS criteria) for new varieties to be officially registered (mandatory for official distribution / sale), and the financially costly approval procedure, leave little scope for less uniform crop varieties like *traditional varieties* or *landraces* (Serpolay et al., 2011; Christinck and Tvedt, 2015).

In the vegetable sector, breeding targets have been dominated by uniformity, simultaneous fruit ripening, and a defined fruit quality to meet market demands (Riggs, 1988; Department of Agriculture and Cooperation, 2012). Especially, hybrid breeding (**Figure 1**) has become the most prominent method, as it is a very efficient way to achieve these targets (Department of Agriculture and Cooperation, 2012). The share of hybrid seeds on the seed

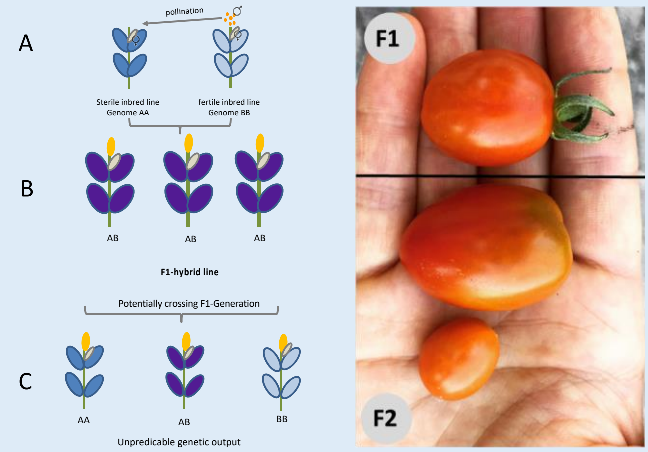

Figure 1: Process and characteristics of hybrid breeding: two homozygotic parental lines that are as genetically different as possible to each other are crossed (A). Due to the heterosis-effect, the F1-hybrid line (B) is much more productive in its general performance compared to the parental lines and also to comparable open-pollinated varieties. Increase of the hybrid plant vigor remains only for the F1-generation and is lost in the next (C). Therefore, farmers have to rebuy seeds every growing season from seed selling companies (Dias and Ryder, 2011). Since the development of hybrid varieties is very labor intensive, development-costs are reflected in high seed retail price (Kotschi and Wirz, 2015).

market in the vegetable sector has been increasing rapidly worldwide by 8-10% per year, replacing many traditional varieties (Dias, 2010).

Studies on variety comparison in recent years have shown on the one hand, that the introduction of conventional varieties has led to the hoped-for yield enhancements for example for maize (Lafitte et al., 1997), sorghum (Kante et al., 2017), or tomato (Devkota et al., 2018). On the other hand, for small-scale farmers who practice subsistence farming under sub-optimal cultivation conditions, conventional varieties may cause crop failure on marginal farmland, increasing hunger and reducing food sovereignty in the global South (Sthapit et al., 2008; Olson et al., 2012; Salgotra and Gupta, 2015). As a result, despite decades of aid programs, the FAO still reports a figure of 767 million people with an insecure nutritional situation (FAO, 2017), and just a few crops species like rice, maize, and wheat provide for half of the worldwide human requirement of carbohydrates and proteins (Ladha et al., 2016).

Current studies have furthermore shown a possible decline in trait variance through crop domestication and plant breeding for and in monoculture systems, leading to a genetic bottleneck and resulting in the loss of crop, variety, and allele diversity (Van de Wouw et al., 2009; Messmer et al., 2015; Chacón-Labella et al., 2019). This in turn can lead to the loss of trait-based complementary effects (Chacón-Labella et al., 2019), disregarding important characteristics relevant for mixed-cropping and sub-optimal growing conditions, as is often the case for organic farming in the global North.

Despite the evidence that conventional varieties might fail under sub-optimal growing conditions, organic and small-scale farmers worldwide often rely on conventional varieties, because of their typically higher provisioning services such as crop yield, and also due to lack of variety alternatives (Lammerts van Bueren, et al., 2004). This is because there are still many plant species for which seeds of traditional and organic varieties – possibly adapted to sub-optimal organic and small-scale growing conditions by breeding and propagation under these conditions (see glossary *Traditional varieties* & *Organic varieties*) – are not available or not in sufficient quantities.

In such cases, in Europe the Council Regulation (EC) on organic production allows organic farmers to use seeds of conventional varieties bred for conventional farming systems: *"for the production of products other than seed and vegetative propagating material only organically produced seed and propagating material shall be used. To this end, the mother plant in the case of seeds and the parent plant in the case of vegetative propagating material shall have been produced in accordance with the rules laid down in this Regulation for at least one generation, or, in the case of perennial crops, two growing seasons."* (Council Regulation (EC) No 834/2007 of 28 June 2007 on organic production and labelling of organic products and repealing Regulation (EEC) No 2092/91).

However, in order to increase variety diversity and to provide organic and small-scale farmers with varieties adapted to sub-optimal growing conditions, organic breeding organizations are scaling up their range of varieties and seed production.

Organic breeding organizations in Europe

In Europe, organizations like Kultursaat e.V. (Germany) and Sativa Rheinau (Switzerland) develop crop and vegetable varieties for organic and small-scale farming systems. With their work, they strive to protect and enlarge genetic diversity by conserving traditional varieties and developing new varieties under organic low-input conditions without using pesticides and synthetic fertilizers. Their aim is to offer a range of alternative varieties, which deliver good yields, are resistant to pests and diseases, and can cope with local growing conditions like limited water supply, weed stress, or mixed-cropping. Plant breeding for the organic sector rejects genetically modified organisms, protoplast fusion, in vitro propagation, and induced mutation. Hybrid breeding is also avoided as it is not conducive to maintaining genetic diversity (Lammerts van Bueren and Struik, 2004; Messmer et al., 2015). Another notable aspect of most organic breeding organizations worldwide is the rejection of controlling their products (and thus the profits from them) through patents or intellectual property protection. With respect to food sovereignty, seeds and varieties are seen as common goods and acknowledged worldwide as so-called *seed and variety commons* including participatory breeding and seed exchange arrangements (Wirz et al., 2017; Gmeiner et al., 2018). Seeds and varieties as a common good form an alternative "second path" in contrast to the private-property seed system, expanding the scope for action and co-determination by the farmers and breeders (Wirz et al., 2017; Gmeiner et al., 2018). The RightSeeds research group – in which this dissertation is embedded in – examines the link between forms of organization within this "second path" and their role in promoting a social-ecological transformation of crop production.

Research questions and experimental approach

Until now it is unknown whether acknowledging crop varieties as a common good supports agrobiodiversity and sovereign food production. In my work I investigate ecological and social effects of two forms of *seed and variety commons.* In the global South as traditional varieties and landraces, which are bred in participatory ways and exchanged between farmers. In the global North as varieties from organic breeding and conservation without private property protection.

Furthermore, little has been known about the extent to which the efforts of organic variety breeding and conservation can contribute to ecologically more sustainable agricultural cultivation systems. It is therefore important to test whether the conservation of traditional varieties and breeding under organic conditions preserve and create varieties that can be competitive alternatives to conventional varieties for organic and small-scale farming. My dissertation delivers new answers to these questions by assessing the role of different varieties and the farmers’ perception of agronomic, ecological, and social factors, including provisioning, regulating, and cultural ecosystem services. Furthermore, I tested the performance of organic and conventional crop varieties as single crops and species mixtures under stress. I expected that breeding for conventional varieties takes place at the expense of functionally important traits such as resistance to stress from weeds and drought, thereby compromising the resilience (i.e. the capacity to reorganize after disturbance) of cultivation systems in less favored locations.

My common garden experiments took place in the experimental botanical garden of the University of Göttingen (**Figure 2**).

Figure 2: Experimental set up for the vegetation periods 2017 and 2018. Seedlings were cultivated inside the plant nursery until temperatures below zero degrees were no longer expected (A). During the main growing season, single and mixed-cropped plants were planted into small (B) or big (C optimal condition & D under weed pressure) plastic buckets and arranged in a 15 x 12 meter roofed and graveled area with water supply as a randomized block design with four repetitions. Each plant was harvested individually by hand (E).

My study species were tomato (*Solanum lycopersicum* L.) (**Figure 3**) and pepper (*Capsicum* spp.) (**Figure 4**) since they are economically highly important for the EU vegetable market, popular among consumers, and known to be sensitive to biotic and abiotic stress (Rossi, 2019; Suguru, et al., 2003; Wahb-allah et al., 2011).

Figure 3: Impressions of different tomato varieties used in the experiments in 2017 and 2018.

Figure 4: Impressions of different pepper varieties used in the experiment in 2017.

Overarching hypotheses

- ***Relevance of traditional varieties for provisioning, regulating, and cultural ecosystem services under sub-optimal growing conditions***. Modern varieties and traditional varieties differ in their potential for ecosystem services under optimal and sub-optimal growing conditions. Provisioning and regulating services under sub-optimal growing conditions are thereby more strongly supported by traditional varieties through higher adaptation to local conditions. Traditional varieties – developed and conserved by small social groups – are furthermore of higher importance for cultural services.
- ***The relative importance of organic, conventional, and hybrid varieties for sustainable crop production***: Central functions of agro-ecosystems, such as resilience to unstable growing conditions like limited water supply, are supported by the use of organic varieties. Trait diversity is thereby higher in organic varieties compared to conventional or hybrid varieties, through variety preservation and development under organic farming conditions without synthetic fertilizers, pesticides and as mixed-crops.
- ***Enhancing the resilience of a mixed-cropping system against weed stress through organic varieties***: Diversification of a farming system through mixing different crop species on one production unit is an effective strategy to increase the resilience of the farming system to environmental instability. The performance under weed stress (yield, yield quality, yield stability) of a mixed-cropping system using organic varieties is higher than a system with conventional varieties.

Overview of the following chapters

The chapters two to four of this dissertation answer these above hypotheses.

Chapter two "*Systematic Literature Review*"

I performed a systematic literature review comparing agronomic, ecological and cultural characteristics of *landraces* against *modern varieties* to collate scientific evidence on the provisioning, regulating, and cultural ecosystem services of varieties with different breeding backgrounds. After scanning the academic publications from 1945 to 2017 from the Web of Science database, I chose to use the term *landraces,* since it was most commonly used over all disciples to describe traditional, locally adapted varieties. Landraces are defined as "dynamic population(s) of a cultivated plant that has historical origin, distinct identity and lacks formal crop improvement, as well as often being genetically diverse, locally adapted and associated with traditional farming systems" (Villa et al. 2005).

In contrast, in the review the term *modern varieties* describes varieties which are bred for high yield levels in high-input environments and are often genetically homogeneous. Specifically, I aimed to understand (i) if modern varieties and landraces differ in terms of provisioning and regulating ecosystem services and (ii) when and why farmers prefer cultural ecosystem services of landraces over modern varieties.

The results document that modern varieties are preferred over landraces because of their typically higher provisioning services such as crop yield. However, landraces are often part of commons-based seed systems and ensure high provisioning services under sub-optimal farming conditions. Landraces can show high resilience under harsh environmental conditions and are a trusted source achieving stable crop yield (e.g., under droughts stress). Furthermore, small-scale farmers typically prefer local landraces due to regional cultural features such as family traditions and cooking characteristics for special dishes.

Chapter three *"Hybrid, Conventional and Organic Under Drought"*

In a common garden experiment during the growing season in 2017, I investigated whether the overall performance (yield, yield stability, and yield quality) of organic tomato and sweet pepper varieties is higher under drought stress than that of hybrids or open-pollinated conventional varieties. The results confirm the positive effect of hybrid breeding to some extent, since hybrid varieties produced higher yield in terms of fruit number, both under optimal and drought stress growing conditions. However, since total fresh fruit weight and distribution of marketable and non-marketable fruits was quite similar for all varieties, the results challenge the widely held assumption that conventional open-pollinated and organic varieties bred under low-input conditions cannot be seen as equivalent alternatives to hybrids. Thus, these varieties should be considered as highly important for maintaining a diverse variety portfolio for local adaptation to unstable climate and water-supply conditions.

Chapter four *“Variety Comparison in Mixed-cropping under Weed Stress”*

In a second common garden experiment (during the growing season of 2018), I investigated whether organic varieties perform better than conventional varieties in mixed-cropping with a legume and under weed stress. Specifically, I tested yield performance in terms of harvested yield, yield stability and fruit quality. As treatments, I cultivated varieties as single plants or in mixed-cropping with a legume and with or without exposure to weed stress. The results show that organic varieties outperformed conventional varieties. Specifically, in mixed cropping systems, organic varieties produced higher yield and more fruit of the highest quality. The findings challenge the widely held assumption of the merits of monoculture agriculture and conventional varieties.

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CHAPTER TWO: SYSTEMATIC LITERATURE REVIEW

More than Yield: Ecosystem Services of Traditional versus Modern Crop Varieties Revisited

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Abstract

Agricultural intensification with modern plant breeding focuses on few high-yielding crops and varieties. The loss of traditional crop species and variety diversity contributes to the current decline of provisioning, regulating, and cultural ecosystem services, as reported in the Millennium Ecosystem Assessment. Access to local and adapted varieties is pivotal for resilient agroecosystems, in particular under current global change. We reviewed the scientific literature to understand the role of different crop varieties for ecosystem services, comparing the performance and perception of traditional landraces versus modern varieties and ask the following questions: 1. Do landraces and modern varieties differ in terms of provisioning and regulating ecosystem services? 2. When and why do farmers prefer cultural ecosystem services of landraces over high-yielding varieties? Based on 41 publications, our results document that modern varieties are preferred over landraces because of their typically higher provisioning services such as crop yield. However, landraces often guarantee higher provisioning services under non-optimal farming conditions. Landraces can show high resilience under harsh environmental conditions and are a trusted source achieving stable crop yield (e.g., under droughts stress). Regulating services such as resistance against pests and diseases appear to often become lost during breeding for high-yielding, modern varieties. Furthermore, small-scale farmers typically prefer local landraces due to regional cultural features such as family traditions and cooking characteristics for special dishes. In conclusion, both landraces and modern varieties have merit depending on the farmers' priorities and the social-ecological context. In any case, maintaining and restoring the huge diversity of landrace varieties is necessary for sustaining current and future needs.

Keywords

Agrobiodiversity; ecosystem services; food sovereignty; seed commons; variety diversity; protection laws; landraces

Introduction

Despite the success of agricultural intensification and the green revolution toward mitigating global hunger (Dalrymple, 1986; Evenson and Gollin, 2003), the FAO (2017) reports 767 million people remaining in an insecure nutritional situation (FAO, 2017). With approximately one third of the planet's population earning less than $2 a day (Von Braun et al., 2009; United Nations Secretary, 2003), hunger is inevitably caused by poverty as a result of unequal resource distribution (Holt-Giménez et al., 2012). At the same time, global agrobiodiversity continuously decreases due to the loss of diversity in species and varieties of food crops (Tscharntke et al., 2005; Messmer, 2015). Since the start of modern plant breeding (cross-breeding, F1-hybrid breeding, in vitro breeding, gene technology, smart breeding, and genomics), breeding efforts focus on the development of a few economically important plant species like maize, rapeseed, soy, and rice (Danial et al., 2007; Messmer, 2015). The intensive spread and wide use of improved, modern varieties has led to a genetic bottleneck, resulting in the loss of crop, variety and allele diversity (Peroni et al., 2002; Tsegaye and Berg, 2007). For example, 75% of the genetic diversity of farmers' crops has been lost since the 1900s in favor of genetically uniform, high-yielding varieties, and only 150–200 out of the 300,000 known edible plant species are used by humans (FAO, 1999). This concentration on few crops and varieties is promoted by the privatization of seed material and usage restrictions by patents and variety protection laws (Van de Wouw et al., 2010; Buck and Hamilton, 2011). However, high-yielding crop varieties may cause crop failure under sub-optimal cultivation conditions on marginal locations, thereby increase hunger and downgrade sovereign food production in countries of the global South (Sthapit et al., 2008; Olson et al., 2012; Salgotra and Gupta, 2015). Further, this development contributes to the proceeding decline of ecosystem services as reported in the MEA (2005) (MEA, 2005). Hence, provisioning, regulating, and cultural ecosystem services in agricultural systems/farming evolved from a diversity of food crops and varieties that are highly endangered. Within this context, a wide range of species and varieties represents an important component of agrobiodiversity (Thrupp, 2000), and access to locally adapted varieties is pivotal for resilient agroecosystems (Altieri et al., 2012; Gruber, 2017). Farming systems using agroecological practices focus on resilient agricultural practices that also consider the socio-economic background of farmers and their families (Li, 2001). Such an approach often includes high functional biodiversity, farming techniques rooted in traditional knowledge systems, and locally adapted landraces, aiming at a sovereign food production and providing the ecosystem services that are essential for human well-being (MEA, 2005; Garibaldi et al., 2017).

In this review we compare the performance and the farmers' perception of improved, modern varieties versus traditional and locally adapted landraces, and synthesize their agronomic, ecological and social role for agroecosystems, i.e., provisioning, regulating and cultural services. Improved modern varieties are bred for high yield levels in high-input environments and are often genetically homogeneous (Newton et al., 2010). In contrast, landraces are "dynamic population(s) of a cultivated plant that has historical origin, distinct identity and lacks formal crop improvement, as well as often being genetically diverse, locally adapted and associated with traditional farming systems" (Villa et al., 2005). Thus, landraces aim to provide genetic resources and plant traits that are well adapted to local environmental and cultural conditions. Landraces have been maintained and selected over time by farmers to meet their personal economic, ecological and cultural needs and cultivated in small-scale farming systems with low input of external factors and high surrounding diversity (Teshome et al., 1997). Genetic heterogeneity vs. homogeneity influences the performance of a variety and the degree of diversity within the cultivation systems (Jackson et al., 2007). By comparing modern varieties with traditional landraces, we aim to identify the role of plant genetic diversity for resilient food production systems, providing for food security, and the role of freedom of variety choice, providing for food sovereignty. To our knowledge, this topic has not yet been studied in a systematic review.

To collate scientific evidence on the services of modern varieties versus landraces for agroecosystems and the entire food system, we raise the following questions:

1) Do landraces and modern varieties differ in terms of provisioning and regulating ecosystem services?
2) When and why do farmers prefer cultural ecosystem services of landraces over high-yielding, modern varieties?

Material and methods

We reviewed academic publications from 1945 to 2017 using the Web of Science database, which includes peer-reviewed international journals in agricultural and social disciplines. Our search string included the following terms: “landrace, participatory plant breeding, farmer participatory breeding, collaborative plant breeding, participatory variet* selection, participatory crop improvement, community based seed*, client-oriented breeding, seed variety, commons based seed*, open source seed*,” AND “soil quality, pollination, fertilization, yield, product*, harvest, divers*, variet*, variation*, pesticides, agrobiodiversity, agrodiversity, nitrogen, nutrient*, trait*, resistance, ecosystem, ecosystem service*.” We excluded the terms: “pig” or “piglet” because the term “landrace” is also used in animal breeding and searched in title, keywords, and abstract, only including scientific publications from the following fields: Agronomy, plant science, horticulture, genetics heredity, agriculture multidisciplinary, multidisciplinary science, evolutionary biology, ecology, soil science, environmental science, reproductive biology, environmental studies, forestry, biology, green sustainable science technology, entomology, sociology, biodiversity conservation, zoology, parasitology, social science interdisciplinary, and ethics. After title and abstract scanning of 344 papers and completely reading of 113 papers, we evaluated 41 full texts as eligible, because these texts compare the agronomic, ecological, and/or cultural characteristics of landraces against modern varieties (for detailed information see Supplementary Materials: Table S1 List of included 41 publications comparing landraces against other variety types). The group of modern crop varieties captures all commercial varieties that have been greatly improved towards high yields though advanced plant breeding techniques. These techniques include traditional on field selection methods, use of inbred-lines creating F1-hybrids, laboratory techniques at the tissue or cell level, and techniques at DNA level. The group of modern varieties includes cultivars, improved cultivars, modern cultivars, local cultivars, improved varieties, modern varieties, commercial varieties, research breed lines, and F1-hybrids.

Provisioning ecosystem services refer in our case to the performance and productivity of a variety. In addition to crop yield (n = 26), we also refer to the crop nutrient use efficiency (n = 6) and the cultivation effort and the storability of harvested crops (n = 4). The regulating ecosystem services refer in our case to the interaction of a crop variety with its biotic and abiotic environment. We focus on the resilience to environmental changes (n = 24) and also to biological pest and disease control (n = 10), biodiversity richness (n = 1), and crop pollination (n = 1). We finally refer to tradition, cooking characteristics, nutritional values, taste, and color (n = 5) as measurable performances for cultural ecosystem services. Landraces can exhibit a positive, negative or unclear (i.e., varying or absent) performance in comparison with modern varieties (see Table 1). We are aware that there are more subcategories for every group of ecosystem services. In our review we present a selection composed out of ecosystem services mentioned in the included publications.

Table 1: Detailed performance classification, showing the effect of selecting landrace varieties over modern varieties. More precise context of the findings is given in the results section.

