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Combining land-based organic and landless food production: a concept for a circular and sustainable food chain for Africa in 2100

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Abstract Even optimistic assumptions about population growth, agricultural productivity, and potentially available cropland produce a grim image for the future food security and sovereignty of many developing countries, in particular in sub-Saharan Africa. Here, we review literature and datasets on the current and future state of food security, with focus on Africa, and propose a plan of ten interconnected actions to create sustainable, circular, and local food systems to feed a global population between 11.2 and 16.6 billion people in 2100. In particular, we focus on "action number 10": landless food systems in combination with land-based food production, using modern "organic agricultural strategies." The concept shall be applicable to the needs and conditions in low-income countries with high population densities and small-scale farming systems, as expected in sub-Saharan Africa in 2100. We designed the concept "LandLessFood" with research recommendations for a circular bioreactor-based system of "calorie food and feed." Our aim is to "replace one hectare of cropland with one square meter of bioreactor space." Released cropland can and has to be used for "quality food" production to have enough, healthy, and affordable food for everyone on the earth in the year 2100.

Keywords Africa · Bioreactor · Circular economy · Food security 2100 · Landless food · Organic agriculture

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Introduction

How can we feed the world in 2100? This question must be asked especially with regard to Africa, where agricultural land is far too scarce to provide for a human population that will be at least three times its current size in 80 years. Sustainable agricultural intensification is a must, but no realistic, unbiased concepts for a transformation that can meet this challenge seem to exist for now. Two extreme positions can be outlined from the current discourse about the agricultural future (Paarlberg 2009): On the one side, proponents of industrial agriculture, who stand for the use of chemical fertilizers and pesticides, in conjunction with the use of genetically modified crops, as well as an increased irrigation and mechanization of the agricultural system. On the other side, those who want to update the traditional smallholder system with "organic strategies," like improved crop rotation, intercropping, and nutrient-cycling, and are opposed to the use of any chemicals and genetically modified crops. We doubt that either approach can adequately solve the problem. The industrial approach produces high yields, but relies on unsustainably high input levels, which causes high environmental costs and undermines the very basis agriculture is built upon in the long run (Godfray et al. 2010). The organic approach is considered to be more environmentally friendly, but produces lower yields (Rahmann et al. 2017; Rahmann et al. 2009; Paarlberg 2009), which would necessitate more cropland expansion or lead to an overall failure to produce enough food. Therefore, only if the pressure on cropland as the most important unit of food production can be reduced will it be possible for sustainable land use practices to prevail, to prevent excessive agricultural expansion and produce enough food in Africa.

We discussed with experts and reviewed literature to produce a possible solution to this problem (Rahmann et al. 2017). Setting aside ideological boundaries of the opposing sides described above, we designed a concept in which sustainable land-based agriculture, which takes advantage of “organic strategies” as well as modern and conventional farming methods, is combined with landless food production, to create a circular agricultural system. Land-based food production should deliver “quality food,” mainly in the form of vegetables, fruits, and animal products, while landless, bioreactor-based food production, should focus on providing “calories,” for example in the form of starch and oils. Microalgae in photobioreactors can produce lipids for biofuel production with yields per unit area 100 times or more than possible with any plant system (Rittmann 2008). It is well established that similar systems can also be used for food production (Brányiková et al. 2011; Chew et al. 2017). By extracting only “food ingredients” like starch or lipids from microalgae or bacteria cultivated in bioreactors, it would even be possible to use waste streams like sewage for food production, while also providing clean water and recycling valuable nutrients, like phosphate. Such a production system could produce food year-round, as it is not bound to a harvesting season. Possible additional benefits of bioreactor-based systems are the production of fertilizers and energy, as well as CO_2 mitigation. By combining these different benefits, and through technological improvements in cultivation and processing, we think that it is possible to make contributions to the agricultural system that far exceed the possibility of replacing 100 m^2 of cropland with 1 m^2 of bioreactor. Our vision is to replace 1 ha of cropland with 1 m^2 of bioreactor. This ambitious goal might be ridiculed, but our analysis of the future of food security in Africa, especially south of the Sahara, has led us to believe that this is the order of magnitude we have to aim at.

Population growth and land availability

According to the latest Population Prospects by the United Nations (2017), it can be predicted with 95% probability that the world population in 2100 will be between 9.6 and 13.2 billion people, with a medium estimate of 11.2 billion. If the fertility rate will not decline as expected, the global population can even grow up to 16.6 billion. The challenges are especially great for Africa, where the population is expected to increase more than anywhere else. The United Nations predict a population growth in Africa from current 1.2 billion to between 3.6 and 5.8 billion people, with a medium estimate of 4.4 billion. High estimates even see the African population at above 6.2 billion in 2100 (United Nations 2017) (Table 1).