Ecosystem Services	Measured Performance	Total No. of Publications	Positive Effect	Negative Effect	Unclear Effect	Most Important Findings
Provisioning services	Crop yield	26	9	8	9	Landraces yield equally or higher under harsh local conditions (Yadav, 2010; Brocke et al., 2014; Li et al., 2012) Modern varieties exhibit higher yield, but costs for fertilizers and pesticides may be also high, even counterbalancing the benefit from higher yields (Li et al., 2012) Modern varieties typically outyield landraces under optimal conditions (Kante et al., 2017)
	Crop nutrient use efficiency	6	3	1	2	Landraces tend to deliver more stable yields under limited environments (Lafitte et al., 1997; Sangabriel-Conde et al., 2014) But modern breeding can improve the water use efficiency (Fang et al., 2014)
	Cultivation effort and crop storability	4	2	1	1	Higher storability of landraces, and lower levels of storage losses to insects using landraces (Maggs-Kolling et al., 2003; Moreno et al., 2006)
Regulating services	Resilience to environmental changes	24	22	1	1	Landraces are often better adapted to drought stress (Annicchiarico, 2006; Munoz-Perea et al., 2007; Mazvimbakupa et al., 2015) Landrace varieties may be more pest resistant (Olson et al., 2012) Landraces are better adapted to local climate conditions (Olson et al., 2012; Fenzi et al., 2017)

Ecosystem Services	Measured Performance	Total No. of Publications	Positive Effect	Negative Effect	Unclear Effect	Most Important Findings
	Biological pest & disease control	10	6	2	2	Landraces maintain high levels of resistance against pest and disease (Tamiru et al., 2011; Patil et al., 2014; Sánchez-Martín, 2017)
	Crop pollination	1	1	0	0	Small sized vineyards based on the use of local landraces maintain complex ecological infrastructures, i.e., treed riparian strips, as well as forest remnants, natural edges, out of forest trees, which positively influence pollinator's presence (Biasi and Brunori, 2015)
	Biodiversity richness	1	1	0	0	To maintain landscape complexity, and therefore biodiversity richness, accounts also the viticulture that is tightly linked to the local grapevine genetic resources. The structure of the vineyards, at the base of a traditional use of the local landraces, reflects the principle of landscape ecology. That maintains landscape complexity, and therefore species and biodiversity richness (Biasi and Brunori, 2015)
Cultural services	Tradition, cooking characteristics, nutritional values, taste, and color	5	5	0	0	Cooking characteristics are highly important for variety decisions (Moreno et al., 2006; Zimmerer, 2014) Landraces are passed over generations together with recipes (Montes-Hernandez, et al., 2005)

Results and discussion

In our review, we found a total of 41 publications with results from 28 experiments testing different varieties against each other, 10 surveys among small-scale farmers investigating reasons of variety selection and 3 conceptual papers from 19 different countries. The larger share of publications focuses on countries in developing regions such as Africa, South and Central America, Asia as well as Eastern Europe (n = 13; 68.4%). The remaining countries are mainly located in Europe (n = 5; 26.3%), and just one study in the western USA.

Crop yield and resilience to environmental changes were the two most measured performances when comparing landraces with modern varieties, followed by biological pest and disease control (Table 1). Most publications deal with several types of variety performance. In the following the results will be presented along the three categories of ecosystem services (provisioning, regulating, and cultural).

Provisioning services

Crop yield

Twenty-six studies used crop yield as a response variable comparing landraces against modern varieties: one conceptual paper, seven surveys among farmers, and 18 experimental approaches testing varieties. Among these 26 publications, a positive effect of landraces on crop yield was found nine times, a negative effect eight times, and an unclear effect nine times. Stability of crop yield is a major economic value, in particular under harsh and changing environments and plays a key role for food security (Zeven, 1998; Mazvimbakupa et al., 2015).

Findings from field experiments

Results from the 18 publications on field experiments show that landraces tend to produce fewer yields than modern varieties if environmental conditions are optimal. Lafitte et al. show for example that improved maize varieties had on average 56% higher yields (independent of N-levels). Kante et al. (2017) also showed that mean yields for F1-hybrids varieties were 3 to 17% (ranging from 60 to 28 kg/ ha) higher across different environmental conditions compared to local landraces.

In contrast, Maggs-Kolling and Christiansen (2003) found that the yield of watermelon landraces in Namibia was higher than that of modern varieties. Landrace varieties of water melon produced smaller, less sweet fruits with larger seed, and a thicker rind compared to modern varieties, attributes which are considered positive by local people. Under non-optimal farming conditions, results from field experiments show that landraces tend to yield the same or even higher than modern varieties. These trends are confirmed by Noguera et al. (2011) for rice. They found that local landraces are highly adapted to harsh environmental conditions and respond well in biomass to earthworm application. However, they cannot compete with modern varieties in terms of rice grain biomass under optimal conditions. In Burkina Faso, farmers have a strong interest in sorghum landraces due to their ability to produce secure and stable yields in the face of unpredictable climate conditions (Brocke et al., 2014). Field experiments from semi-arid and arid regions of South Asia and Africa comparing pearl millet landraces against modern varieties also showed that landraces yielded significantly more grain under drought stress than modern varieties Yadav, 2010). Annicchiarico, P. (2006) documents the high provisioning value of lucerne landraces in Italy in comparison to modern varieties in terms of forage yield. Farmers chose landraces for sandy soils in their region due to a lower winter mortality of landraces. Olson et al. (2012) tested factors that influence farmers' choices between landraces and modern varieties of maize for small-scale coffee farms in El Salvador. Yields in plots planted with modern varieties were significantly higher than yields in plots planted with landraces. However, landrace varieties were more commonly planted on steep slopes compared to modern varieties, suggesting negative effects of the slope rather than seed type appeared to drive the yield difference. Slope was negatively correlated with yield for both seed types, while other analyses showed that yield between modern varieties and landraces did not differ (Olson et al., 2012).

Findings from farmer surveys

Farmers' perceptions of yield differences between landraces and modern varieties were also studied. Li et al. (2012) and Knezevic-Jaric et al. (2014) compared via farmer interviews the yield of landraces with the yield of F1-hybrid varieties and concluded that F1-hybrids provide higher yield. Li et al. (2012) found that 71% of the respondents within their survey among small-scale farmers in China mentioned the yielding qualities of F1-hybrid varieties compared to landrace varieties, but only 4% of them increased their final income by adopting F1-hybrids due to additional costs for inputs such as pesticides and fertilizers. The farmers also reported that the maize F1-hybrids were not adapted to upland and infertile land and that weather variation as well as pest and diseases easily influenced the yield. Sixty-two percent of the interviewed farmers considered landraces better adapted to the local conditions leading to a more stable productivity. A similar outcome was reported from Serbia where commercial maize F1-hybrids are increasingly used since they offer higher yields in shorter time frames (Knezevic-Jaric et al., 2014). However, interviewed farmers mentioned that even if the yield of maize landraces is lower, they still show higher production stability under changing environmental conditions. Farmers in Northeast Turkey were found to prefer Kirik, a local landrace wheat variety, over modern wheat varieties, even if the suggested yield of modern varieties was higher (Bardsley and Thomas, 2005). This is because, unlike modern varieties, landraces (especially Kirik) can sometimes be sown twice per year, in spring and autumn, giving the farmers a flexibility to match seasonal changes and a higher level of protection against extreme agronomic conditions (Bardsley and Thomas, 2005).

Crop nutrient use efficiency

The crop nutrient use efficiency describes the capacity of a variety to use available soil nutrients in an efficient way (Sangabriel-Conde et al., 2014). We found six studies (five experiments and one conceptual paper) that use crop nutrient use efficiency as a response variable comparing landraces against modern varieties. In terms of maize landraces, Lafitte et al. (1997) found that landraces have a higher capability to use available nitrogen (N) under limited N-levels compared to modern varieties and therefore, perform better in N-limited environments, although modern varieties outyielded landraces under optimal farming conditions. Sangabriel-Conde et al. (2014) conducted a greenhouse experiment evaluating the response of maize landraces and a F1-hybrid maize variety to arbuscular mycorrhizal fungi under different phosphorus (P) levels. Results show that local landraces interacted better with mycorrhiza resulting in an enhanced P-uptake. P acquiring capacity of the F1-Hybrid is severely lower than those of some landrace varieties, despite a high mycorrhizal dependency. According to Sangabriel-Conde et al. (2014) some landraces appear to have adaptive mechanisms to obtain P more efficiently, a trait important in milpa cultivation systems. In contrast, Fang et al. (2014) provide evidence that modern breeding towards greater and more stable yield can also promote water use efficiency. Hence, modern varieties may overtake landraces even under environmental stress (Fang et al., 2014).

Cultivation effort and crop storability

Many factors influence farmers' working time and how it is affected by a certain crop variety. The timespan of the growing period, the time spent for crop storage minimizing losses from pest infestation or decay, and finally the time spent on field during the growing period was dealt with in four studies. They analyze the farmers' time required during cultivation and the storability of the harvested crops for different varieties, with three studies reporting results from field experiments and one survey among farmers. In one publication, local landraces were connected with a higher required time because of additional work for seedbeds for landraces (Calvet-Mir et al., 2011). The other studies (n = 3) state a positive or unclear effect of landraces on the time of required work during cultivation and the storability of the harvested crops. As an example, watermelon landraces could be stored up for more than 12 months in the shade, while the storability of modern varieties was limited to just a few weeks (Maggs-Kolling and Christiansen, 2003). Anastasi et al. (2017) mention the earliness of sesame landraces as a useful trait in semiarid environments, because it shortens the cropping cycle, reduces water use and makes the field available sooner for the next crop. Moreno et al. (2006) analyzed how different landraces and modern varieties affect crop storability for small-scale farmers in México and found that they have more problems with pest infestation in case of modern varieties than landraces. One third of farmers does not report high levels of storage losses to insects when using their local landraces, and do not see the need to implement pest control measures.

CONTEXT DEPENDENCY OF PROVISIONING ECOSYSTEM SERVICES

The yield outcome of landraces and modern varieties appears to be contingent on local environmental conditions. Modern varieties have often higher yields, which may be much reduced under harsh local conditions. In contrast, landraces are a trusted, resilient and successfully cultivated seed/crop source of reliable yields for many small-scale farmers around the globe. This applies especially to the nutrient-use efficiency of the crop and the storability of harvested crops. Therefore, landraces should be considered for their production potential in marginal areas and as genetic material for the future, even if modern varieties yield better under optimal farming conditions (Boutraa and Sanders, 2001; Yadav, 2010; Oupkaew et al., 2011). Both landraces and modern varieties have merit, and the right variety choice depends on the site-specific conditions, since it is impossible to find all desired performances realized in a single variety (Kolech et al., 2015). Crop variety selection needs to take advantage of a portfolio of (agronomic) performances corresponding to different land qualities (Li et al., 2012).

Regulating services

Resilience to environmental changes

High yields from landraces are in most cases directly connected with their ability to sustain under local environmental changes or sub-optimal farming conditions. Out of the 24 publications on resilience to environmental changes, we found seven surveys among farmers, three conceptual papers, and 14 publications experimentally testing varieties against each other, in the categories positive effects (n = 22), negative effects (n = 1), and unclear (n = 1) respectively.

Findings from field experiments

Eleven out of 14 publications reporting results from field experiments found positive effects of landraces compared to modern varieties under sub-optimal farming conditions. In one publication, the authors conclude that resilience capacity is unclear, and one study detected a negative effect. A merit of landraces in comparison with modern varieties is their ability to use limited water resources more efficiently and therefore be better adapted to drought stress (Annicchiarico, 2006; Vaezi et al., 2010; Yong'an et al., 2010). For example, pearl millet landraces yielded significantly more grain when the plants were under drought stress compared to modern varieties, while crosses of landraces with modern varieties resulted in the highest mean "Drought Response Index" based on flowering and grain yield (Yadav, 2010). With this index, Yadav (2010) quantifies that landraces are more productive than modern varieties under poor or changing water conditions and should especially be considered as gene material in breeding for water stress resilience. In the case of maize landraces, they yielded poorer under optimal conditions, but often performed similar to, or even better under stress conditions (Mazvimbakupa et al., 2015). In general, under severe water stress, a more stable prolificacy of landrace varieties may compensate for lower yields. Therefore, landraces should be considered for breeding and production in areas with non-optimal farming conditions (Mazvimbakupa et al., 2015). Furthermore, Leiser et al. (2015) detected that photoperiod sensitive landraces showed better P-tolerance and less delay of heating under P-limited conditions for grain yield compared with modern varieties. Dry beans and watermelons led to comparable results in that landraces outperformed modern varieties under stress (Maggs-Kolling and Christiansen, 2003; Munoz-Perea et al., 2007). The only study that detected a negative result of landraces comparing old, modern and newly released varieties was the case of winter wheat varieties, showing that improved and newly released varieties consume more soil water during anthesis (compared to landraces) under drought stress conditions, leading to higher yields (Fang et al., 2017).

Findings from farmer surveys

Responses from surveys among farmers to the resilience of a variety to environmental changes proved a generally high valuation of landraces compared to F1-hybrids or modern varieties. Strikingly, in China, steadily fewer households use maize landraces (Li et al., 2012). In the two Chinese provinces Guangxi and Yunnan, the area cultivated with landraces decreased significantly from 65% to 7% and from 84% to 18%, respectively, between 1998 and 2008. This reduction was accompanied by a rapid expansion of F1-hybrids of maize, especially in Guangxi, where the area under hybrids reached up to 93%. Seventy-one percent of the farmers were positive about the F1-hybrid yields, but still, 54% of them also indicated that they are concerned about the yield stability of F1-hybrids due to uncertainties about the performance by weather extremes, high pest and disease infestation levels. Sixty-two percent of the farmers considered maize landraces as better adapted to their local conditions, offering more stable productivity. In Serbia, respondents claimed that old maize varieties mature earlier, an attribute that is considered positively, and are more resistant to unfavorable environmental conditions such as drought (Knezevic-Jaric et al., 2014). In El Salvador, farmers stated that landrace seeds are more pest resistant. In focus groups the respondents explained landrace seeds as generally "stronger," having "stronger roots" and F1-hybrid seeds as "more prone to rotting" and "less resistant to rain" (Olson et al., 2012). Despite an increased introduction and supply of modern maize varieties in the Yucatan Peninsula (México), farmers maintained a substantial amount of traditional maize varieties over 12 years and still plant more than three quarters of milpa, which is a crop mixture of corn, legumes, and squashes (see **Figure 1**) (López-Forment, 1998) with traditional varieties (Fenzi et al., 2017). Also, in the Catalan Pyrenees, farmers prefer potato landraces to modern varieties due to their higher adaptability to the local climate and pests (Calvet-Mir et al., 2011). In Ethiopia, several local potato varieties were preferred over new ones even for yield, since they are well adapted to the particular agroecological zones. Additionally, they may serve as valuable resources for further variety improvement (Kolech et al., 2015).

Figure 1: Small-scale Milpa cultivation in Guatemala, April 2014.

Biological pest and disease control

Biological pest and disease control emerges as an important performance in the literature changing with variety selection (n = 10). We found 5 farmer surveys, 2 conceptual papers, and 3 publications experimentally testing landraces against modern varieties. These papers found positive (n = 6), negative (n = 2), and unclear (n = 2) effects respectively. Sánchez-Martin et al. (Sánchez-Martín et al., 2017) showed that oat landraces maintain high levels of resistance against rust, and their degree of infestation was generally 25% lower than that of modern varieties. Similar effects were also cited for sorghum landraces, where F1-hybrid varieties entail good yield potential, are weaker in combining the performance for yield with resistance against pests and diseases such as shoot fly or charcoal rot (Patil et al., 2014). In the case of maize landraces, results from field experiments demonstrate that landraces have a higher degree of plant defense mechanisms like herbivore-induced plant volatiles, an advantage in defending themselves against pest damage (Tamiru et al., 2011). This performance only occurred in certain landraces and was undetectable in the tested F1-hybrid varieties. The landraces attracted not only egg parasitoids but also larval parasitoids (Tamiru et al., 2011). Tamiru et al. (2011) conclude that these defense traits of plants against herbivores may have been lost over time due to crop breeding toward high yields at the cost of other traits.

When farmers were asked about the ecological benefits of landraces over modern varieties, most argued that landraces are better adapted to the local environment and are more resistant to pests and diseases (Olson et al., 2012). For instance, farmers had no problem with the potato beetle (Leptinotarsa decemlineata) before the implementation of modern potato varieties. This pest resistance, in combination with other benefits, was the reason why almost 90% of the respondents preferred landraces to modern varieties (Calvet-Mir et al., 2011).

Biodiversity richness and pollination

Biodiversity richness (n = 1) and crop pollination (n = 1) are neglected topics and information about comparing landraces against modern varieties is missing.

LANDRACE PROMOTE REGULATING ECOSYSTEM SERVICES

Overall, we detect a positive effect of local landraces on regulating ecosystem services. They are a valuable source for resistance genes (like indirect plant defense mechanisms), which may have become lost during crop breeding (Tamiru et al., 2011; Calvet-Mir et al., 2011; Patil et al., 2014), and are better adapted to local climate conditions (Olson et al., 2012). Landraces are often cultivated in complex landscapes (riparian strips, forest remnants, single big trees, hedgerows, orchards, etc.), which may further improve the local biodiversity and its functional benefits such as regulating ecosystem services.

Cultural services

According to the MEA (2005), cultural ecosystem services are the "nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreating, and aesthetic experiences" (MEA, 2005). Within the reviewed literature, five publications are directly relating to cultural services (four surveys among small-scale farmers, one experiment). All publications state a positive influence of choosing landraces over modern varieties on providing people with cultural ecosystem services. These services include traditional values, cooking characteristics, nutritional values, as well as taste and color of harvested crops or prepared dishes.

Findings from farmer surveys

Farmers and related user groups deciding for or against a landrace in comparison to modern varieties link different functional preferences for landraces related to various cultural services. Li et al. (2012) asked 162 farmers in semi-structured interviews the reasons maintaining landraces on their fields. One identified reason was pressure from the social environment (13% of respondents), meaning that the landraces play an important role within their traditional food culture. In a study from the Iberian Peninsula on the general use of landraces, the question "Why do you consider the conservation of landraces important?" (Calvet-Mir et al., 2011) provided the following responses: (1) taste and the nutritional value (37.5%), (2) tradition and food security (25%), and (3) ideological reasons (16.7%), although the respondents also stated that extra work in making seedbeds is seen as an disadvantage of cultivating landraces (18.7%). The remaining three studies analyze the impact of choosing maize landraces over modern varieties in South America. In an example from Bolivia by Zimmerer (2014), small-scale farmers state that varieties must be suitable for diverse food items such as maize beer (chicha), toasting, soup thickener, and further maize-based foods and drinks. Zimmerer (2014) concludes that each landrace maintains certain cooking characteristics and that the high diversity of landrace varieties in the region is a major part of the overall agrobiodiversity. This example in Bolivia shows that a high degree of landrace diversity not only supports the production of local food types but also reduces the risk of crop failure through variety diversification.

Findings from field experiments

In a study from El Salvador, Olson et al. (2012) investigated different seed types in milpa pots to understand the value of "agroecological and livelihood variables." Farmers stated that farmers' seed markets (were landraces are traded), are more reliable concerning information about the varieties than the commercial seed market, allowing best fitting choices (see **Figure 2**). Additionally, seeds from the farmers' seed markets were lower in cost and can be re-produced. These findings are in line with the results from Mexíco by Moreno et al. (2006), who found the main reasons for persisting local maize landraces in small-scale farming systems is their popularity and high value of cooking characteristics, nutritional values, taste, and color. Other farmers also stated that—although landraces are harder to process compared to modern varieties—they are much tastier. The recipes for their families' special maize dishes are even passed over the generations together with the according landrace varieties (2005).

Figure 2: Diversity of potato varieties on a local market in Peru, October 2015.

LANDRACE PROVIDE CULTURAL ECOSYSTEM SERVICES

Small-scale farmers in many developing countries still prefer local landrace varieties because they fill social and cultural niches that modern varieties are lacking (Tripp, 1994; Brush and Meng, 1998; Thrupp, 2000; Zimmerer, 2014). Cooking characteristics are a classical example for these cultural services (Calvet.Mir et al., 2011; Zimmerer, 2014). In our review we found primary scientific evidence from South America concerning maize landraces. But the role of traditional farming practices including traditional varieties like landraces as providers for cultural services is becoming increasingly recognized globally. In conclusion, the use of landraces is a potential way to achieve social-ecological resilience, i.e., the capacity of human-environment systems to absorb shocks induced by changes, so that the system continues to support human well-being (Chapin et al., 2010; Biggs et al., 2015). Adapted varieties in turn play a key role for socio-ecosystematic processes within small-scale farming systems (Chappell, 2013). In conclusion in-depth knowledge of the cultivation and cooking characteristics of landraces can therefore be seen as fundamental for biocultural diversity as it interlinks biodiversity knowledge with the diversity of cultures and human societies (Maffi and Dilts, 2014).

General conclusion

The results of this review show that small-scale farmers evaluate a multitude of crop features before deciding for or against a given variety. From crop yield to resilience toward environmental changes to taste or storage characteristics and finally family traditions, landraces represent a portfolio of desired plant performances. With this review, we illustrate that local landraces are in many cases better adapted to local farming conditions, do not need as much agrochemical resource input compared to modern varieties, and maintain a diversity of regionally and/or personally specified performances. In some cases, modern varieties become replaced again by landraces due to their higher resistance to pests, diseases, and abiotic stresses, which may help to meet the needs of sustainable agriculture systems facing global climate change. As a part of traditional agricultural systems landraces continue to evolve and adapt to changing social, ecological, and environmental systems. Embedding variety decision in the ecosystem service framework of the Millennium Ecosystem Assessment illustrates that landraces can provide farmers and related user groups with high provisioning services under changing climate conditions because of their resilience under sub-optimal farming conditions. In comparison to modern varieties, landraces are often a trusted source for small-scale farmers globally, achieving stable crop yield with longer storability of the harvest. With specialized resistance genes and other features such as indirect plant defense mechanisms these varieties also provide farmers with regulating services that may be lacking in many cases of modern plant breeding. With regard to food security, landraces are in many cases better adapted to local, environmentally diverse farming conditions and require less artificial resource input compared to modern varieties. With that, they are a valuable component of agrobiodiversity that decreases the vulnerability of agroecosystems to global change. Our results underline the significance of landraces for provisioning and regulating ecosystem services, which needs to be better acknowledged by regional and global authorities.

In addition, small-scale farmers often prefer local landraces to modern varieties due to typical cultural features like family traditions and cooking characteristics for special dishes. In many cases, farmers recognize the role of landraces for the fulfillment of personal non-agronomic features. The diversity of landraces is therefore a viable part of various ways of living and farming, sustaining vivid cultures. Our review shows that genetic diversity and freedom to choose from a large variety pool is a substantial part of cultural ecosystem services and sovereign food production. Unfortunately, cultural ecosystem services are often neglected, but need to be much better acknowledged as a vital part of satisfying living standards.

Last not least, the current legal framework regulating seed usage and variety protection needs to be taken into account. Since seeds and varieties are the foundation for food production, their free access—including the right to save and replant seeds, the right to share seeds and the right to use seeds to breed new varieties—is often considered as a mandatory part for sovereign agriculture and nutrition (Kloppenburg, 2014). Landraces are often maintained and developed in informal, commons-based seed systems, such as participatory breeding arrangements (Wenzel and Wilbois, 2011; Galie, 2013) and seed exchange systems (Calvet-Mir et al., 2012; Pautasso et al., 2013). Such systems need to be acknowledged by national and international authorities to provide small-scale farmers with a stable and independent livelihood—an essential part toward food sovereignty.

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Supplementary

Table S1: List of included 41 publications comparing landraces against other variety types. (Declaration of the comparing variety type according to the used term in the publication)

Paper	Landrace	Comparing variety type	Crop species	Country	Approach	Results within the field of:	Plus/minus/ unclear effect
1. Biasi 2015	LR	NO	Grapewine	Italy	Experiment	Crop pollination Biodiversity richness Resilience to environmental changes	plus plus Plus
2. Li J. et al. 2012	LR	F1-Hybrid	Maize	China	Survey (semi-structured interviews)	Resilience to environmental changes Crop yield Tradition, cooking characteristics, nutritional values, taste, and color	Plus Minus Plus
3. Tamiru A. et al. 2011	LR	F1-Hybrid	Maize	Kenya	Experiment	Biological pest & disease control	Plus
4. Munoz-Perea et al. 2007	LR	cultivar	Dry bean	Western USA	Experiment	Resilience to environmental changes	Plus
5. Sangabriel-Conde W. et al. 2014	LR	F1-Hybrid	Maize	Mexico	Experiment	Crop nutrient use efficiency	Plus
6. Fang Y. et al. 2011	LR	Improved variety	Winter wheat	China	Experiment	Crop yield Crop nutrient use efficiency	Plus/minus Plus
7. Noguera D. et al. 2011	LR	F1-Hybrid, improved variety	Rice	Columbia	Experiment	Crop yield	Plus/minus
8. Lafitte H. R. et al. 1997	LR	Improved cultivar	Maize	Mexico	Experiment	Crop yield Crop nutrient use efficiency	Minus Plus
9. Ghosh R. et al. 2014	LR	Improved cultivar	Chickpea	India	Experiment	Crop yield	Minus

10. Fang Y. et al. 2014	LR	Modern cultivar	Winter wheat	China	Experiment	Crop yield	Minus
11. Annicchiarico P. et al. 2012	LR	Local cultivar	Lucerne	Italy	Experiment	Crop yield	Unclear
12. Vaezi B. et al. 2010	LR	Genotype	Barley	Iran	Experiment	Crop yield Resilience to environmental changes	Unclear Plus
13. Brocke K. et al. 2014	LR	Improved variety	Sorghum	Bukina Faso	Experiment	Resilience to environmental changes Crop yield	Plus Plus
14. Mwololo J.K. et al. 2012	LR	F1-Hybrid	Maize	Kenya	Experiment	Biological pest & disease control	Unclear Unclear
15. Knezevic-Jaric J.et al. 2014	LR	F1-Hybrid	Maize	Eastern Serbia	Survey (interview-based open-ended questions)	Resilience to environmental changes Crop yield Storage ability	Plus Minus Plus
16. Calvet-Mir L. et al. 2011	L R	Commercial variety	several	Iberian Peninsula	Survey (semi-structured interviews)	Biological pest & disease control Resilience to environmental changes Crop yield Cultivation effort and crop storability Tradition, cooking characteristics, nutritional values, taste, and color	Plus Plus Minus Minus Plus
17. Yadav O. et al. 2010	LR	Improved variety	Pearl millet	India (Rajasthan)	Experiment	Resilience to environmental changes Crop yield	Plus Plus
18. Annicchiarico P. et al. 2007	LR	Improved variety	Lucernce	Italia	Experiment	Crop yield	Unclear
19. D'Antuono L.F. et al. 2006	LR	Commercial variety	Lineseed, flax	Italy	Experiment	Resilience to environmental changes	Plus

						Crop yield	Unclear
20. Vom Brocke K. et al. 2003	LR	Modern variety	Pearl millet	India (Rajasthan)	Experiment	Resilience to environmental changes Crop nutrient use efficiency	Plus Unclear
21. Boutraa T. et al. 2001	LR	Cultivar	Common bean	Great Britain	Experiment	Crop yield	Plus
22. Moreno L. et al. 2006	LR	Improved variety	Maize	Mexico	Survey (semi-structured interviews)	Biological pest & disease control Cultivation effort and crop storability Tradition, cooking characteristics, nutritional values, taste, and color	Plus Plus Plus
23. Mazvimbakupa F. et al. 2015	LR	F1-Hybrid	maize	NA	Experiment	Resilience to environmental changes Crop yield	Plus Minus
24. Kolech S. A. et al. 2015	LR	Improved variety	potato	Ethiopia	Survey (data collection of socio-economic situation of farmers, variety assessment and identification of farmers)	Resilience to environmental changes Nutritional status of plants	Plus Plus
25. Leiser W. L. et al. 2015	LR	Research bred line	Sorghum	Mali (West Africa)	Experiment	Resilience to environmental changes Crop yield	Plus Plus
26. Patil J.V. et al. 2014	LR	F1-Hybrid	Sorghum	India	Conceptual paper	Biological pest & disease control Resilience to environmental changes	Plus Plus

						Crop yield	Plus
27. Yong'an L. et al. 2010	LR	Modern variety	Spring wheat	China	Experiment	Resilience to environmental changes	Plus
						Crop yield	Unclear
28. Olson M.B. et al. 2012	LR	Improved variety	Maize	El Salvador	Survey (semi-structured interviews and focus groups)	Biological pest & disease control	Minus
						Resilience to environmental changes	Plus
						Crop yield	Minus
						Tradition, cooking characteristics, nutritional values, taste, and color	Plus
29. Almekinders C. et al. 2007	LR	Improved variety	NA	Bolivia	Conceptual paper	Resilience to environmental changes	Plus
30. Bardsley D. et al. 2005	LR	Improved variety	Wheat	Northeastern Turkey	Survey (semi-structured, interactive, open-ended interviews approach with farmers and stakeholders)	Biological pest & disease control	Minus
						Resilience to environmental changes	Plus
						Crop yield	Unclear
31. Annicchiarico P. et al. 2006	LR	Improved variety	Lucerne	Italy	Experiment	Resilience to environmental changes	Plus
						Crop yield	Plus
32. Maggs-Kolling G.L. et al. 2003	LR	Modern variety	Watermelon	Namibia	Experiment	Resilience to environmental changes	Unclear
						Crop yield	Plus
						Cultivation effort and crop storability	Unclear
33. Joshi D.K.et al. 2001	LR	Popular variety	Rice	Nepal & India	Survey	Crop yield	Plus

					(semistructured interviews)		
34. Newton A.C. et al. 2010	LR	Improved variety	cereals	NA	Conceptual paper	Biological pest & disease control Resilience to environmental changes Crop nutrient use efficiency	Plus Plus Plus
35. Zimmerer K.S. 2014	LR	NA	Maize	Bolivia	Survey (semi-structured interviews)	Resilience to environmental changes Tradition, cooking characteristics, nutritional values, taste, and color	Plus Plus
36. Oupkaew P. et al. 2011	LR	Landrace	Rice	Thailand	Survey (farmers' interviews and rapid appraisals of seed selection of farmers)	Biological pest & disease control Crop yield	Unclear Plus
37. Anastasi U. et al. 2017	LR	Improved variety	Sesame	Italy	Experiment	Crop yield Cultivation effort and crop storability	Unclear Plus
38. Fang Y. et al. 2017	LR	Modern cultivar	Winter wheat	China	Experiment	Crop nutrient use efficiency	Minus
39. Fenzi M. et al. 2017	LR	Improved variety, F1-Hybrid	Maize	Mexico	Experiment	Resilience to environmental changes	Plus
40. Sánchez-Martín J. et al. 2017	LR	Commercial variety	Oat	Mediterranean region (Spain and Egypt)	Experiment	Biological pest & disease control Crop nutrient use efficiency	Plus Unclear
41. Kante M. et al. 2017	LR	F1-Hybrid	Sorghum	Africa	Experiment	Resilience to environmental changes	Minus

CHAPTER THREE: HYBRID, CONVENTIONAL AND ORGANIC UNDER DROUGHT

Similar Yield Benefits of Hybrid, Conventional, and Organic Tomato and Sweet Pepper Varieties Under Well-Watered and Drought-Stressed Conditions

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Abstract

Global agrobiodiversity is threatened by the replacement of traditional, locally adapted crop varieties with high-yielding and hybrid varieties during the past 60 years, resulting in associated losses of crop, variety, and allele diversity. Locally adapted, traditional varieties are known to perform equal or even better under environmental stress conditions and to be more resilient in unstable cultivation environments. Therefore, European organic vegetable breeding organizations conserve local, traditional varieties and breed new varieties in low-input organic environments, aiming to increase the range of varieties for sustainable cultivation under sub-optimal growing conditions. However, performance of organic vegetable varieties, in comparison to conventional high-yielding and hybrid varieties, under different environmental conditions has not been intensively researched. To contribute to this scientific field, we compared the agronomic and quality performance between hybrid, conventional, and organic tomato and sweet pepper varieties, two economically important species on the EU market under a) well-watered and b) drought stress conditions, using five different varieties (i.e., 30 varieties) as replicates in each of the six groups. Performance of both species was negatively affected by drought, regardless of the breeding background. Equally, for tomato and sweet pepper, hybrids produced higher amounts of individual fruits, however total yield in kg was comparable for hybrid, conventional and organic plants. Considering the agro-ecological importance of enlarging and securing variety diversity in light of changing environmental conditions, we show that the assumed benefits of the hybrids can also be delivered by the organic and conventional varieties. These varieties should be considered as an important source of genetic resources, supporting farmers to adapt to their local climate and environmental conditions in the future.

Keywords

Agrobiodiversity; drought stress; genetic diversity; seed commons; sustainable vegetable production; variety comparison; vegetable breeding

Introduction

Agrobiodiversity and the associated diversity of crop varieties is one of the global keystones in farming to secure stable harvest and livelihood under changing environmental and socio-economic conditions (FAO, 2018). A major ongoing threat to agrobiodiversity is the loss of traditional, locally adapted crop varieties equally for cereal, and vegetable species (MEA, 2005). One relevant reason for this loss is the replacement of traditional, open-pollinated varieties with commercial high-yielding and hybrid varieties during the past 60 years, resulting in a genetic bottleneck for crop, variety, and allele diversity (Gmeiner et al.,2018; Nemeskéri and Helyes, 2019). In the vegetable sector, the share of hybrid seeds on the market is increasing worldwide by about 8–10% per year (Da Silva Dias, 2010; Department of Agriculture Cooperation, 2012). At the same time, genetic resources in the form of vegetable variety diversity are declining all over the world at a rate 1–2% annually (Da Silva Dias, 2010

This progressive concentration on a limited amount of commercial high-yielding and hybrid varieties is further promoted by usage restrictions via patents and variety protection laws and the privatization of seed material (Kotschi and Wirz,2015; Messmer et al., 2015). Improvements in plant breeding techniques, such as field selection methods, use of inbred-lines creating F1-hybrids, laboratory techniques at the tissue or cell level, and techniques at DNA level have made high-yielding and hybrid varieties to a reliable source for high harvest quantity and quality under well-adjusted, optimal growing conditions, despite the often higher charged price for the seeds (Riggs,1988; Ficiciyan et al., 2018). However, locally adapted, traditional varieties can deliver equal or even higher yields under suboptimal conditions and are known to be more resilient in unstable cultivation environments (Ficiciyan et al., 2018).

The increase of drought periods and their higher frequency is thereby currently one of the most critical environmental stress factors, lowering productivity in both, arable and vegetable production (Kumar et al., 2012; Kahiluoto et al., 2019). Especially, vegetable species are known for their high drought sensitivity during flowering and seed development (Kumar et al., 2012; Nemeskéri and Helyes, 2019), and yield reductions through drought occur in important species such as tomato, sweet pepper, bean, and sweet corn (Kumar et al., 2012). Thus, for agro-ecological and organic farming systems, a high diversity of crop varieties – including locally adapted, traditional varieties – is considered to support the resilience of vegetable production systems under unpredictable future weather conditions (Kumar et al., 2012; Conti et al., 2019).

Hence, more and more organic plant breeding organizations are scaling up on the European plant breeding sector, aiming to enlarge the diversity of vegetable varieties and to offer alternatives to high-yielding and hybrid varieties that still deliver reasonable yields, but are resistant against diseases and can cope with adverse local growing conditions such as limited water supply. Driven by a heightened awareness of consumers, these organizations conserve traditional varieties and develop new varieties under organic standards without synthetic pesticides and fertilizers (Gmeiner et al., 2018). Organic plant breeding rejects techniques such as genetically modified organisms, protoplast fusion, *in vitro* propagation, and induced mutation. Hybrid breeding is also avoided as it is not conducive to maintain genetic diversity (Lammerts van Bueren and Struik, 2004; Messmer et al., 2015). Another notable aspect of organic breeding is the rejection of plant variety protection via patents or private property protection. Most organic breeding organizations believe that commons-based rights, as opposed to private protection, on seeds and varieties are essential for a social-ecological transformation of plant production (Kotschi and Wirz, 2015; Gmeiner et al., 2018). To our knowledge, no study has yet tested experimentally the performance of well-replicated sets of organic vegetable varieties in comparison to commercial high-yielding and hybrid varieties under different environmental conditions. To fill this knowledge gap, we used tomato and sweet pepper varieties as model species in this study and tested the following hypotheses:

I. Compared to organic and commercial high-yielding varieties, hybrids perform best in terms of yield, yield stability and yield quality under optimal, well-watered conditions.
II. The overall performance (yield, yield stability, yield quality) of organic varieties is higher under drought stress than that of commercial high-yielding and hybrid varieties.

We focused on tomato (*Solanum lycopersicum* L.) and sweet pepper (*Capsicum* spp.) as model species, since they are economically highly important for the EU vegetable market and popular among consumers. Moreover, tomatoes and sweet peppers are known to be sensitive to drought at all development stages, which underlines the necessity to identify drought tolerant varieties (Suguru et al., 2003; Wahb-Allah et al., 2011; Rossi, 2019).

Material and methods

This experiment was carried out in a greenhouse (180 m^2, graveled area with water supply) with two open sides and a translucent *Perspex* roof of the experimental botanical garden of the University of Göttingen between March and October 2017. Cultivating the plants in the open-sided greenhouse allowed controlling soil moisture while the environmental parameters in the greenhouse stayed under nearly natural light and temperature conditions (detailed information on location and climate data see **Supplementary Annex 2**). The experiment took place as a pot experiment to investigate the performance of the plants under controlled, standardized conditions, minimizing potential confounding effects of heterogeneous biotic and abiotic factors (Schwarz et al., 2014; **Figure 1**).

We designed our study to experimentally compare variety groups from (i) hybrid breeding under conventional farming methods (*hybrid group*) (ii) open-pollinated high-yield breeding under conventional farming methods *(conventional group*), and (iii) open-pollinated organic breeding/conservation under organic farming methods (*organic group*) under well-watered as well as drought stress conditions.

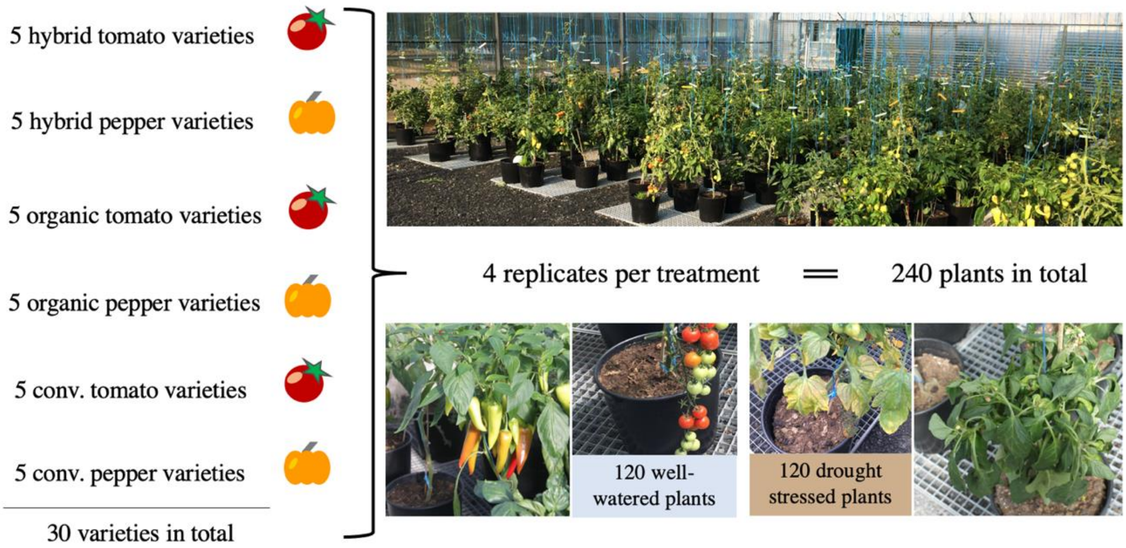

Figure 1: Experimental setup including 15 tomato and 15 sweet pepper varieties. In a randomized block design (above picture) with 4 replicates per treatment the whole experiment contained 120 well-watered plants (60 tomato and 60 sweet pepper plants, left pictures) and 120 drought stressed plants (also 60 tomato and 60 sweet pepper plants, right pictures).

Each of these six groups consisted of five varieties (i.e., all together 15 tomato and 15 sweet pepper varieties involved) as replicates. The groups were tested for agronomic performance in terms of yield (total fresh harvested weight and number of fruits), as well as yield stability (variability of yield between varieties of one breeding group), and quality performance expressed in fruit quality (commercial quality classes).

Organic varieties came from the German organic vegetable breeding and preservation association *Kultursaat e.V.* (sold by *Bingenheimer Saatgut AG*). Hybrid and conventional varieties came from the *Bruno Nebelung GmbH*, selling conventional varieties under the *Kiepenkerl* label. All varieties have a variety approval according to the German Seed Marketing Act (Verbraucherschutz, 2018). One dwarf variety of the conventional group (Vilma) was heavily infected by botrytis and thus had to be removed from the second half of the experiment, to avoid infestation of the other plants. Furthermore, the variety Pyros of the conventional tomato group turned out to be a hybrid instead of an open-pollinated variety and had to be excluded from the analysis. A detailed description of all varieties that were finally included in the analysis can be found in **Supplementary Annex 1**. The hybrid tomato and sweet pepper varieties were highest in retail price with 0.66 Euro and 0.75 Euro per seed (**Table 1**). For tomato price per seed for varieties from the hybrid group was thus 3.5 times higher than that of the organic group and 5 times higher than that of the conventional group (**Table 1**). For sweet pepper price per seed for varieties from the conventional group was in the mid-range with 0.47 Euro per seed, followed by the price for organic sweet pepper seeds, which was lowest with 0.23 Euro (**Table 1**).

Table 1: Averaged retail seed price for hybrid, organic, and conventional tomato and sweet pepper varieties.

	Tomato varieties	**Sweet pepper varieties**
Group	Averaged price per seed[a]	Averaged price per seed[a]
Hybrid	0.66 Euro	0.75 Euro
Organic	0.19 Euro	0.23 Euro
Conventional	0.13 Euro	0.47 Euro

Prices were taken from the 2017 price list.
[a]Retail price year 2017.