Even within the low-to-medium range of these predictions, the question whether there will be enough land to produce food for everyone in 2100 must be asked. Roughly 4.9 billion hectare (ha), or 36% of the 13 billion ha of global land surface, are currently used as agricultural land, 3.3 billion ha of which are pastures and 1.6 billion ha of which are cropland (FAOSTAT 2018). Most of the global food and feed is produced on cropland, rather than pastures, which are mostly used for the grazing of ruminants like cows, goats, or sheep (Ludwig et al. 2018). The potential for cropland expansion is very limited. Most fertile pastures have already been transformed into cropland, and about 80% of the pastures that remain are of low fertility, situated in remote or mountainous terrain or unfavorably cold or arid climate (O’Mara 2012; Ramankutty et al. 2008). On the other hand, significant shares of existing agricultural land are being lost due to urbanization and degradation (d’Amour et al. 2017; Foley et al. 2005; Rahmann et al. 2017). If we assume that the agricultural area does not change until 2100, the area of available cropland per person will decrease from current 0.22 to 0.14 ha in the world and from 0.23 to 0.06 ha in Africa, according to medium population estimations. In the case of Africa, there would be 0.26 ha (roughly half a football field) of total agricultural land available per person, less than a quarter of which would be cropland. Countries such as Nigeria, the population of which is predicted to grow from current 180 million to more than 790 million until 2100, under medium fertility assumptions, and to over a billion if fertility rates stay high, would have even less space available and could not reach self-sufficiency in food production even if yields were increased dramatically.

Table 1 Population and land availability 2015 and 2100 (examples)

	World	Africa	Nigeria	China	India	Germany
Population (1 mio people)						
1950	2525	250	38	544	376	70
2015	7349	1186	182	1.376	1.311	81
2100 (medium case)	11,213	4467	793	1020	1516	71
2100 (worst case[a])	16,600	6236	1082	1586	2388	103
Land (1 mio ha)						
Country area	13,467	3032	91	956	329	36
Agricultural land (%)	36%	37%	78%	55%	55%	47%
• Agricultural area	4869	1133	71	528	180	17
• Cropland	1593	271	40	135	169	12
• Grassland	3275	861	30	393	10	5

Source: Compiled from data by UN 2017, FAOSTAT 2018

[a] + 0.5 children per woman above medium UN estimation

Figure . 1 shows the percentages of country area classified as arable land, permanent grassland, forest, or other land in 2015 (FAOSTAT 2018), as well as "best-case" and "worst-case" scenarios representing the percentage of country area that would have to be used as arable land in 2100 to supply sufficient calories for everyone in grain (rice equivalent) under positive and negative assumptions of population growth and agricultural productivity. It shows that the world could feed the increasing global population, but Africa would have to almost double its cropland area even under "best-case" assumptions. Under "worst-case" assumptions, the whole continent has to use almost all space, including dry and low-fertility savannas, the Sahel zone, and all forests for crop production. Nigeria is a case with severe challenges. The country is not big enough to feed all people by itself, not in the best or worst case.

In Fig. 2, the population growth under medium and high-fertility assumptions is mapped onto today's available cropland of the World, Africa, and Nigeria. Table 2 also shows the total land area ("country area") and agricultural area (grassland plus cropland) that would be available under these projections. Calculations in Fig. 2 about the area needed to supply enough calories for an average person (2100 kcal; plus 400 kcal to account for some food waste or livestock feeding) are based on the actual agricultural production quantities of 2013. Already in the next decades, many countries south of the Sahara will not be able to produce enough food with recent technology and skills unless the cropland area could be significantly expanded.

These forecasts foreshadow not only humanitarian but also environmental disasters. In the past decades, agricultural production in sub-Saharan Africa has barely increased at the rate of the population (Fuglie et al. 2012) and most of this slight increase (86% between 1960 and 2000) has been achieved through agricultural expansion, mostly at the expense of forests, rather than through technology for more efficient crop production (Evenson and Gollin 2003; Chamberlin et al. 2014; Fuglie et al. 2012). As a result of this, Africa has become a net-importer of agricultural products (Rakotoarisoa et al. 2011), including important staple crops, with only about 80% self-sufficiency in cereal production (van Ittersum et al. 2016). If recent productivity growth rates and dietary trends continue, a 185% increase in cereal production area (ca. 97 million ha) would be necessary in sub-Saharan Africa until 2050, to achieve self-sufficiency in this segment alone (van Ittersum et al. 2016).