In a randomized block design with four repetitions, each variety was planted under well-watered conditions and under drought stress. Since the experiment was repeated four times, a total of eight plants (four drought stressed plants plus 4 well-watered plants) were tested for each variety, resulting in a total number of 240 pots (**Figure 1**). We used 15-liter plastic pots filled with 15 liters of Hawita Typ T [pH-value ($CaCl_2$) =5.9, salinity in g/KCl = 2.9, nitrogen (N) in mg/l ($CaCl_2$) = 180, Phosphate (P_2O_5) in mg/l (CAL) = 180, Kalium (K_2O) in mg/l (CAL) = 260, Magnesium (Mg) in mg/l ($CaCl_2$) = 130]. Plants were watered by hand to treat well-watered and drought stress plants differently and in a standardized way. Drought stress was controlled manually in every corresponding pot using a HH2 Moisture Meter from Delta T Devices designed for field use. Water content in the substrate of 9 to 14% was taken to represent drought stress, and between 15 and 20% was considered optimal. Water content below 9% was considered under supply.

Percentages were determined in a preliminary test. Plants with drought stress showed significantly lower turgor pressure (visible through soft leaves and stalks as well as hanging heads) and the substrate should be detached from the pot edge. However, plants were able to regain turgor after reapplication of water in order to survive. Plants were alternatingly fertilized with nitrogen (Wuxal Top N−12% N, 4% P, 6% K) and phosphorus (Wuxal Top P−5% N, 20% P, 5% K) liquid fertilizer, directly mixed into the water according to the mixing ratio recommended by the suppliers. All plants were tied with synthetic baler twine to the ceiling, and tomato plants were thinned out once a week to reduce branching. During the flowering period, two bumble bee colonies were installed between the plants to support pollination.

Harvest

The harvest period covered 9 weeks from the 12th of July to the 14th of September 2017 with fifteen harvest events. At each harvest event (15 harvest events in total), we only harvested individual, ripe tomato and sweet pepper fruits and no complete trusses from the tomato plants. The harvested fruits were collected separately for every plant in individual plastic boxes, marked with the plant and treatment information, and subsequently counted, weighted and subdivided into commercial classes by the same person. We used the regulations for marketing standards for tomatoes and sweet pepper provided by the Federal Office for Agriculture and Food in Germany, which are in accordance with the law in the European Union [Commission Implementing Regulation (EU) No 543/2011, 2011]. We identified 10 different types of deficiency symptoms for commercial class two and minus on the fruits: too small fruits, apical-blossom end rot, gold flecking, color defects, greenbacks, scab, shaping errors, sun burn, color errors, and botrytis (see **Figure 2**).

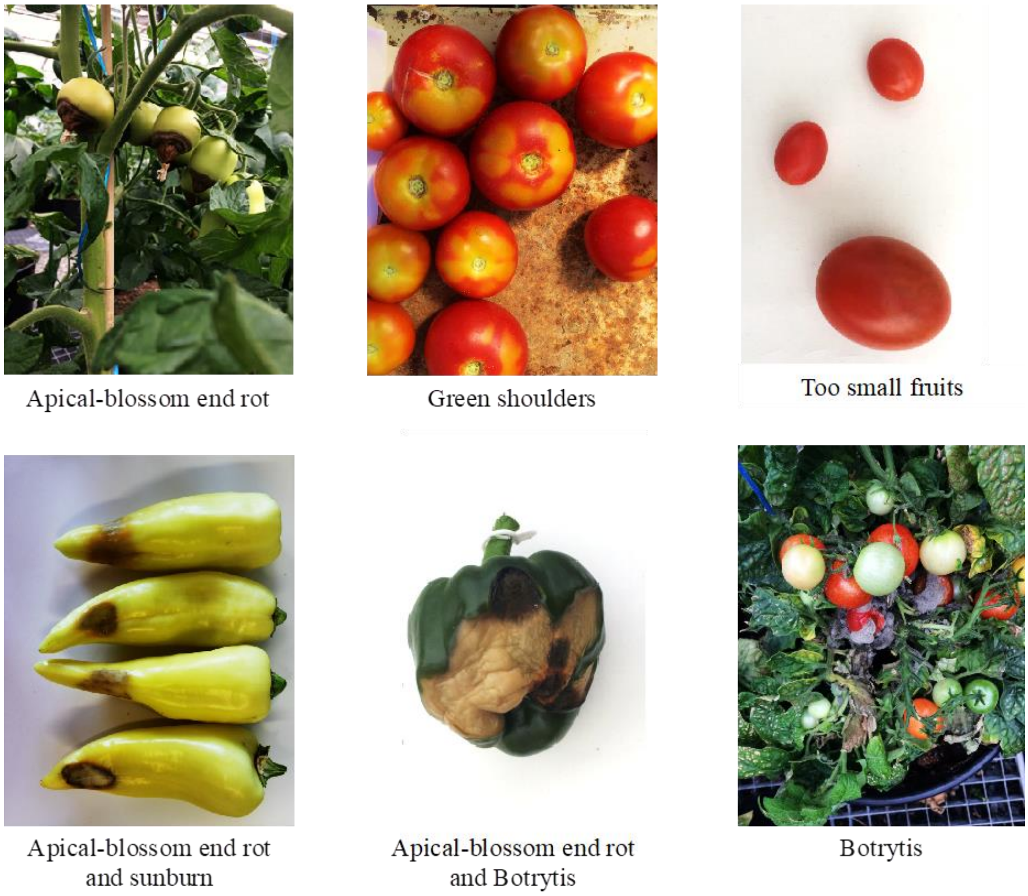

Figure 2: Selection of deficiency symptoms recorded on tomato and pepper fruits. Affected fruits were categorized into commercial class 2 (green shoulders, too small fruits) or minus (botrytis, apical-blossom end rot). Symptoms were detected equally on hybrid, organic and conventional varieties.

Statistical analyses

All statistical analyses were performed using R version 3.6.1 (R Core Team, 2019). We analyzed the performance of the tomato and sweet pepper varieties separately.

For analyzing tomato and sweet pepper yield, we used fruit number and fresh fruit weight (in grams) per plant as the dependent variables in a zero-inflated negative binomial generalized, linear mixed-effect model, using Template Model Builder ("GlmmTMB" Package). Row (1 – 6), treatment (control or drought), and group (hybrid, organic, conventional), were set as fixed factors. Harvest date was set as a crossed random effect. "GlmmTMBs" fit linear and generalized linear mixed models with various extensions, including zero-inflation. The models were fitted using maximum likelihood estimation (Brooks et al., 2019). For the tomato varieties, fruit number and fruit weight data were not normally distributed. For fruit weight, breeding background caused zero-inflation. For fruit number, zero inflation was independent of predictor variables. For the sweet pepper varieties fruit number and weight were also not normally distributed. Zero-inflation was caused by the harvest event ($p < 0.001$) equally for fruit number and weigh.

Zero-inflation was checked using the "DHARMa" package that provides a number of plot and test functions for overdispersion and zero-inflation. In "DHARMa," zero-inflation is accounted for by running the model excluding all zeros caused by the corresponding predictor variable (Hartig, 2019). Final model selection was done by AIC comparison and visual plot analysis. Differences in means were controlled with *post hoc*-tests using the "emmean" package (Lenth et al., 2019). Correlation between fruit number and fruit weight was checked with Spearman-Rank Correlation.

Likewise, for tomato and sweet pepper fruit quality we used the number of fruits per class summed up over all harvest events as the dependent variable. Here too, row (1 – 6), treatment (control or drought), and breed (hybrid, organic, conventional), were set as fixed factors. Number of fruits was summed up over the whole harvest period. For the final model, we used a negative binomial generalized linear mixed ("lme4" package) because the data showed overdispersion. The negative binomial regression model adds a multiplicative random effect for unobserved heterogeneity (Rodríguez, 2013). Again, we controlled for the overdispersion using the "DHARMa" package. Final model selection was also done by AIC comparison and visual plot analysis. Differences in means were tested with *post hoc*-tests using "emmean" package (Lenth et al., 2019).

To evaluate yield stability for hybrid, organic, and conventional tomato and sweet pepper varieties under the control and drought treatment, we calculated and plotted the coefficient of variation for fruit weight and fruit number over the whole harvest period. We used the R package "cvequality" (Marwick and Krishnamoorthy, 2019) and run asymptotic tests to test for significant differences between the coefficients of variation from hybrid, organic, and conventional varieties.

Results

Tomato Results

Agronomic Performance – Yield and yield Stability

Tomato plants under well-watered conditions ($N = 56$ plants) produced a total of 86 kg fresh tomatoes, and plants under drought stress ($N = 56$ plants) a total of 35 kg over the whole harvest period (see **Table 3**). The "GlmmTMB" model showed that drought stress resulted in significantly lower fruit weight and fruit number for the hybrid organic and the conventional group ($p < 0.001$, **Table 2**, see **Figure 3A**). Comparing the three groups revealed that the loss rate for fruit weight under drought stress was similar, with minus 58% for the hybrid, minus 64% for the organic, and minus 51% for the conventional group. For fruit number we found a lower productivity rate of minus 25% for the hybrid group, minus 31% for the organic, and minus 9% for the conventional group under drought stress (**Table 3**). Despite some plant failures within the conventional group (see methods section), the number of fruits of the conventional group under drought stress only decreased by 9%, and thus considerably less than the other two groups. However, fruit weight loss was equivalently high under drought stress. This means that the conventional group produced many, but relatively small fruits under drought stress.

Overall, the hybrid group produced with a total of 3,499 fruits significantly more fruits than the organic (2,161 fruits) or conventional (796 fruits) group, equally under well-watered conditions and drought stress (**Table 2**). Within all three groups, fruit number and fruit weight were positively correlated. The correlation was highest within the conventional group ($R = 0.92$, $p < 0.001$). The coefficients of variation showed no difference in the stability of fruit weight and fruit number between the hybrid, organic, or conventional group.

Table 2: Factors influencing agronomic performance via fruit weight and fruit number of tomato plants as dependent variables.

Agronomic performance				
Fruit weight (g)	**(Intercept)**	**(i)**	**(ii)**	**(iii)**
IRR*	206.62	0.91	1.03	0.45
SE*	0.10	0.05	0.06	0.05
CI*	170 – 250	0.82 – 1.01	0.92 – 1.17	0.41-0.49
St*	54.51	-1.69	0.56	-17.03
P*	<0.001	0.091	0.578	**<0.001**
Marginal R^2 = 0.162	Conditional R^2 = 0.257			
Fruit number				
IRR	6.14	0.76	0.40	0.78
SE	0.25	0.08	0.13	0.06
CI	3.7 – 10.0	0.65-0.89	0.3 – 0.52	0.69-0.89
St	7.19	-3.39	-6.87	-3.81
P	<0.001	**0.001**	**<0.001**	**<0.001**
Marginal R^2 = 0.069	Conditional R^2 = 0.438			

Treatments were (i) = organic breeding, (ii) = conventional breeding, and (iii) = drought stress. Intercept represents well-watered, hybrid plants. N = 1024 observations for tomato plants.

* IRR, Incidence Rate Ratio; SE, Standard Error; CI, Confidence Interval; St, Statistics; P, P-value. Bold values show significance.

Table 3: Total sum, mean and standard deviation (sd) of fruit weight and fruit number over the whole harvesting period (N = 15 harvest events) per hybrid, organic, and conventional (= Conv.) group under well-watered conditions and drought stress.

	Tomato plants		**Sweet pepper plants**	
Group	**Well-watered**	**Drought stressed**	**Well-watered**	**Drought stressed**
Hybrid fruit weight	Sum = 34.3 kg Mean = 131.85 g Sd = 151.45 g	Sum = 14.4 kg Mean = 55.21 g Sd = 73.94 g	Sum = 29.5 kg Mean = 210.47 g Sd = 312.93 g	Sum = 10.3 kg Mean = 73.39 g Sd = 116.67 g
Hybrid fruit number	Sum = 2003 Mean = 7.7 Sd = 10.4	Sum = 1496 Mean = 5.8 Sd = 8.2	Sum = 346 Mean = 2.5 Sd = 3.9	Sum = 204 Mean = 1.5 Sd = 2.2
Organic fruit weight	Sum = 32.6 kg Mean = 125.40 g Sd = 162.31 g	Sum = 11.7 kg Mean = 44.75 g Sd = 62. 89 g	Sum = 23.2 kg Mean = 165.67 g Sd = 256.72 g	Sum = 8.3 kg Mean = 59.01 g Sd = 102.2 g
Organic fruit number	Sum = 1279 Mean = 4.9 Sd = 5.9	Sum = 882 Mean = 3.4 Sd = 4.7	Sum = 241 Mean = 1.7 Sd = 2.7	Sum = 164 Mean = 1.2 Sd = 2.0
Conv. fruit weight	Sum = 19.2 kg Mean = 110.95 g Sd = 150.32 g	Sum = 9.4 kg Mean = 53.43 Sd = 71.34 g	Sum = 25.1 kg Mean = 179.14 g Sd = 305.35 g	Sum = 9.7 kg Mean = 69.53 g Sd = 114.23 g
Conv. fruit number	Sum = 416 Mean = 2.4 Sd = 3.4	Sum = 380 Mean = 2.2 Sd = 3.2	Sum = 228 Mean = 1.6 Sd = 2.6	Sum = 166 Mean = 1.2 Sd = 1.9

Quality Performance – Yield Quality

Of all 6,456 harvested fruits, 62% (4,024 fruits) were categorized as *marketable* for the retail sector, fulfilling the quality requirements for commercial class extra and one. The remaining 2,432 fruits (38%) were categorized here as *non-marketable* (commercial class two, for further processing, or minus, completely non-marketable).

Drought stress had no negative impact on the number of marketable fruits produced per group. However, the number of non-marketable fruits was lower in plants under drought stress (p = 0.017, **Table 4**). Within-group comparisons showed that the hybrid group produced 63% marketable and 37% non-marketable fruits and the organic group 66%

marketable and 34% non-marketable fruits. The conventional group differed noticeable from the other two groups with only 49% marketable and 51% non-marketable fruits. Since the hybrid group produced significantly more fruits in general, this is also reflected in the higher share of marketable and non-marketable fruits in comparison to the organic (p = 0.025 for marketable fruits, p = 0.001 for non-marketable fruits, **Table 4**) or conventional group (p < 0.001 for marketable and non-marketable fruits, **Table 4**).

Table 4: Factors influencing on quality performance via the number of marketable and non-marketable fruits for tomato plants.

Quality performance				
	(Intercept)	**(i)**	**(ii)**	**(iii)**
Marketable fruits				
IRR*	62.19	0.63	0.22	0.79
SE*	0.17	0.20	0.22	0.17
CI*	45.13-87.98	0.42-0.95	0.14 – 0.34	0.56-1.11
St*	24.48	-2.24	-6.82	-1.37
P*	<0.001	**0.025**	**<0.001**	0.172
Nagelkerke R^2	0.413			
Non-marketable fruits				
IRR	36.66	0.59	0.41	0.73
SE	0.13	0.16	0.17	0.13
CI	28.93-47.10	0.43 – 0.79	0.29 – 0.57	0.56-0.95
St	28.40	-3.44	-5.38	-2.39
P	<0.001	**0.001**	**<0.001**	**0.017**
Nagelkerke R^2	0.379			

Treatments were (i) organic breeding, (ii) conventional breeding, and (iii) drought stress. Intercept represents well-watered, hybrid plants, N = 112 observations for tomato plants.

* IRR, Incidence Rate Ratio; SE, Standard Error; CI, Confidence Interval; St, Statistics; P, P-value. Bold values show significance.

Sweet Pepper Results

Agronomic Performance – Yield and Yield Stability

Sweet pepper plants under well-watered conditions (N = 60 plants) produced a total of 78 kg fresh sweet peppers, and plants under drought stress (N = 60 plants) produced a total of 28 kg sweet peppers (see **Table 3**). The "GlmmTMB" model showed that drought stress resulted in significantly lower fruit weight for all three groups ($p < 0.001$, **Table 5**, see **Figure 3B**). The loss rate under drought stress for fruit weight was with minus 65% for the hybrid, minus 64% for the organic, and minus 61% for the conventional group similar in all three groups. Drought stress also lowered the number of fruits compared to well-watered plants ($p < 0.001$, **Table 5**). Comparing the three groups in terms of fruit number shows a loss rate of minus 41% for the hybrid group, minus 32% for the organic, and minus 27% for the conventional group (**Table 3**).

Overall, the hybrid group produced with a total of 550 fruits significantly more fruits than the organic (405 fruits) or conventional (394 fruits) group, equally under well-watered conditions and drought stress (**Table 5**). For all three groups fruit number and fruit weight were positively correlated ($R = 0.97–0.99$, $p < 0.001$). Testing for the equality of coefficients of variation showed no difference in the stability of fruit weight and fruit number between the hybrid, organic, and conventional group.

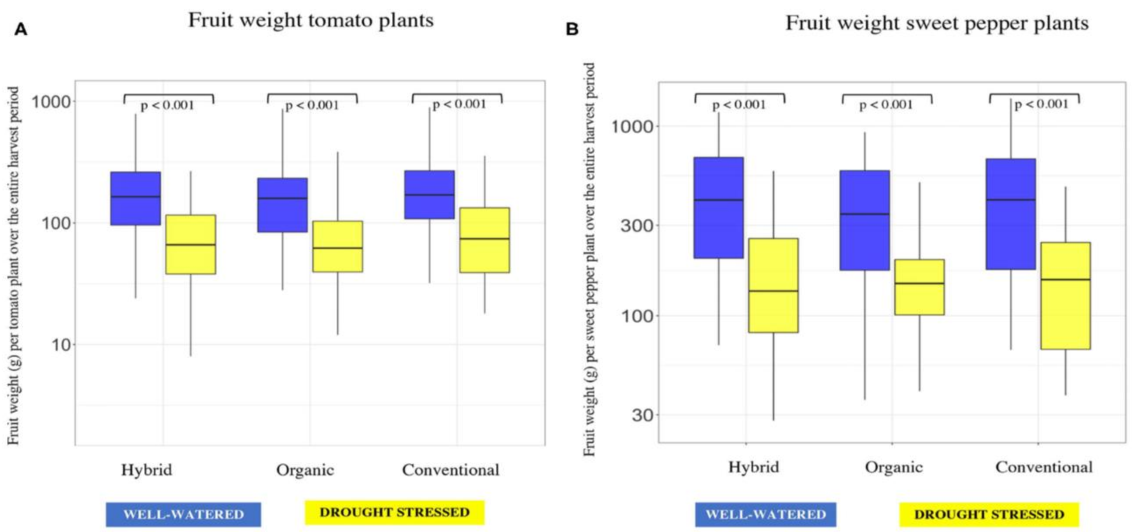

Figure 3: Comparison of fruit weight in grams per plant on average over the entire harvest period between the hybrid, organic, and conventional groups for tomato (**A**) and sweet pepper plants (**B**) under well-watered conditions and drought stress. Differences between treatments were significant equally for tomato and sweet pepper ($p < 0.001$). Each boxplot shows median (line within the box), lower and upper quartile (box), and range (whiskers).

Table 5: Factors influencing agronomic performance via fruit weight and fruit number of sweet pepper plants as dependent variables.

Agronomic performance				
Fruit weight (g)	**(Intercept)**	**(i)**	**(ii)**	**(iii)**
IRR	173.66	0.89	1.01	0.49
SE	0.73	0.08	0.08	0.07
CI	41.5 - 727	0.76.-1.03	0.87-1.18	0.43 - 0.56
St	7.06	-1.55	0.16	-10.39
P	<0.001	0.122	0.875	**<0.001**
Marginal R^2 = 0.024	Conditional R^2 = 0.679			
Fruit number				
IRR	1.89	0.75	0.74	0.66
SE	0.58	0.11	0.11	0.09
CI	0.61- 5.83	0.61 - 0.94	0.59 - 0.92	0.55 - 0.80
St	1.10	-2.54	-2.67	-4.33
P	0.271	**0.011**	**0.008**	**<0.001**
Marginal R^2 = 0.015	Conditional R^2 = 0.555			

Treatments were (i) = organic breeding, (ii) = conventional breeding, and (iii) = drought stress. Intercept represents well-watered, hybrid plants. N = 840 observations for sweet pepper plants.

* IRR, Incidence Rate Ratio; SE, Standard Error; CI, Confidence Interval; St, Statistics; P, P-value. Bold values show significance.

Quality Performance – Yield Quality

From all 1,349 harvested peppers, 63% (853 fruits) were categorized as *marketable* for the retail sector, fulfilling the quality requirements for commercial class extra and one. The remaining 496 fruits (37%) were classified as *non-marketable* (commercial class two, for further processing, or minus, completely non-marketable). Drought stress lowered both the amount of marketable and non-marketable fruits to an equal extend ($p < 0.001$, **Table 6**). The hybrid group produced significantly more marketable fruits than the organic ($p = 0.006$, **Table 6**) or conventional group ($p = 0.001$, **Table 6**). The proportional distribution (in %) within the individual group reveals that the hybrid group produced the highest proportion of marketable fruits with 68 and 32% non-marketable fruits. The organic group produced 63%

marketable and 37% non-marketable fruits. Comparable to the tomato results, the distribution was worst within the conventional group with 57% marketable and 43% non-marketable fruits.

Table 6: Factors influencing on quality performance via the number of marketable and non-marketable fruits for sweet pepper plants.

Quality performance				
	(Intercept)	**(i)**	**(ii)**	**(iii)**
Marketable fruits				
IRR*	14.73	0.66	0.58	0.33
SE*	0.12	0.15	0.16	0.13
CI*	11.41 – 18.27	0.49 – 0.89	0.43 – 0.79	0.25 – 0.42
St*	22.51	-2.73	-3.46	-8.57
P*	<0.001	**0.006**	**<0.001**	**<0.001**
Nagelkerke R^2	0.594			
Non-marketable fruits				
IRR	3.13	0.80	0.95	1.88
SE	0.17	0.21	0.21	0.17
CI	2.27 – 4.41	0.53 – 1.20	0.63 – 1.42	01.34 – 2.63
St	6.65	-1.08	-0.27	3.69
P	<0.001	0.281	0.785	**<0.001**
Nagelkerke R^2	0.154			

Treatments were (i) organic breeding, (ii) conventional breeding, and (iii) drought stress. Intercept represents well-watered, hybrid plants, N = 120 observations for sweet pepper plants.
* IRR, Incidence Rate Ratio; SE, Standard Error; CI, Confidence Interval; St, Statistics; P, P-value. Bold values show significance.

Discussion

In this study we expected that drought stress generally lowers the agronomic and quality performance of all plants. We tested whether the organic tomato and sweet pepper group outperforms the conventional and hybrid group under drought stress, whereas hybrid plants were supposed to deliver highest yield and fruit quality under well-watered conditions. We show that the assumed benefits of the hybrid group can also be delivered by the organic and conventional group, emphasizing the value of securing the organic and conventional diversity in vegetable varieties in changing environmental conditions.

Equivalent Negative Effect of Drought Stress on Organic, Conventional, and Hybrid Varieties

We confirm the negative effect of drought stress on the agronomic and quality performance of all plants, regardless of the breeding background. In line with our results from the drought stress treatment, pepper is known to be highly at risk to limited water supply due to the large leaf surface and high stomata conductance (Alvino et al., 1994). In Nigeria, for e.g., exporting sweet pepper used to be highly important for farmers' incomes in the 1980s. However, due to rainfall limitations, sweet pepper yield in Nigeria decreased in recent decades up to 40% (Showemimo and Olarewaju, 2007). Mardani et al. (2017) tested the effect of different deficit irrigation levels (80, 60, 40%) and demonstrated a water supply below 80% of the optimum significantly reduced sweet pepper yield (fresh mass of fruit per plant) compared to fully irrigated treatment. Similar to our experimental drought stress, highest yield reduction was obtained when drought stress occurred continuously over the whole plant development phase until the time of harvesting (Mardani et al., 2017). Previous studies have also shown the negative effects of drought stress (combined with high air temperatures) on tomato fruit yield (Wahb-Allah et al., 2011; Cui et al., 2020). Santa Rosa et al. (2019) tested tomato hybrids against open-pollinated varieties under organic conditions and showed that hybrids in their study were more productive and resistant to biotic and abiotic stresses. They highlighted that for low-input systems the farmers' choice should not be between hybrids or open-pollinated varieties, but rather the most appropriate choice for the local growing conditions. Furthermore, hybrids which are more productive and resistant can thereby increase the economic output of organic tomato cultivation (Santa Rosa et al., 2019).

Organic and Conventional Varieties Deliver Similar Fruit Weight as Hybrids

The fact that hybrid varieties show a better agronomic and quality performance under optimal cultivation conditions was clearly proven in previous studies and is also shown under the well-watered conditions in our experiment. Similar to our results, Dowker and Gordon (1983) revealed that onion hybrids outperform commercial open-pollinated varieties by 14 to 67%. The same was demonstrated by Wehner (1999) for carrots, showing higher fruit quality for hybrids, leading to 25–30% higher marketable yield over open-pollinated varieties. Hybrid broccoli varieties over-yielded open-pollinated varieties by 40–90%, also pushed by the greater quality characteristics of the hybrids (Wehner, 1999). Also, tomato species are known to have a high hybrid potential, improving early ripening, uniformity, resistance against pest and diseases, as well as total yield (Cheema and Dhaliwal, 2005). However, comparing the total fruit weight of the hybrid group with the organic group in this study revealed that the organic group only produced 9% (4 kg) less total fruit weight. In relation to the total harvest period and the total harvested qualities, a plus of 9% from the hybrid group can be considered marginal. Moreover, since the effect of drought stress and the proportionate distribution of marketable and non-marketable fruits within each group was similar, we did not find that any of the three groups was better adapted to drought stress. Differences became clear in the total number of fruits, as the hybrid group produced 38% more fruits than the organic group. Our findings showed a high market potential of the tested tomato hybrids. However, since fruit weight was similar, it means that the organic group produced bigger fruits compared to the hybrid group. Thus, the conventional tomato group did not offer a satisfactory alternative to the hybrid or organic group since it included varieties that were either highly susceptible to diseases or produced fruits with a high tendency to crack and burst.

Combining our results with previous findings from e.g., Santa Rosa et al. (2019), we highlight that increasing the diversity of crop varieties for vegetables supports resilient and sustainable vegetable cultivation. The greater the supply of genetic diversity in the form of different varieties, the greater the opportunities for farmers to adapt to their local climatic and environmental conditions. From an agro-ecological point of view, certain varieties (whether hybrid, conventional, or organic) should not be rated better or worse *per se*, but rather the overall supply of genetic diversity should be seen as an opportunity to simultaneously enlarge agrobiodiversity and maintain high agronomic and quality performance of a cultivation systems. However, vegetable farmers worldwide increasingly rely on high-yielding and hybrid varieties because of their typically higher provisioning services such as crop yield, and sometimes, also due to lack of variety alternatives (Lammerts van Bueren and Struik, 2004). This is because many seeds of local, traditional and organic varieties are often not available or not in sufficient quantities, despite their potential of adaptation to sub-optimal growing conditions.

Tomato Variety Conservation in Europe

In Europe, countries of the Mediterranean region have recently begun to promote and test local tomato varieties, including landraces in order to protect and increase genetic diversity with tomato varieties selected under severe drought conditions of the Mediterranean summer (Conti et al., 2019; Fullana-Pericàs et al., 2019). Fullana-Pericàs et al. (2019) tested 165 tomato genotypes from the Mediterranean basin and other diverse locations around the world, including landraces and modern varieties under well-watered and water-limited conditions. Their results highlighted that several landraces performed similarly or even better compared to modern varieties in terms of minimizing yield reduction under drought stress (Fullana-Pericàs et al., 2019). Italy promotes the protection and recovery of local tomato varieties on the national level (Conti et al., 2019). Analyses of the response of Italian varieties to drought stress indicated that locally, hot summer adapted varieties can include a "genotype-dependent response" to drought (Conti et al., 2019). Techawongstien et al. (1992) found that pepper varieties from different sweet pepper types responded differently to drought stress. Drought tolerance was higher in genotypes of high leaf water potential, leading to early recovery of the corresponding "photosynthetic ability upon rehydration" and lower negative effect on final fruit yield (Techawongstien et al., 1992). Besides the studies of Santa Rosa et al. (2019) and Fullana-Pericàs et al. (2019) for tomato varieties and Techawongstien et al. (1992) for sweet pepper varieties, the number of previous studies comparing vegetable varieties from different breeding regimes under drought stress is low. Therefore, we are providing new information in an agronomically important field, the role of vegetable variety diversity under environmental stress like limited water supply.

Highest Seed Price for Hybrids—Balance Between Profitability and Equity

For both tomato and sweet pepper, the performance of the hybrid group compared to the organic and conventional group may be related to the total costs incurred in the breeding and cultivating process. Across all vegetable species, higher purchase prices for hybrid seeds are due to higher cost of variety development and seed production (Riggs, 1988). Also, in our study, retail price was highest for the hybrid tomato and sweet pepper seeds. Notably, there is no private property protection of organic seeds. These two factors, price and non-profit ownership, might justify slightly lower total yields of the organic group and emphasize the importance of variety alternatives for sustainable vegetable production. Thus, the inclusion of varieties without legal usage restrictions as a common pool resource on the market for seeds may contribute to the social-ecological balance between profitability and equity of different farming systems by increasing the sovereignty of the farmers (Kremen et al., 2012).

Conclusions

With our results we challenge the widely held assumption that conventional and organic varieties cannot be seen as equivalent alternatives to hybrids. Thus, these varieties should be considered as important for maintaining a diverse variety portfolio for local adaptation to unstable climate and water-supply conditions. Especially varieties of the organic group, which are not protected via private property rights, should be considered essential for the sustainability of vegetable production. A system, including all variety options will be the most efficient and equitable way to offer varieties for all kinds of farming and growing systems. Simultaneously, the use of open-pollinated varieties will expand genetic diversity in the vegetable breeding sector. In this sense, a wide range of varieties represents an important component of agrobiodiversity, and access to locally adapted varieties is and will be pivotal for crop production under expanding drought periods and further climate extremes.

Data availability statement: The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions: AF, JL, and TT developed the methodology and the experimental design, wrote and edited the manuscript, and approved the final version of the manuscript. AF performed the experiment. All authors contributed to the article and approved the submitted version.

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Supplementary

Annex 1: Variety list

Organic tomato varieties: Sunviva, St. Pierre, Bogus Fruchta, Dorenia, and Trixi

Organic sweet pepper varieties: Fernec Tender, Liebesapfel, Yolo Wonder, Panthos, and Afrodita

Conventional tomato varieties: Ananas, Roma, Matina, Vilma, (and Pyros excluded)

Conventional sweet pepper varieties: Topgirl, Sweetgreen, Yollow California Wonder, Roter Augsburger, and Polka

Hybrid tomato varieties: HartzfeuerF1, VispolinoF1, RomelloF1, ArielleF1, and PozzanoF1

Hybrid sweet pepper varieties: ColettiF1, LozornoF1, PinokkioF1, SkytiaF1, and AmboyF1

Tomato varieties			
Variety name	**Plant and fruit type; fruit ripeness time**	**Approx. Fruit weight**	**Breeder and extra variety information**
Organic varieties			
Sunviva	Stake type; round, cherry tomato; yellow color; early ripeness	20 g	Breeder: Dr. Bernd Horneburg (organic outdoor tomato cultivation / University Göttingen); Open-source licensed
St. Pierre	Stake type; round, beef tomato; red color; medium ripeness	100-150 g	Propagated by: Stefan Penov; EU-Bio certification
Bogus Fruchta	Bush type; round, normal sized; red color; early ripeness	40 g	Breeder: Kultursaat e.V. / Christoph Matthes; Propagated by: Matthias Funk; Demeter certification
Dorenia	Stake type; round, normal sized; red color; early/medium ripeness	Ca. 80 – 100 g	Breeder: Kultursaat e.V. / C. Matthes; authorization: Amateur variety (AS) with official approval according to Directive 2009/145 / EC
Trixi	Cherry type; round, oval; red color; medium ripeness	20 g	Breeder: Kultursaat e.V. / Silke Wedemeyer; authorization: Amateur variety (AS) with official approval according to Directive 2009/145 / EC

Conventional varieties			
Ananas	Stake type; beef tomato; red color; medium ripeness	200-300 g	*Kiepenkerl profi-line* for commercial and home-garden cultivation
Roma	Stake type; roma-, plum tomato; red color; medium/late ripeness	80-90 g	*Kiepenkerl profi-line* for commercial and home-garden cultivation
Matina	Stake type; round, oval; red color; early ripeness	50-100 g	*Kiepenkerl regional-historical line*; breeder: Hild Seeds GmbH, Germany
Vilma	Bush type; round, cherry tomato; red color; medium ripeness	15-20 g	*Kiepenkerl profi-line* for commercial and home-garden cultivation
F1-Hybrid varieties			
Harzfeuer F1	Stake type; round/oval; red color; early/medium ripeness	50-100 g	Breeder: Dr. Friedrich Fabig (East Germany - Quedlinburg 1961)
Vespolino F1	Stake type; plum, cherry tomato; red color; early/medium ripeness	30 g	*Kiepenkerl profi-line* for commercial and home-garden cultivation; Breeder: Herlaar, Frits (Westwoud, NL)Mooij, Marcellinus Jacobus Johannes (Bovenkarspel, NL) 2011 - United States Patent Application 20100306870 (http://www.freepatentsonline.com/20100306870.pdf); robust against tomato mosaic virus, nematodes and Fusarium-wilt
Romello F1	Bush type; plum, cherry tomato; red color; early/medium ripeness	10-30 g	*Kiepenkerl profi-line* for commercial and home-garden cultivation; Origin: Great Britain, 2013; robust against blight and brown rot
Arielle F1	Stake type; cherry tomato; red color; early/medium ripeness	10-30 g	*Kiepenkerl profi-line* for commercial and home-garden cultivation

Pozzano F1	Stake type; san Marzano type; red color; medium ripeness	150 g	*Kiepenkerl profi-line* for commercial and home-garden cultivation; Robust against tomato mosaic virus as well as Verticulum-, and Fusarium-wilt

Sweet pepper varieties			
Variety name	**Plant height; fruit type; fruit color**	**Approx. fruit length or weight**	**Breeder, extra variety information**
Organic varieties			
Fernec Tender	Ca. 80 cm plant height; pointed fruit type; yellow/red color	10-12 cm	Breeder: ReinSaat; Propagated by: Stefan Penov; EU Bio certification
Liebesapfel	Ca. 80 cm plant height; oval/round fruit type; red color	Ca. 150 g	Breeder: organic-dynamic conservational breeding; Propagated by: Gärtnerhof Oldendorf, Hofgut Rengoldshausen / Ulrike Behrendt; *Amateur-variety*
Yolo Wonder	Ca. 80 cm plant height; block fruit type; red color	Ca. 200 g	Breeder: organic-dynamic conservational breeding; Propagated by: Azienda agricola Sol Ribaldo, Erdmuthe Weißer, Gärtnerei der Lebensgemeinschaft Bingenheim, Gärtnerei Piluweri, Hofgut Rengoldshausen, Sativa Rheinau, Vita Verde; Bioland and Demeter certification
Panthos	Ca. 80 cm plant height, pointed fruit type, red color	20 cm	Breeder: Kultursaat e.V. / R. Specht; Propagated by: Matthias Funk, Gärtnerei Piluweri; Demeter certification
Afrodita	Ca. 80 cm plan height; block type; yellow color	200 g	Breeder: organic-dynamic conservational breeding; Propagated by: Gärtnerei der Lebensgemeinschaft Höhenburg / Matthias Funk; Demeter certification
Conventional Varieties			

Topgirl	70-100 cm plant height; oval/round freuit type; red color	100-150 g	*Kiepenkerl profi-line* for commercial and home-garden cultivation
Sweetgreen (E. 42.0088)	Ca. 70 cm plant height; block type; green color; high vitamin C content	180-210 g	*Kiepenkerl profi-line* for commercial and home-garden cultivation; Resistant against: Viruses, cracks, apical blossom end rot
Yellow California Wonder	Ca. 80 cm plant height; block type; yellow color	Ca. 200 g	*Kiepenkerl* standard line;
Roter Augsburger	Ca. 80 cm plant height; pointed type; red color	12 cm	*Kiepenkerl profi-line* for commercial and home-garden cultivation; Regional/historical variety
Polka	Ca. 80 cm plant height; block type; red color	Ca. 200 g	*N.L. Chrestensen* line; Resistant against Tomato mosaic virus; Cold-resistant
F1-Hybrid varieties			
Coletti F1	Ca. 80 cm plant height; block type; yellow color	Ca 8-9 cm; 150-180 g	*Kiepenkerl profi-line* for commercial and home-garden cultivation; Robust against tomato mosaic virus
Lozorno F1	Ca. 70 cm plant height; block type; green-red color	Ca. 150 g	*Kiepenkerl standard line;* Regional/historical variety
Pinokkio F1	Ca. 80 cm plant height; pointed type, yellow-red color	Ca. 20 cm	*Kiepenkerl profi-line* for commercial and home-garden cultivation; Resistant against tomato mosaic virus
Skytia F1	70-80 cm plant height; pointed type; white color	12-18 cm	*Kiepenkerl standard line;* Regional/historical variety
Amboy F1	80 cm plant height; pointed type, red color	15 cm	*Kiepenkerl profi-line* for commercial and home-garden cultivation

Annex 2: location and climate data

The city of Göttingen is located in the transitional area between maritime and continental climates of the temperate latitudes.

Coordinates: 51° 38' northern width

Height: 171 meter above sea level

Annual average temperature: 9.9 °C

Average total precipitation: 750.8 mm

Average temperature, daily maximum and minimum, day length and average relative humidity at the Göttingen site between March and October 2017. The data was taken from the Göttingen weather station database (see: http://www.wetterstation-goettingen.de/wetterarchiv-2017.html)

Month	Average temp. °C	T max. °C	T min. °C	Daylength	Average relative humidity (%)
March	7.6	22.4	-1.7	12 h	77.3
April	7.7	21.8	-3.8	14 h	74.9
May	14.8	32.3	0.7	16 h	75.1
June	17.5	33.2	7.4	17 h	76.2
July	18.1	32.4	9.1	16.5 h	79.1
August	17.3	29.1	5.7	14.5 h	79.4
September	12.9	22.6	3.0	13 h	83.5
October	11.5	22.3	5.0	10.5	87.2

CHAPTER FOUR: VARIETY COMPARISON IN MIXED-CROPPING UNDER WEED STRESS

Better Performance of Organic than Conventional Tomato Varieties in Single and Mixed-cropping

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Abstract

Replacing traditional crop varieties with commercial, high-yielding varieties during the last decades is one of the main drivers for the decline in farmland and crop diversity. However, it is unclear how commercial, high-yielding varieties adapt to less environmental conditions such as weed pressure and mixed cropping cultivation systems. In Europe, organic breeding organizations conserve local, traditional varieties and develop new varieties under low-input conditions, aiming at increasing the range of varieties adapted to harsh cultivation conditions and mixed cropping. To evaluate whether organic varieties (i) cope better with weed pressure and (ii) have a higher adaptability to mixed cropping, we compared the agronomic and quality performance of eight organic varieties with eight commercial, high-yielding varieties, focusing on tomato, the economically most important vegetable in the EU. Each group was cultivated as single plants and in a mixed cropping system respectively with a legume and with or without exposure to weed stress by a grass. The organic group outperformed the commercial, high-yielding group, specifically, in mixed cropping systems. Weed stress lowered yield of both groups, but the organic group showed higher fruit weight stability across the varieties than the commercial, high-yielding varieties when grown as single plants under weed stress.

Keywords

Agrobiodiversity, genetic diversity, organic breeding, variety comparison, vegetable diversity, weed stress

Introduction

Providing food for up to 9.8 billion people in 2050, while simultaneously protecting agrobiodiversity and ecosystem services, is one of the greatest challenges of our time

(Zimmerer, 2017). A major threat to agrobiodiversity and ecosystem services is the loss of traditional crop varieties (MEA, 2005). One of the reasons for this loss is their replacement with commercial, high-yielding varieties (MEA, 2005). Through advanced plant breeding techniques in the last decades, commercial varieties have been greatly improved towards standardized, high crop performance at low production costs, including concurrent ripening, uniformity in color, nutrition value and fruit size within cost-efficient, intensified farming systems (Van de Wouw et al., 2010; Casals et al., 2011).

Nowadays, these commercial, high-yielding varieties - mostly bred by few private companies, closely linked to the chemical industry - dominate the global seed market (Da Silva Dias, 2010). As a consequence, also organic farmers with cultivation systems where pesticides and synthetic fertilizers are not allowed, often rely on commercial varieties because of their convenient yield, as it has been shown for globally important crops like maize (Lafitte et al., 1997; Li et al., 2012), sorghum (Kante et al., 2017), and wheat (Murphy et al., 2007). However, regulating services such as resistance against crop stresses seem to be declining during breeding for commercial, high-yielding varieties, and especially weed stress challenges organic and particularly outdoor vegetable production, as chemical weed control is forbidden and hand weeding is a tremendous cost factor (Niggli and Dierauer, 2000; Gianessi and Reigner, 2007; La Selva, 2019).

One approved strategy for low-input and organically managed production systems to reduce weed stress and thereby push yields, is mixing different species and varieties on the same production unit (Bohlool et al., 1992; Peoples et al., 2009; Ponisio et al., 2009; Abouziena and Haggag, 2016). Due to complementary resource use of species and varieties, so called mixed cropping systems can outcompete monocultures (Anders et al., 1996). In organic farming, mixed cropping with legumes is a popular way to enhance the nitrogen supply for the main crop and simultaneously suppress weeds through shading (Edwards, 1989; Pimentel et al., 2005; Paulsen et al., 2006; Ahmad et al., 2017). However, especially breeding of commercial, high-yielding varieties for and in monoculture systems seems to lower the performance of varieties in plant mixtures (Chacón-Labella et al., 2019). Thus, there is increased recent interest in traditional crop varieties conserved under organic conditions and varieties specifically bred for organically managed production systems to be implemented in mixed cropping systems (Lammerts van Bueren et al., 2011; Stagnari et al., 2013).

In general, traditional varieties tend to be lower in yield than commercial ones, but may deliver a range of regulating services (e.g., over-yielding in mixtures, weed competition, nutrient uptake, resistance to pests and diseases) under non-optimal growing conditions where commercial varieties may perform worse (Annicchiarico, 2006; Noguera et al., 2011; Vom Brocke et al., 2014; Ficiciyan et al., 2018, but see Voss-Fels et al., 2019).

As a result, in Europe organic breeding organizations are scaling up on the market for vegetable varieties, aiming to enlarge the diversity of varieties and thereby offer alternatives to commercial, high-yielding varieties that still deliver reasonable yields, but can cope with adverse local growing conditions such as weed pressure. These organizations conserve traditional varieties and develop new varieties under organic standards without synthetic pesticides and fertilizers (Gmeiner et al., 2018). Organic plant breeding rejects techniques such as genetically modified organisms, protoplast fusion, *in vitro* propagation, and induced mutation. Hybrid breeding is also avoided as it is not conductive to maintain genetic diversity (Lammerts van Bueren and Struik, 2004; Messmer et al., 2015). From the start on in the phases of crossing and selection, organic plant breeding, as well as variety development and conservation, takes place under organic farming conditions and must harmonize with the guiding principles of organic agriculture (Messmer et al., 2015). Neither chemical synthetic pesticides nor mineral fertilizers are allowed under organic regulations. Selection criteria therefore include plant types with a morphology intended to provide weed suppression through, for example, shading.

To our knowledge, no study has yet tested experimentally whether varieties from the organic breeding approach perform better under suboptimal cultivation conditions and in mixed cropping than conventional high-yielding varieties.

To fill this knowledge gap, we used tomato as model species in this study and tested the following hypotheses:

I. Compared to commercial, high-yielding varieties, organic varieties produce higher yield, yield stability, and quality under weed pressure.

II. The overall performance (yield, yield stability, yield quality) of the organic varieties is higher in mixed cropping systems with a legume than the performance of the commercial, high-yielding varieties.

We focus on tomato (*Solanum lycopersicum L.)*, the economically most important vegetable produced in the EU, generating about 20% of the overall vegetable output value (Rossi, 2019). Being the most popular vegetable crop, tomato is also the most cultivated vegetable species worldwide on round about 4.7 million ha under diverse conditions, ranging from open-field, low-input systems to controlled greenhouse and pot production (Schwarz et al., 2014). As there is a wide portfolio of different tomato varieties available on the market and tomato cultivation is relatively easy, it makes tomato a popular model plant for experimental studies (Schwarz et al., 2014).

Material and methods

This experiment was carried out in a greenhouse (180 m^2, graveled area with water supply) with two open sides and a translucent *Perspex* roof of the experimental botanical garden of the University of Göttingen between April and October 2018. The experiment took place as a pot experiment to investigate the performance of the plants under controlled, standardized conditions, minimizing potential confounding effects of heterogeneous biotic and abiotic factors (Schwarz et al., 2014; **Figure 1**). Cultivating tomato plants in pots with minimum 12 liters for commercial production as well as experimental purposes is a simple to handle and control system and therefore recommended (Schwarz et al., 2014). Cultivating the plants in the open-sided greenhouse allowed to protect the plant against extreme weather events, while the environmental parameters in the greenhouse stayed under nearly natural light and temperature conditions.

We designed our study to experimentally compare two groups of open-pollinated tomato varieties. One variety group consisted of eight different varieties from high-yielding breeding under conventional farming methods (conventional group) and the other group consisted of eight different varieties from organic conservation and breeding under organic farming methods (organic group). We established four different treatments to test the two groups' performance: (i) single tomato plants under weed stress (ii) single tomato plants without weed stress as control group (iii) legume mixed cropped tomato plants under weed stress and (iv) legume mixed cropped tomato plants without weed stress as control group (**Figure 1**). The conditions of the cultivation system were equal in terms of soil, fertilizer, irrigation and microclimate for both groups.

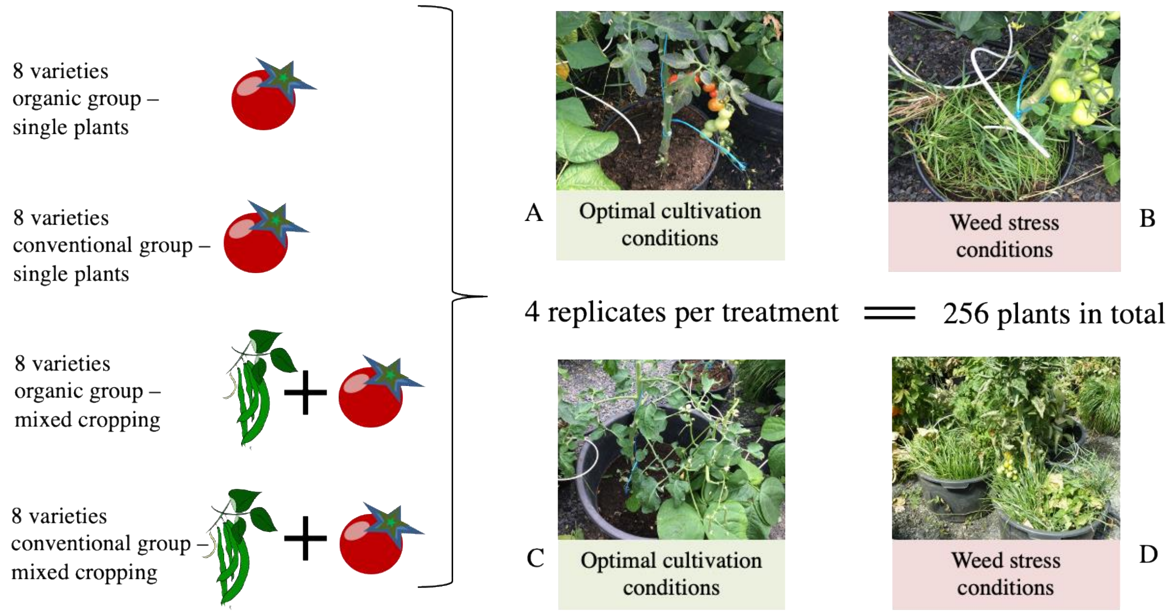

Figure 1: Experimental set up including 16 tomato varieties (8 of the organic and 8 of the conventional group) in a randomized block design with four replicates per treatment. The whole experiment contained 64 single plants under optimal cultivation conditions (A), 64 single plants under weed stress (B), 64 mixed cropped plants under optimal cultivation conditions (C) and 64 mixed cropped plants under weed stress (D).

Each of these four groups consists of eight varieties as replicates. The groups were tested for agronomic performance in terms of yield (total fresh harvested weight and number of fruits), as well as yield stability (variability of yield between varieties of one breeding group), and quality performance expressed in fruit quality (commercial quality classes).

Experimental set-up

Varieties of the organic group came from the German organic vegetable breeding and preservation association *Kultursaat e.V.* (sold by *Bingenheimer Saatgut AG*). Varieties of the conventional group came from the *Bruno Nebelung GmbH*, selling varieties under the label *Kiepenkerl*. *Kiepenkerl* varieties are either bred direly by the company or purchased from trading companies around the globe. All varieties have been approved according to the Germany Seed Marketing Act (Verbraucherschutz, 2018). A detailed description of all varieties can be found in **Supplementary Annex 1**. We used dwarf beans (*Phaseolus* *vulgaris*) as a legume for mixed cropping. Selection of dwarf beans for mixed cropping with organic tomato varieties came also from *Kultursaat e.V.* and *Kiepenkerl* for mixed cropping with tomato varieties of the conventional group.

In a randomized block design with four repetitions, each variety was planted as single plans under optimal and weed stress cultivation conditions, as well as in mixed cropping with a legume also under optimal and weed stress cultivation conditions. We randomly mixed one tomato variety of the conventional group with a conventional dwarf bean variety and one organic tomato variety with one organic dwarf bean variety. Since the experiment was repeated four times, a total of 16 plants (four single control plants, four single plants under weed stress, four mixed cropping control plants, four mixed cropping weed stressed plants) was tested for each variety.

We used 15 liter plastic pots for single plants under optimal and weed stress cultivation conditions, and 60 liter plastic pots (filled with 30 liter substrate) for mix cropping under optimal and weed stress cultivation conditions, resulting in a total of 256 pots (**Figure 1**). Distance between the pots was set between 10 and 20 cm.

Pots were filled with *Hawita Typ T*, produced on the basis of German peat [pH-value ($CaCl_2$) = 5.9, salinity in g KCl = 2.9, nitrogen (N) in mg/l ($CaCl_2$) = 180, phosphate (P_2O_5) in mg/l (CAL) = 180, potassium (K_2O) in mg/l (CAL) = 260, magnesium (Mg) in mg/l ($CaCl_2$) = 130], and 150 g of horn shavings. During the whole cultivation period no fertilizer was added nor did we apply any pesticides or other plant protection products. Weed stress treatment was implemented by transplanting two handfuls of rhizomes and whole plant parts of couch grass (*Elymus repens*) (extracted from an organic field in the surrounding of Göttingen) into the corresponding buckets on the same day. We choose couch grass because it is highly competitive, rapidly multiplies and reduces crop yield in most agricultural crops. Couch grass is a major threat to yield in most conventional and organic outdoor farming systems

(Holzner and Glauninger, 2005; Burrill et al., 2012). Plants were irrigated with an automatic dripping system, supplying the small pots with a flow rate of water of 2 liter per hour and the big pots with 4 liter per hour. Each pot was equipped with two drippers to ensure an even water distribution in the pot. We manually fitted the period of irrigation with a watering computer to the daily climate conditions, ranging from two times per day for 30 minutes (very hot days) to 20 minutes every 48 hours (cool days). Tomato plants were tied up with synthetic baler twine to the ceiling, and thinned out once a week – a common practice in commercial and home garden tomato cultivation – to achieve a straight growing plant. During the flowering period, two bumble bee colonies were installed next the plants on from the 20th of June on to support pollination.

Harvest period

The harvest period covered ten weeks from of July to September 2018 with eight harvest events. At each harvest event (eight in total) we only harvest individual, ripe tomato fruits and no complete trusses from the tomato plants. The harvested fruits were collected separately for every plant in individual plastic boxes and marked with the plant and treatment information. Harvested fruits were counted, weighed and subdivided into commercial classes by the same person. We used the regulations for marketing standards for tomatoes provided by the Federal Office for Agriculture and Food in Germany, which are in accordance with the law in the European Union (Commission Implementing Regulations, 2011). We identified five different types of deficiency symptoms for commercial class two and minus on the tomato fruits: defects in development and size, apical-blossom end rot, gold flecking, color defects, and greenbacks (see **Figure 2**).

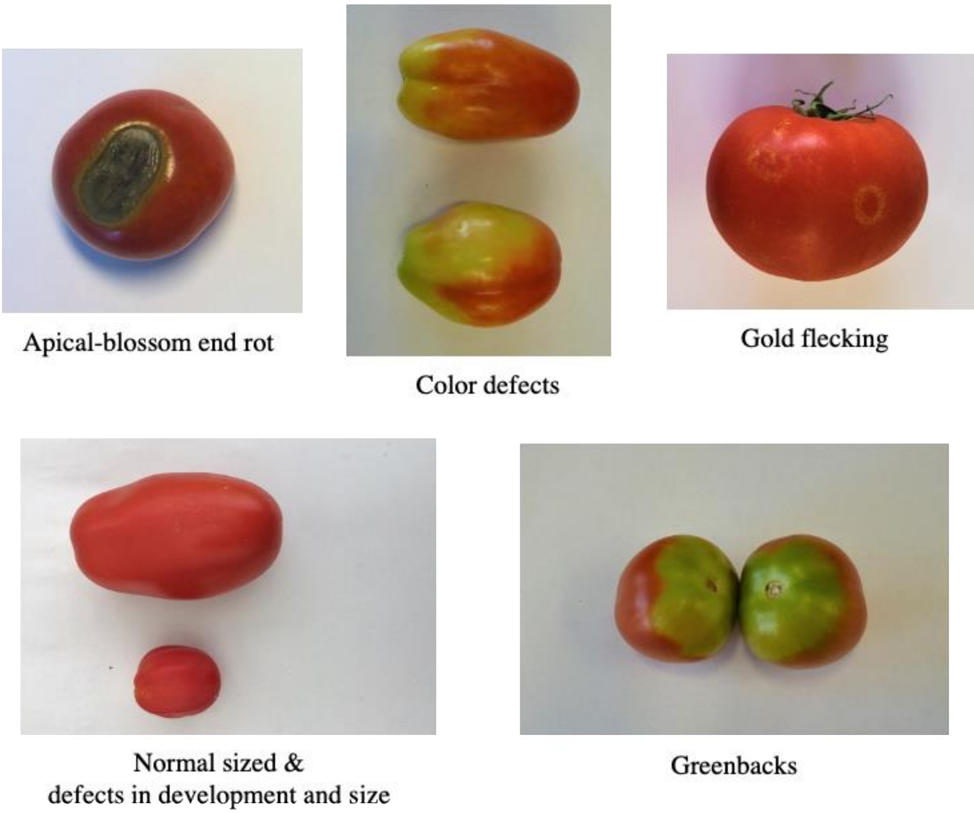

Figure 2: Five deficiency symptoms recorded on tomato fruits. Affected fruits were categorized into commercial class 2 (gold flecking, defects in development and size) or minus (color defects, apical-blossom end rot, greenbacks).

Statistical analysis

All statistical analyses were performed using R version 3.6.1 (R Core Team, 2019).

For analyzing yield, we used fruit number and fruit fresh weight (in grams) per plant as the dependent variables. The location of the pot per row (1-8), treatment (control or weed), and breeding group (organic or conventional), were set as fixed factors. Harvest date was set as a crossed random effect. For the final model we used a zero-inflated negative binomial generalized linear mixed model using Template Model Builder ("GlmmTMB" Package). GlmmTMBs fit linear and generalized linear mixed models with various extensions, including zero-inflation. The models are fitted using maximum likelihood estimation via "TMB" (Template Model Builder) (Brooks et al., 2019). Fruit number and fruit weight data were not normally distributed and harvest date caused zero-inflation ($p < 0.001$). Zero-inflation was checked using the "DHARMa" package that provides a number of plot and test functions for overdispersion and zero-inflation. "DHARMa" accounts for zero-inflation by running the model excluding all zeros caused by harvest date (Hartig, 2019). Final model selection was done by AIC comparison and visual plot analysis. Differences in means were controlled with posthoc-tests using the "emmeans" package (Lenth et al., 2019). Correlation between fruit number and fruit weight was checked with Spearman-Rank Correlation. Single treatment and mixed treatment were analyzed separately.

To evaluate yield stability for the organic versus conventional varieties under the different treatments, we calculated and plotted the coefficient of variation for fruit weight and fruit number over the whole harvest period. We used the R package "cvequality" (Marwick and Krishnamoorthy, 2019) and run asymptotic tests to control for significant differences between the coefficients of variation from organic and conventional varieties.

For fruit quality, we used the number of fruits per class summed over all harvest dates as the dependent variable. Here too, row (1-8), treatment (control or weed), and breed (organic or conventional) were set as fixed factors. Harvest date as random factor was not needed since number of fruits was summed over the whole harvest period. For the final model, we used a negative binomial generalized linear mixed model ("lme4" package) because the data showed overdispersion. The negative binomial regression model adds a multiplicative random effect for unobserved heterogeneity (Rodríguez, 2013). Again, we controlled for the overdispersion using the "DHARMa" package. Final model selection was also done by AIC comparison and visual plot analysis. Differences in means were controlled with posthoc-tests using the "emmeans" package (Lenth et al., 2019).

Results

Single tomato plants

Agronomic Performance – yield and yield stability

Tomato plants cultivated as single plants under optimal cultivation conditions ($N = 64$ plants) produced a total of 170.84 kg fresh tomatoes (Ø 3 kg per plant of the organic group, Ø 2.4 kg per plant of the conventional group). Tomato plants cultivated as single plants under weed stress ($N = 64$ plants) produced a total of 130.36 kg fresh tomatoes (Ø 2.2 kg per plant of the organic group, Ø 1.8 kg per plant of the conventional group). The "GlmmTMB" model showed that weed stress resulted in significantly lower fruit weight for both, the organic and conventional group ($p = 0.009$, **Figure 3** and **Supplementary Annex 2** Table 1). Comparing the two groups revealed that the loss rate under weed stress was similar with minus 22.2% for the organic group and minus 25.5% for the conventional group.

Overall, the organic group produced with 3859 fruits significantly more fruits than the conventional group with 2586 fruits, equally under optimal and weed stress cultivation conditions ($p < 0.001$, **Figure 3** and **Supplementary Annex 2** Table 1). Fruit number and fruit weight per plant were positively correlated for plant from the organic group ($R = 0.81$, $p < 0.001$) and plants from the conventional group ($R = 0.89$, $p < 0.001$). Testing for differences in the coefficients of variation (across the eight varieties in each group) revealed higher fruit weight stability of the organic group under weed stress compared to the conventional group (asymptotic test, $p = 0.02$).

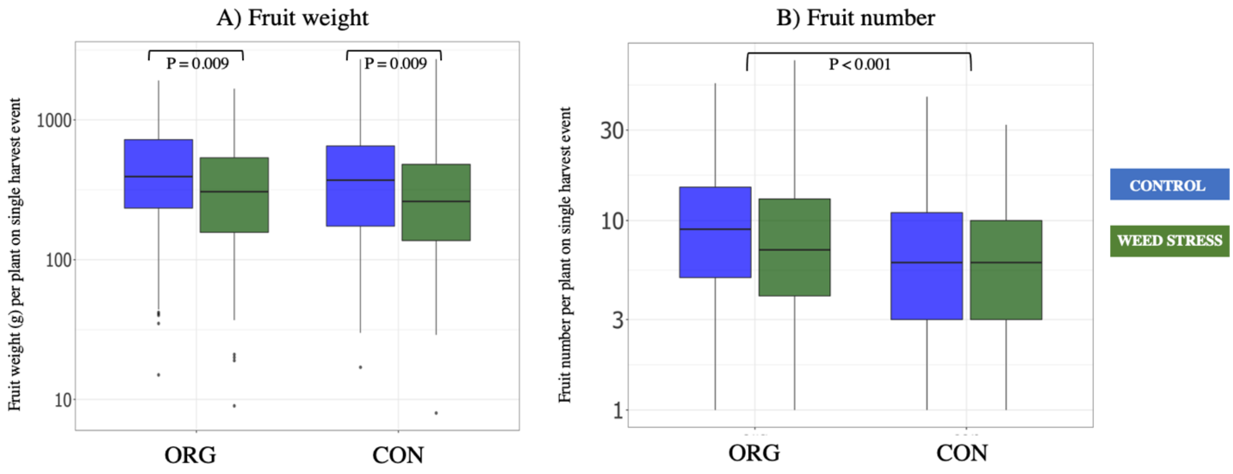

Figure 3: Comparison of A) Fruit weight and B) Fruit number per plant on single harvest event between the group of organic single plants (ORG) and the group of conventional single plants (CON). Weed stress resulted in significantly lower fruit weight for the organic (ORG) and conventional (CON) group ($p = 0.009$). The organic group produced significantly higher fruit number compared to the conventional group on single harvest event equally under optimal and weed stress cultivation conditions ($p < 0.001$). Each boxplot shows median (line within the box), lower and upper quartile (box), range (whiskers) and outliers (dots).

Quality Performance – Yield Quality

Of all 6445 harvested tomato fruits, 77% were categorized as *marketable* for the retail sector (organic group = 3022 fruits; conventional group = 1919 fruits), fulfilling the quality requirements for commercial class extra and one. The organic group produced 46.5 high-quality fruits on average per plant; the conventional group produced 30 high-quality fruits on average per plant. The remaining 1504 fruits (23%) were categorized as non-marketable (commercial class two for further processing, or minus, completely non-marketable). The organic group produced a total of 837 non-marketable fruits with 13 fruits on average per plant, while the conventional group produced a total of 667 non-marketable fruits and average of 10 fruits per plant. Weed stress had no impact on the number of produced marketable or non-marketable fruits. However, the "glm.nb" model showed that the organic group produced significantly more high-quality, marketable tomatoes ($p < 0.008$, **Figure 4** and **Supplementary Annex 2** Table 2).

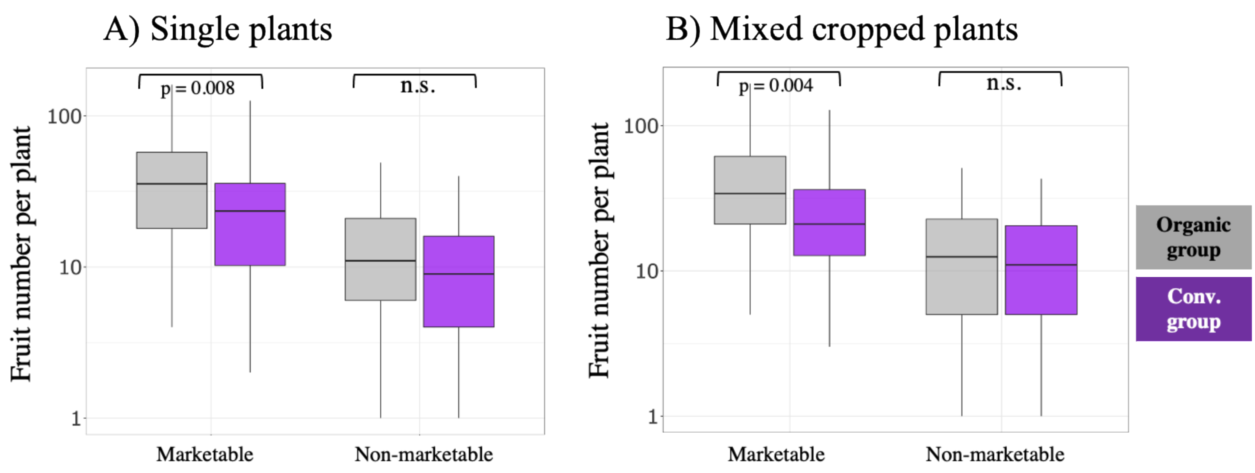

Figure 4: Comparison of marketable and non-marketable number of fruits on average per plant over the whole harvest period between the organic and conventional group as single plants (A) and mixed-cropped with a dwarf bean (B). Each boxplot shows median (line within the box), lower and upper quartile (box), range (whiskers) and outliers (dots). Organic varieties produced highest number of marketable fruits equally as single and mixed-cropped plants. Differences between the groups were significant for marketable fruits equally for single and mixed cropped plants.

Mixed-cropped tomato plants

Agronomic Performance – yield and yield stability

Tomato plants cultivated under optimal cultivation conditions in mixed cropping with a dwarf bean (N = 64 plants) produced a total of 174.07 kg fresh tomatoes (Ø 3 kg per plant of the organic group, Ø 2.3 per plant of the conventional group). Tomato plants under weed stress cultivation conditions in mixed cropping with a dwarf bean (N = 64 plants) produced a total of 167.07 kg fresh tomatoes (Ø 2.8 kg per plant of the organic group, Ø 2.5 kg per plant of the conventional group.) The "GlmmTMB" model showed that irrespectively of weed stress the organic group produced higher fruit weight (p = 0.043, **Figure 5** and **Supplementary Annex 2** Table1) and more fruits (4232 fruits, p < 0.001, **Figure 5** and **Supplementary Annex 2** Table 1) compared to the conventional group (2923 fruits) in mixed cropping with a dwarf bean.

Fruit number and fruit weight were positively correlated for organic ($R = 0.8$, $p < 0.001$) and conventional ($R = 0.85$, $p < 0.001$) varieties. Organic and conventional varieties did not show any difference in fruit weight or fruit number stability. Also, the variation of fruit weight and number between single and mixed cropping showed no differences in yield stability between mixed cropped and single plants.

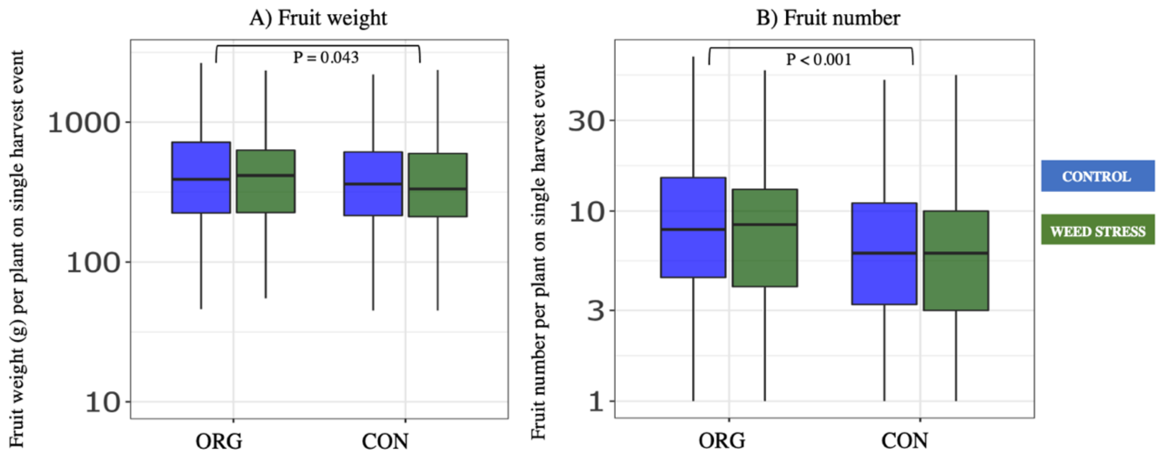

Figure 5: Comparison of A) Fruit weight and B) Fruit number per plant on single harvest event between the group of organic mixed cropped plants (ORG) and the group of conventional mixed cropped plants (CON). Irrespectively of weed stress the organic group (ORG) produced higher A) Fruit weight ($p = 0.043$) and higher B) Fruit number ($p < 0.001$) compared to the conventional group (CON). Each boxplot shows median (line within the box), lower and upper quartile (box), range (whiskers) and outliers (dots).

Quality Performance – Yield Quality

Of all 7155 harvested tomato fruits from the mixed cropping systems, 75% (5367 fruits) were categorized as *marketable* for the retail sector, fulfilling the quality requirements for commercial class extra and one. In total, the organic group produced 3277 fruits for commercial class extra and one, with 51 fruits on average per plant. The conventional group produced 2090 fruits for commercial class extra and one, with 33 fruits on average per plant. The "glm.nb" model showed that the organic group produced significantly more high-quality tomatoes in mixed cropping than the conventional group ($p = 0.004$, **Figure 4** and **Supplementary Annex 2** Table 2). The remaining 1789 fruits (25%) were *non-marketable,* meaning that they were categorized into commercial class two (for further processing) or minus (completely non-marketable). The organic group produced in mixed cropping 53% non-marketable fruits (956 fruits in total – 15 fruits on average per plant), which is, as for single plants, similar to the conventional group, which produced 47% non-marketable fruits (833 fruits in total – 13 fruits on average per plant). Thus, of all marketable fruits (N = 10308), the group of organic varieties produced proportionally the largest share in mixed cropping (31.8%) and as single plants (29.3%).

Discussion

In this experimental study, we systematically compared one group of eight organic tomato varieties with one group of eight commercial, high-yielding tomato varieties in terms of harvested yield, yield stability, and yield quality under weed stress and in mixed cropping. We found that in mixed cropping systems, the organic group produced higher yield and more fruits of the highest quality. Even though weed stress lowered yield of both groups as single plants, the organic group showed higher fruit weight stability across all varieties than the conventional group when grown as single plants under weed stress cultivation conditions.

Tomato performance under weed pressure

In our study, we found a negative influence of weed stress on yield and fruit quality, while the group of organic and the group of conventional varieties were similarly affected. For tomato production, Clark et al. (1999) similarly illustrated that organic and low-input production systems have the same yield potential as conventional systems, but are more difficult to manage especially regarding weeds and nitrogen (Clark et al., 1999).

For yield stability, previous studies mostly refer to temporal stability of one variety. To compare the stability of two variety groups with each other, we analyzed the stability across the varieties, resulting in higher fruit weight stability across all organic varieties compared to conventional varieties when grown as single plants under weed stress. Byerlee (1996) showed that modern breeding goals – especially for pest and disease resistances – are crucial for the yield stability of a variety (Byerlee, 1996). Furthermore, trade-offs occur between yield stability and high yield under non-optimal growing conditions like in our experiment (Barker and Winkelmann, 1981; Cleveland et al., 1993). However, yield stability can also easily be influenced by aspects other than breeding, and factors like water control (Barker and Winkelmann, 1981), fertilization, plant density, or sowing date can have a direct influence (Berzsenyi et al., 2011).

Weed stress is a well-known problem in organic vegetable production, increasing production costs. The manual workload for hand weeding in organic carrot production is up to 350 to 500 hours per hectare. Weeding costs are - over all vegetable species - estimated between \$8.75 to \$10 per hour (Niggle and Dierauer, 2000; Gianessi and Reigner, 2007). However, also in conventional vegetable production farmers are looking for alternatives to chemical weed control to reduce environmental damage caused by herbicides. Further, herbicide resistance in weeds is an increasing problem (Heap, 2014; Gurr et al., 2016), which calls for variety-specific evidence on performances under weed pressure.

Comparative studies examining the role of varieties reducing the impact of weed stress outline that variety breeding for modern, conventional agricultural systems reduced the competitive ability of conventional varieties against weeds, i.e. there is a trade-off between breeding for tolerance of weeds and high yield. From an organic perspective, a wide portfolio of varieties with the ability to suppress weeds is crucial (Hoad et al., 2008; Lammerts van Bueren, 2011). Important traits for high weed suppressing ability are mostly related to fast seeding emergence, canopy establishment, high growing rates at the beginning of the growing season, and tolerance to mechanical weed control (Bàrberi, 2002; Lammerts van Bueren et al., 2011).

The number of experimental studies comparing organic and conventional varieties is relatively low for vegetable species. Most studies refer to selected crop species - like wheat, maize, and rice - according to their relevance for economy and food production. Traditional tall rice cultivars often produce lower but more stable yields under weed pressure (Garrity et al., 1992). It is generally argued that plant height in rice is positively correlated with weed competiveness (Garrity et al., 1992; Mahajan and Singh, 2013). For wheat varieties researchers report that high-yielding varieties suffer great yield losses, unlike traditional varieties under weed and other stress conditions (Mason et al., 2007). Ceccarelli et al. (1992) showed that barley cultivars selected in high-input environments yielded up to 49% less under stress than cultivars selected in low-input environments (Ceccarelli et al., 1992). Murphy et al. (2007) demonstrated that the highest yielding winter wheat genotypes in conventional systems are not the highest yielding genotypes in organic systems (Murphy et al., 2007). This latter study points out that increasing yield in sub-optimal organic systems requires other plant traits than in conventional systems and that separate breeding programs are necessary. This is in contrast to the recent study by Voss-Fels et al. (2019), which shows that modern, high-yielding varieties of wheat performed better than old, traditional varieties even when cultivated in low-input systems. Genetic analysis revealed that modern varieties exhibited an improvement in disease resistance, increased nutrient efficiency, and highest yield performance (Voss-Fels et al., 2019). Since organic tomato production (especially outdoor production) is a small agronomic sector, the number of studies on variety-related weed suppression is small.

For weed suppression in outdoor tomato cultivation previous studies advise methods like herbicides (Hartz et al., 2008), or mulching (Herrero et al., 2001; Grassbaugh et al., 2004). Variety comparisons and the importance of wild relatives consider pest and disease resistance but not any weed-suppressing abilities (Bettiol et al., 2004; Singh et al., 2009; Lammerts van Bueren et al., 2011; McKenzie, 2014). Hence, breeding under organic, low-input selection conditions should be also considered as an important selection factor to achieve varieties that have a higher resistance against weeds. For organic farming, a management strategy combining biological, mechanical, cultural, and genetic practices provides successful weed suppression (Webber et al., 2012). In this context, our results show that additionally focusing on variety selection plays a decisive role.

Tomato performance in mixed cropping

Our results for the higher performance of the group of organic varieties in mixed cropping highlight that organic varieties do not rank behind varieties from commercial, high-yielding breeding. According to our results, productivity was highest for the group of organic varieties mixed cropped with a legume, leading to the highest marketable output.

Previous studies showed general advantages of mixed cropping vegetables with legumes, like tomato with cowpea (Olasantan, 1991), cabbage with bean (Guvenc and Yildirim, 2006), or chili with bean (De Costa and Perera, 2008). Abd El-Gaid et al. (2014) showed that mixed cropping tomato plants with common bean plants does not affect the yield of the tomato plants, but leads to an increase in farmers' profit due to the extra income from the beans (Abd El-Gaid et al., 2014). The same was shown for onion plants mixed with carrots, spider plant, and French bean, reducing not only foliar diseases, but also improving gross return per unit area by extra income from the additional crop species (Narla et al., 2011). Furthermore, weeds can be effectively suppressed in mixed cropping systems. Linseed-wheat-mixtures showed high effectiveness suppressing weeds, and pea-flax mixtures balanced the plant growth of both species and lowered negative weed influences (Paulsen et al., 2006). For cassava cultivation, mixed cropping with maize or cowpea resulted in less weed dry matter production per plot compared to cassava monoculture. Mixed cropping with legumes ensures high soil surface coverage and lowers surface light penetration reducing weed growth (Mohamed et al., 2006). Furthermore, when manual weeding is already necessary for one crop, the amount of extra labor is low in mixed cropping with an additional plant (Innis, 1997).

However, biodiversity studies show that mixtures demand genetic variability in order to promote complementary resource use (Chacón-Labella et al., 2019). In line with the results of Chacón-Labella et al. (2019), we expected that best-practice mixed cropping in low-input systems requires special traits (Chacón-Labella et al., 2019). These traits - relevant for plant performance in mixtures - might have been lost in breeding for high-yielding, commercial varieties, due to the absence of interspecific competition in monoculture systems.

Conclusion

The finding that the performance of the group of organic tomato varieties is equivalent or even outperforms the group of conventional varieties clearly shows the potential value of organic varieties for mixed cropping systems and weed suppression. Organic varieties appear to have potential for high and stable yields, in particular under crop stress conditions, but their commercial value seems to be underdeveloped so far. This might be due to the fact that commercial organic breeding is still a niche sector. Our results are promising, but a deeper understanding and commercial application can be only gained with longtime and large-scale field tests, which was beyond the scope of our study. Further, since mixed cropping has been already successfully implemented in organic cereal production, we propose mixed cropping field trials concentrating on those vegetable varieties that perform better in mixed than monoculture cropping, given the many advantages of mixed cropping for biodiversity and ecosystem services.

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Author Contributions: A.M.F., J.L., and T.T. developed the methodology and the experimental design. A.F. performed the experiment. A.M.F., J.L., and T.T. wrote and edited the manuscript. A.M.F., J.L., and T.T. read carefully and approved the final version of the manuscript.

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

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Data available statement: The raw data supporting the conclusions of this study will be made available by the authors, without undue reservation.

Supplementary

Annex 1: Variety list

Organic varieties were: Berner Rose, Pilu, Quadro, Tica, Dorenia, Goldina, Ruthje, and Trixi

Conventional varieties were: Indigo^{TM} Pear Drops, Yellow Pearshaped, Goldene Königin, Moneymaker, Hoffmanns Rentita, Ananas, Roma, and Martina

Annex 2: Details of the statistical evaluation

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Supplementary

Annex 1 Variety List

Organic varieties were: Berner Rose, Pilu, Quadro, Tica, Dorenia, Goldina, Ruthje, and Trixi

Conventional varieties were: Indigo™ Pear Drops, Yellow Pearshaped, Goldene Königin, Moneymaker, Hoffmanns Rentita, Ananas, Roma, and Martina

Tomato varieties					
Variety name	**Fruit type - color**	**Plant type**	**Ripeness time**	**Approx. Fruit weight**	**Extra information**
Organic varieties					
Berner Rose	Beef tomato - red	Stake type	Medium	Ca. 100-150 g	Breeder: Kultursaat e.V., conservational breeding
Pilu	Round, normal sized – red	Stake type	Medium early	80-100 g	Breeder: Kultursaat e.V. / Richard Specht; resistances: Fusarium oxysporum f. sp. Lycopersici, Cladosporium
Quadro	Oval, normal sized - red	Stake type	Medium	80-100 g	Breeder: Kultursaat e.V. / Hartmut Spieß; largely phytophthora tolerant

Tica	Round, normal sized - red	Stake type	Medium early	70-80 g	Breeder: Kultursaat e.V. / Richard Specht; resistances: Fusarium oxysporum, tobacco mosaic virus, Verticillium
Dorenia	Round, normal sized – red	Stake type	Medium early	Ca. 80 – 100 g	Breeder: Kultursaat e.V. / C. Matthes; authorization: Amateur variety (AS) with official approval according to Directive 2009/145 / EC
Goldiana	Round - orange	Cherry tomato	Medium early	20 g	Breeder: Kultursaat e.V. / Silke Wedemeyer; authorization: Amateur variety (AS) with official approval according to Directive 2009/145 / EC
Ruthje	Heart-shaped, round - red	Cherry tomato	Medium	40-55 g	Breeder: Kultursaat e.V. / Ulrike Behrendt
Trixi	Round, oval - red	Cherry tomato	Medium	20 g	Breeder: Kultursaat e.V. / Silke Wedemeyer; authorization: Amateur variety (AS) with official

					approval according to Directive 2009/145 / EC
Conventional varieties					
Indigo^{TM} Pear Drops	Pear shaped – yellow, purple striped	Cherry tomato	Medium	Ca. 20 g	*Kiepenkerl profi-line* for commercial and home-garden cultivation; high content of anthocyanins; breeder: Dr. Jim Myers, Oregon State University (2015)
Yellow Pearshaped	Pear shaped – yellow	Cherry tomato	Medium	20-25 g	*Kiepenkerl profi-line* for commercial and home-garden cultivation
Goldene Königin	Round – yellow	Stake type	Medium	80-90 g	*Kiepenkerl regional-historical profi-line* for commercial and home-garden cultivation
Moneymaker	Round – red	Stake type	Early	Ca. 50 g	*Kiepenkerl standard line*
Hoffmanns Rentita	Round – red	Bush type	Medium	60-80 g	*Kiepenkerl standard line*

Ananas	Beef tomato – red	Stake type	Medium	200-300 g	*Kiepenkerl profi-line* for commercial and hoem-garden cultivation
Roma	Roma-, Plum tomato – red	Stake type	Medium late	80-90 g	*Kiepenkerl profi-line* for commercial and home-garden cultivation
Matina	Round, oval - red	Stake type	Early	50-100 g	*Kiepenkerl regional-historical line*; breeder: Hild Seeds GmbH, Germany

Annex 2 statistical details

Table 1: Factors influencing agronomic performance via fruit weight and fruit number of single and mixed cropped tomato plants as dependent variables. Treatments were (i) organic breeding, (ii) weed stress, (iii) interaction between organic breeding and weed stress. Intercept represents the conventional group under optimal cultivation conditions. *N* = 1024 observations equally for single and mixed-cropped plants.

	Single tomato plants				**Mixed-cropped tomato plants**			
Fruit weight	(Intercept)	Organic breeding	Weed treatment	Interaction organic + weed	(Intercept)	Organic breeding	Weed treatment	Interaction organic + weed
IRR*	372.68	1.12	0.81	1.00	267.73	1.15	1.05	0.90
SE*	0.19	0.08	0.08	0.11	0.17	0.07	0.07	0.10
CI*	258.24-537.82	0.96-1.31	0.68-0.95	0.80-1.24	262.17-515.80	1.00-1.32	0.91-1.20	0.74-1.10
St*	31.64	1.47	-2.62	-0.03	34.22	2.03	0.62	-1.02
P*	<0.001	0.143	**0.009**	0.976	<0.001	**0.043**	0.536	0.306
Marginal R^2 = 0.014, Conditional R^2 = 0.255					Marginal R^2 = 0.003, Conditional R^2 = 0.250			

Fruit number								
IRR*	5.65	1.36	0.89	1.06	6.05	1.50	1.03	0.87
SE*	0.26	0.09	0.10	0.13	0.22	0.09	0.10	0.13
CI*	3.42- 9.33	1.15- 1.62	0.73- 1.09	0.83- 1.37	3.92- 9.36	1.24- 1.80	0.85- 1.24	0.67- 1.12
St*	6.76	3.53	-1.15	0.48	8.10	4.28	0.30	-1.09
P*	<0.001	**<0.001**	0.252	0.634	<0.001	**<0.001**	0.761	0.276
Marginal R^2 = 0.022, Conditional R^2 = 0.363					Marginal R^2 = 0.024, Conditional R^2 = 0.315			

*IRR, Incidence Rate Ratio; SE, Standard Error; CI, Confidence Interval; St, Statistics; P, P-value

Table 2: Factors influencing quality performance via number of marketable fruits of single and mixed cropped tomato plants as dependent variables. Treatments were (i) weed stress and (ii) organic breeding. Intercept represents marketable fruits of the conventional group under optimal conditions. *N* = 131 observations for single plants and 129 observations for mixed cropped plants

	Marketable fruits – single plants			**Marketable fruits – mixed cropping**		
	(Intercept)	Weed stress	Organic breeding	(Intercept)	Weed stress	Organic breeding
IRR*	32.88	0.79	1.56	32.92	0.95	1.59
SE*	0.15	0.17	0.17	0.14	0.16	0.16
CI*	25.01 – 44.08	0.57 – 1.10	1.12 – 2.18	25.16 – 43.89	0.69 – 1.31	1.16 – 2.19
St*	23.75	-1.42	2.65	24.99	-0.29	2.86
P*	<0.001	0.156	**0.008**	<0.001	0.774	**0.004**
R^2 Nagelkerke 0.092				R^2 Nagelkerke 0.089		

*IRR, Incidence Rate Ratio; SE, Standard Error; CI, Confidence Interval; St, Statistics; P, P-value

Summary

The conservation of agrobiodiversity is considered a priority to ensure the sustainability and sovereignty of food production under changing climatic and socio-economic conditions. In this context, substantial value is placed on the conservation and promotion of plant genetic diversity in the forms of seeds and varieties. The spread of modern, high-yielding crop varieties has led to an increasing loss of traditional and locally adapted varieties. However, access to traditional and locally adapted crop varieties may be crucial for crop cultivation in locations with sub-optimal growing conditions. A high diversity of crop varieties is also of importance for the preservation of agrobiodiversity and associated provisioning, regulating and cultural ecosystem services. In addition, crop diversification through mixed-cropping is a promising strategy to strengthen the resilience of farming systems under changing environmental conditions.

However, scientific research on the use of crop varieties and variety mixtures from organic plant breeding, meaning plants conserved and bred without synthetic fertilizers and pesticides, remains especially for vegetable species limited, which may hinder the potential to build more resilient cultivation systems. In this dissertation, I address this knowledge gap from an agroecological perspective. My dissertation addresses the question of whether the cultivation of traditional and locally adapted crop varieties has a positive impact on agrobiodiversity and ecosystem services.

In the first part (Chapter TWO), this dissertation focuses in a systematic review on the existing scientific literature on the contributions of traditional varieties (also known as landraces) to provisioning, regulating and cultural ecosystem services with those of modern, high-yielding varieties.

The evaluation of 41 publications showed that modern, high-yielding crop varieties are often preferred by farmers worldwide due to their provisioning services (e.g. higher yield) under optimal cultivation conditions. However, performance benefits, such as resistance to pests and diseases, appear to be often decreasing among modern, high-yielding varieties. Traditional crop varieties, on the other hand, often show higher resistance under sub-optimal growing conditions and are considered a trusted source of stable crop yields, especially by small-scale farmers in the global South. Furthermore, due to their cultural characteristics, such as importance for traditional cuisine, traditional crop varieties play a socially formative role in family and cultivation traditions. The value of a crop variety must therefore be considered within the social-ecological context of the farmers, consumers, and cultural communities. It goes beyond performance and economic value and includes the intrinsic value and the cultural relation between the crop variety and people.

In the second part (Chapter THREE), the yield performance between hybrid, conventional and organic varieties of tomato and sweet pepper is examined in a cultivation experiment from 2017. Yield, yield stability and fruit quality were tested under optimal irrigation and under drought stress conditions. Performance of both species was negatively affected by the lack of water. The results confirm the expected positive effect of hybrid breeding for performance to some extent, as hybrid varieties delivered higher fruit numbers under both optimal and drought stress conditions. Yield in harvested kilograms and the distribution of marketable and non-marketable fruits were comparable for hybrid, conventional, and organic tomato and sweet pepper varieties. The benefit of the higher yield of the hybrid varieties was mitigated by higher seed costs and the impossibility of reusing the seed. These results call into question the widespread assumption that open-pollinated conventional and organic varieties cannot be regarded as equivalent alternatives to hybrid varieties, especially when considering that organic crop varieties, in contrast to hybrid and conventional varieties, are not restricted for use by private intellectual property rights.

The third part (Chapter FOUR) of the dissertation compares the yield performance (yield, yield stability, fruit quality) of eight conventional and eight organic tomato varieties from a cultivation experiment in 2018. These varieties were cultivated either as single plants or in mixed-cropping with a legume, with or without weed stress. The results showed that the organic varieties outperformed the conventional varieties. In mixed-cropping, the organic crop varieties produced higher yields and more fruit of the highest quality than conventional crop varieties. Under weed stress, the organic crop varieties as single plants showed higher fruit weight stability. These results demonstrate the ability of the organic crop varieties to produce good yields under sub-optimal growing conditions. Furthermore, the results justify the maintenance and restoration of a diverse crop variety portfolio for diversified cultivation systems such as mixed-cropping.

In summary, the literature review provides for the first time a structured overview of the high importance of traditional crop varieties for regulating and cultural ecosystem services worldwide. Based on this review, I recommend to farmers and growers the seed market supply of a portfolio of crop varieties that is as large and diverse as possible. Since traditional crop varieties are, in many cases, still the more reliable source of stable yields for small-scale farmers, a seed system should be promoted that ensures the availability of these traditional varieties in the long term. The design and execution of the stress tests with crop varieties from different breeding approaches are novel, and provide new insights for the promotion of resilient farming systems. The findings provide evidence that organically-bred crop varieties may be often better suited for mixed-cropping. My crop variety experiments thus should mark the beginning of a series of new experimental studies that should be extended to as many vegetable and cereal species as possible and to a wide range of stress scenarios.

Zusammenfassung

Der Erhalt und die Förderung von (Agro-)Biodiversität gelten als Priorität für eine nachhaltige und souveräne Nahrungsmittelproduktion unter sich ändernden klimatischen und sozioökonomischen Bedingungen. Pflanzengenetischer Vielfalt in Form von Saatgut und Sorten wird in diesem Zusammenhang ein signifikanter Wert beigemessen.

Die Verbreitung moderner Hochertragssorten hat zu einem zunehmenden Verlust traditioneller und lokal angepasster Sorten geführt. Doch gerade der Zugang zu diesen Sorten kann entscheidend für den Anbau an Standorten mit sub-optimalen Wachstumsbedingungen sein. Eine hohe Vielfalt an Sorten ist zudem von zentraler Bedeutung für den Erhalt der Agrarbiodiversität sowie der damit verbundenen bereitstellenden, regulierenden und kulturellen Ökosystemleistungen. Zusätzlich wird Anbaudiversifizierung durch Mischkulturen als vielversprechende Strategie angesehen, um die Resilienz von Anbausystemen gegenüber schwankenden Umweltbedingungen zu stärken.

Die wissenschaftliche Forschung über die Verwendung von Pflanzensorten und Sortenmischungen aus der ökologischen Pflanzenzüchtung, d.h. Pflanzen, die ohne synthetische Düngemittel und Pestizide erhalten und gezüchtet werden, ist jedoch bisher speziell für Gemüsearten überschaubar, was das Potenzial zum Aufbau widerstandsfähigerer Anbausysteme behindern kann. In dieser Dissertation adressiere ich diese Wissenslücke aus einer agrarökologischen. Perspektive. Meine Dissertation befasst sich mit der Frage, ob sich der Anbau traditioneller und lokal angepasster Pflanzensorten positiv auf die Agrobiodiversität und den damit verbundenen Ökosystemleistungen auswirkt.

Im ersten Schritt (Kapitel ZWEI) untersucht diese Arbeit zunächst die bisherige wissenschaftliche Literatur und vergleicht den Beitrag von traditionellen Sorten (oftmals sogenannte Landrassen) mit modernen Hochertragssorten in Bezug auf bereitstellende, regulierende und kulturelle Ökosystemleistungen.

Die Auswertung von 41 Publikationen zeigte, dass moderne, Hochertragssorten aufgrund ihrer bereitstellenden Leistungen (z.B. höhere Ernteerträge) unter optimalen Anbaubedingungen von Landwirten weltweit oft bevorzugt werden. Allerdings scheinen regulierenden Leistungen wie z.B. die Resistenz gegen Schädlinge und Krankheiten, bei modernen, Hochertragssorten häufig abzunehmen. Traditionelle Sorten hingegen weisen unter suboptimalen Anbaubedingungen oft eine höhere Resistenz auf und gelten als vertrauenswürdige Quelle für stabile Ernteerträge, insbesondere bei Kleinbauern im globalen Süden. Darüber hinaus spielen traditionelle Sorten aufgrund ihrer kulturellen Merkmale, wie z.B. der Bedeutung für die traditionelle Küche, eine sozial-prägende Rolle in Familien- und Anbautraditionen. Der Wert einer Sorte muss daher im sozio-ökologischen Kontext der einzelnen Landwirte, Konsumenten und kulturellen Gemeinschaften betrachtet werden und geht über die Ertragsleistung und den wirtschaftlichen Wert hinaus. Damit kommt ihr eine individuelle Daseinsberechtigung zuteil.

Im darauffolgenden Kapitel DREI wird die die Ertragsleistung zwischen fünf Hybridsorten, fünf konventionellen Sorten und fünf ökologischen Sorten jeweils für Tomaten und Paprika aus einem Anbauexperiment aus dem Jahr 2017 verglichen.

Ernteertrag, Ertragsstabilität und Fruchtqualität wurden unter optimaler Bewässerung und unter Trockenstressbedingungen getestet. Die Leistung beider Arten wurde durch den Wassermangel negativ beeinflusst. Die Ergebnisse bestätigen teilweise den erwarteten positiven Einfluss der Hybridzüchtung auf die Ertragsleistung, da die Hybridsorten sowohl unter optimalen als auch unter Trockenstressbedingungen höhere Fruchtzahlen lieferten. Der Ertrag (in Kilogramm) und die Verteilung von vermarktbaren und nicht-vermarktbaren Früchten waren allerdings bei allen drei Sortengruppen, sowohl für Tomaten und Paprika, vergleichbar.

Die Hybridsorten waren mit höheren Saatgutkosten und der Unmöglichkeit der eigenen Nachzucht des Saatgutes verbunden. Der Vorteil der Hybridsorten im Vergleich zu den ökologischen oder konventionellen Sorten wird dadurch abgeschwächt.

Diese Ergebnisse stellen die weit verbreitete Annahme in Frage, dass nachbaufähige, konventionelle und ökologische Sorten nicht als gleichwertige Alternativen zu Hybridsorten angesehen werden können, insbesondere wenn man bedenkt, dass ökologische Pflanzensorten im Gegensatz zu Hybrid- und konventionellen Sorten nicht durch private Eigentumsrechte eingeschränkt werden.

Der dritte Teil (Kapitel VIER) der Dissertation vergleicht die Ertragsleistung (Ernteertrag, Ertragsstabilität, Fruchtqualität) von acht konventionellen und acht ökologischen Tomatensorten aus einem Anbauversuch im Jahr 2018. Diese Sorten wurden entweder als Einzelpflanzen oder im Mischanbau mit einer Leguminose, mit oder ohne Unkrautstress angebaut. Die Ergebnisse zeigen, dass die ökologischen Sorten die konventionellen Sorten in ihrer Ertragsleistung übertrafen. Im Mischanbau erbrachten die ökologischen Sorten höhere Ernteerträge und mehr Früchte von höchster Qualität als die konventionellen Sorten. Unter Unkrautstress zeigten die ökologischen Sorten als Einzelpflanzen eine höhere Fruchtgewichtsstabilität. Diese Ergebnisse belegen die Fähigkeit der ökologischen Sorten, unter suboptimalen Anbaubedingungen gute Erträge zu erzielen. Darüber hinaus rechtfertigen die Ergebnisse die Erhaltung und Wiederherstellung eines vielfältigen Sortenportfolios für diversifizierte Anbausysteme wie z.B. Mischkulturen.

Zusammenfassend bietet der Literaturüberblick erstmals eine strukturierte Übersicht über die hohe Bedeutung traditioneller Sorten für regulierende und kulturelle Ökosystemleistungen weltweit. Auf der Grundlage dieser Übersicht empfehle ich die Gewährleistung und Bereitstellung eines möglichst großen und vielfältigen Sortenportfolios auf dem Saatgutmarkt. Da traditionelle Pflanzensorten in vielen Fällen immer noch die zuverlässigere Quelle für stabile Erträge für Kleinbauern sind, sollte ein Saatgutsystem gefördert werden, das die Verfügbarkeit dieser traditionellen Sorten langfristig sichert. Die Gestaltung und Durchführung der Stresstests mit Sorten aus verschiedenen Züchtungsansätzen sind neuartig und liefern neue Erkenntnisse für die Förderung widerstandsfähiger Anbausysteme. Die Ergebnisse zeigen deutlich, dass ökologisch gezüchtete Sorten oft besser für den Mischanbau geeignet sein können. Meine Sortenversuche sollten daher den Beginn einer Reihe neuer experimenteller Studien markieren, die auf möglichst viele Gemüse- und Getreidearten und auf eine breite Palette von Stressszenarien ausgedehnt werden sollten.

Glossary

Crop variety

A *crop variety* is defined by the FAO as "(…) a plant grouping, within a single botanical taxon of the lowest known rank, defined by the reproducible expression of its distinguishing and other genetic characteristics." (FAO, 2009), and by *the International Union for the Protection of New Varieties of Plants* (UPOV) more precisely as "A plant grouping within a single botanical taxon of the lowest known rank, which grouping, irrespective of whether the conditions for the grant of a breeder's right are fully met, can be (i) defined by the expression of the characteristics resulting from a given genotype or combination of genotypes, (ii) distinguished from any other plant grouping by the expression of at least one of the said characteristics and (iii) considered as a unit with regard to its suitability for being propagated unchanged." (UPOV, 2020).

High-yielding variety

High-yielding varieties are in principle defined as improved varieties, highly responsive to fertilizer and water supply as well as having a high degree of resistance towards pest and diseases. Thus, being high yielding refers to the yield potential of a variety. For rice, for example, these features were made possible through dwarf or semi-dwarf growth height (Dalrymple, 1986).

Hybrid /hybrid variety

The term *hybrid* describes F1-hybrids consisting of genetically different inbred parental lines, resulting in the so-called heterosis effect, which triggers the high vigor of the hybrid generation (for detailed explanations see also **Figure 1**, page 4).

Landrace

Landraces are defined as "dynamic population(s) of a cultivated plant that has historical origin, distinct identity and lacks formal crop improvement, as well as often being genetically diverse, locally adapted and associated with traditional farming systems" (Villa et al., 2005). Landraces have been maintained and selected over time by farmers to meet economic, ecological and cultural needs and cultivated in small-scale farming systems with low input of external factors and high surrounding diversity (Teshome et al., 1997).

Traditional variety

Farmers worldwide have domesticated, improved, and conserved a wide variety of crop species and varieties on their land. These varieties are referred to today as *traditional varieties*. Through in-situ breeding and conservation traditional varieties are adapted to specific regions and climate conditions, and are known to be genetically more diverse than conventional modern varieties /

conventional varieties. The term *traditional varieties* is often considered synonymous with the term *landrace* (CBD Secretariat, 2010).

Modern variety / conventional varieties

In my dissertation, the terms *modern varieties* and *conventional varieties* capture all commercial varieties that have been improved though advanced plant breeding techniques. These techniques include traditional on-field selection methods, use of inbred lines creating F1-hybrids, laboratory techniques at the tissue or cell level, and techniques at DNA level. These varieties are mostly intended for monoculture cultivation systems, and should show a high level of uniformity and be suitable for a wide range of locations and climate conditions (Newton, et al., 2010).

In most cases, intellectual property rights or patents are applied on modern / conventional varieties and a license fee for re-seeding is charged (Helfer, 2002).

Open-pollinated variety

"Open-pollinated" refers to varieties that received pollen from another representative of the same variety or to self-pollination. Pollination can be achieved through wind, birds, insects, or human hands. Variety characteristics are passed on stably to the next generation.

Organic variety

In my dissertation, new varieties bred under organic conditions and traditional varieties from organic conservational breeding are collectively referred to as *organic varieties*. Organic breeding is supposed to be participatory (i.e. involving both farmers and plant breeders in the decision making for breeding targets). The breeding focus is on the creation of varieties for diversified organic cultivation systems and mixed-cropping for specific regions and climate conditions. The rules for organic plant breeding are embedded in the general model of organic agriculture (including ethic and society-relevant criteria). Breeding aims are geared towards the sustainable use of natural resources, and the maintenance of plant genetic diversity for the promotion of agrobiodiversity (FIBL, 2011, Messmer et al., 2015).

All organic varieties have been open-pollinated and no intellectual property protection or patent has been granted. Varieties are registered to non-profit organizations and the most organic breeding organizations advertise among costumers the re-use of the varieties by harvesting and saving own seeds for the next vegetation period (FIBL, 2011, Messmer et al., 2015).

Seed and variety commons

The term s*eed and variety commons* emerged from the work of the *RightSeeds* project (Kliem and Tschersich 2017). Main aspect is the common ownership of seeds and varieties, participatory plant breeding, as well as common seed production. Core targets are thereby collective forms of ownership and protection mechanisms, re-usable varieties and sharing of breeding knowledge, as well as community management in polycentric institutions. In the global North seed and variety commons are mainly implemented via common-based variety breeding. In the global South the seeds themselves are often seen as a common resource and exchanged between user groups like plant breeders and farmers (Gmeiner et al., 2018).

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Co-Authorship

Gmeiner N., Kliem L., Ficiciyan A., Sievers-Glotzbach S., Tschersich J. 2018. **Gemeingüterbasierte Rechte an Saatgut und Sorten als Treiber für eine sozial-ökologische Transformation des Pflanzenbaus.** Bundesamt für Naturschutz (Hrsg.), Treffpunkt Biologische Vielfalt, Interdisziplinärer Forschungsaustausch im Rahmen des Übereinkommens über die biologische Vielfalt. Bonn – Bad Godesberg: BfN-Skripten 487.

Grass, I., Loos, J., Baensch, S., Batáry, P., Librán-Embid, F., Ficiciyan, A., Klaus, F., Riechers, M., Rosa, J., Tiede, J., Udy, K., Westphal, C., Wurz, A., Tscharntke T. 2019. **Land-sharing/-sparing connectivity landscapes for ecosystem services and biodiversity conservation.** *People and Nature* 2019.

Ficiciyan, A., Gmeiner, N., Kliem, L., Marscheider, N., Tschersich, J., Sievers-Glotzbach, S. 2020. **Vielfalt statt Macht. Wenn Saatgut zum Gemeingut wird.** *ÖkologischesWirtschaften* 1.2020, 35, pp. 16-19.

Sievers-Glotzbach, S., Tschersich, J., Gmeiner, N., Kliem, L., Ficiciyan, A.. 2020. “**Diverse Seeds – Shared Practices: Conceptualizing Seed Commons**.” International Journal of the Commons 14(1): pp. 418–438. DOI: https://doi.org/10.5334/ijc.1

Conference talks

Review results for *More than Yield: Ecosystem Services of Traditional versus Modern Crop Varieties Revisited* presented at:

- IASC Workshop ‘Conceptualizing the New Commons’. Oldenburg, Germany, June 6-8, 2018
- Ecosystem Service Partnership World Conference 2019. ESP 10 Hanover, 21-25 October 2019
- CiBreed Workshop on Breeding Challenges and Opportunities in the Realm of Biotic Stress at the Center for Integrated Breeding Research University of Göttingen, Germany, 9th and 10th September 2019

Conference poster

Crops under environmental stress: Comparing F1-hybrid, conventional and organic vegetable varieties (Results from the field season 2017). At: Joint Annual Meeting: Ecology Across Borders 11 – 14 December 2017 ICC Ghent, Belgium

Other

RightSeeds project. 2019. Report on the German and Philippine practice partners from 4-9.2.2019 in Rajal Centro (Philippines) RightSeeds homepage: https://www.rightseeds.de/wp-content/uploads/2019/09/RS_Workshop_Philippinen_Bericht_2019final.pdf

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At this point I would like to express my sincere thanks to the Agroecology working group. We share deep friendships and the desire to be part of a healthy and flourishing planet. It's no secret that my office mates Julia, Manuel, and Svenja make me shine. Meeting you enriched my life in all aspects. I also thank the experimental botanical garden of the University of Göttingen and especially Regina Helbig, Gabi Kuchenbuch, Dietrich Hertel, and Birgit Bode (tropical Plant Production and Agricultural System Modeling) for their support cultivating the plants. It was only through their expertise and love for plants that these experiments and my passion for gardening could grow and flourish. Also, I am grateful to Julia, Johanna, Tristan, Laura and Susanne for assistance in cultivation and harvest. Furthermore, I am thankful for Laura for English proofreading and supportive times.

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Curriculum vitae

Personal data

Date and place of birth:	21.2.1990, Hüttenberg-Volpertshausen, Hessen
Nationality:	German

Higher education and professional career

Since 2019	Program manager for international cooperation at the Andreas Hermes Akademie, Bonn - Germany. With focus on organizational development and professionalization of farmer organization in Africa and India.
Since 2016	Member of the BMBF junior research group *RightSeeds*: *"Commons-based rights on seeds and varieties for a social-ecological transformation of plant cultivation* “
Since 2016	PhD at the Georg-August-University Göttingen, Department of Agroecology Topic: *"Performance of organic and conventional crop varieties and species mixtures under stress”* Supervisors: Prof. Dr. Teja Tscharntke, Prof. Dr. Jacqueline Loos and Prof. Dr. Stefanie Sievers-Glotzbach
2016	Master thesis in cooperation with the *Working Group Behavioural Biology and Didactics of Biology* at the Ruhr-University Bochum: *“Varroosis control with formic acid in 60% concentration after honey harvest - comparing the long-term impact of three popular treatment methods”*
2013–2016	Master program in Crop Science at the Friedrich-Wilhelms-University of Bonn

2013	Bachelor thesis in cooperation with the research sector on renewable resources: *“Terra Preta - ein historischer Überblick, Entwicklung und Bedeutung für den Landbau in Mittel- und Südamerika“*
2010–2013	Bachelor program in agricultural sciences at the Friedrich-Wilhelms-University of Bonn with focus on economics of the agricultural and food sector
2009	Abitur

Stays abroad

Since 2019	Working in Uganda and India as part of the program management activities at the Andreas Hermes Akademie
2019	*RightSeeds* Research stay on the Philippines (3 weeks)
2015	Studies on Mayan culture in Guatemala (4 weeks)
2009	Internship at the Kolping Society in Sucre, Bolivia (10 month)
2002	Social internship in Abancay, Peru (6 weeks)

Languages

German	mother tongue
English	Very good written and spoken
Spanish	Good written and spoken

Further activities

Since 2019	Chairwoman of the VDL state association NRW e.V.
Since 2018	Trainer for group sport programs
July 2017	Participation in the excursion module "Sugar beet production in Finland" (University of Göttingen)
July 2016	Participation in the excursion module "European ecosystems - land use, nature conservation, diversity" in Berchtesgaden National Park (University of Bonn)
2012–2014	Chairwoman of the VDL Student Group Bonn
Since 2010	Member of the VDL Professional Association for agriculture, nutrition, and environment e.V.

Declarations

1. I, hereby, declare that this Ph.D. dissertation has not been presented to any other examining body either in its present or a similar form.

   Furthermore, I also affirm that I have not applied for a Ph.D. at any other higher school of education.

   Göttingen, ...

   ....

   Anoush Miriam Ficiciyan

2. I, hereby, solemnly declare that this dissertation was undertaken independently and without any unauthorised aid.

   Göttingen, ...

   ....

   Anoush Miriam Ficiciyan