However, the question by how much the agricultural area can or should be increased is controversially debated. Of the 456 million ha of African land that some estimations consider to be "potentially available cropland," 46% are forested (Chamberlin et al. 2014). It should not be overlooked that this enormous area, which amounts to 168% of the 272 million ha that are currently being used as cropland in Africa, includes pastures and land that are arid, water-logged, steeply sloped, or have low-fertility and high-disease burdens (Chamberlin et al. 2014).

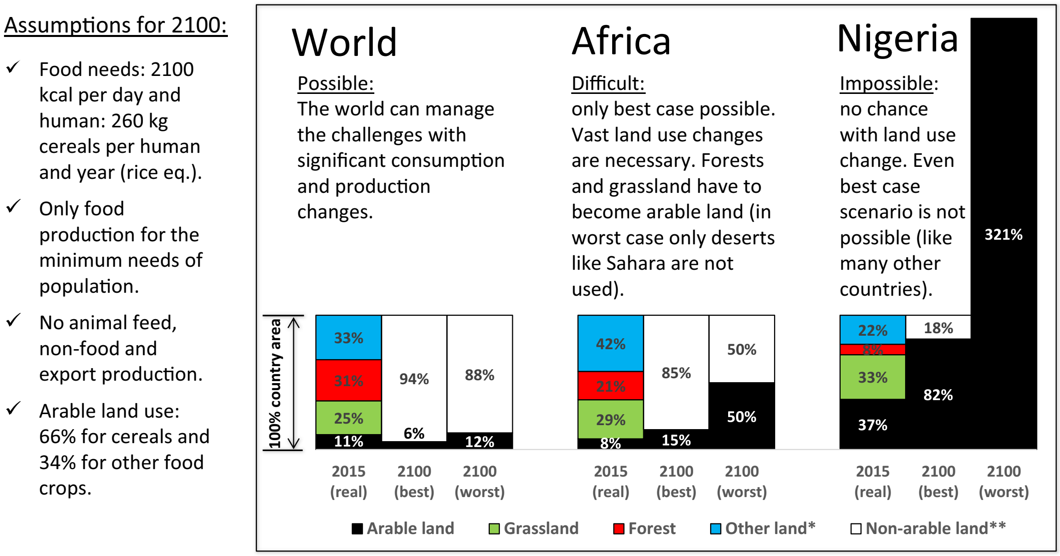

Fig. 1 Land requirements for sufficient (minimum) food production in 2015 and 2100 (medium and worst case scenario). Remarks: 2015 real scenario: population: World 7.4, Africa 1.2, Nigeria 0.18 billion people; cereals yields: World 3.9, Africa: 1.6, Nigeria: 1.4 tons/ha; 2100 best-case scenario: population: World 11.2, Africa 4.4, Nigeria 0.75 billion people; cereals yields: World 5.7, Africa 3.9, Nigeria 3.9 tons/ha; 2100 worst-case scenario: population: World 16.6, Africa 7, Nigeria 1 billion people; cereals yields: World 3.9, Africa 1.6, Nigeria 1.4 tons/ha. Single asterisk indicates other lands: mountains, deserts, ice, water, cities, roads, etc. Double asterisk indicates non-arable land: total land without arable land (only for food, no feed, or non-food). Source: Own calculation based on data from UN 2017 and FAOSTAT 2018

Of the only 242 million ha of potentially available cropland that could allegedly be transformed with "only medium" instead of high levels of inputs such as irrigation, fertilizer, and pesticides, 67% are forested. This leaves only 80 million ha of forest-free, relatively fertile potential cropland (Chamberlin et al. 2014). But even if an additional 456 million ha—an area almost half the size of Europe—could be used as cropland, and even if only the low end of population growth predictions (3.6 billion people in 2100) came true, the area of cropland available per person in Africa would decrease, from current 0.23 to 0.20 ha. Therefore, even under the most optimistic of assumptions, and with complete disregard for social and environmental concerns, it is certain that cropland availability in Africa is going to decrease.

Fig. 2 Cropland requirement per person versus land availability from 2015 to 2100. Remarks: Population growth under medium and high-fertility assumptions (from UN data: http://data.un.org/Default.aspx) mapped onto available cropland of the World/Africa/Nigeria complemented with calculations about the cropland area needed to provide enough calories for one person, based on FAO food balance sheets for the year 2013. Source: Own calculation based on FAOSTAT 2018 and UN 2017

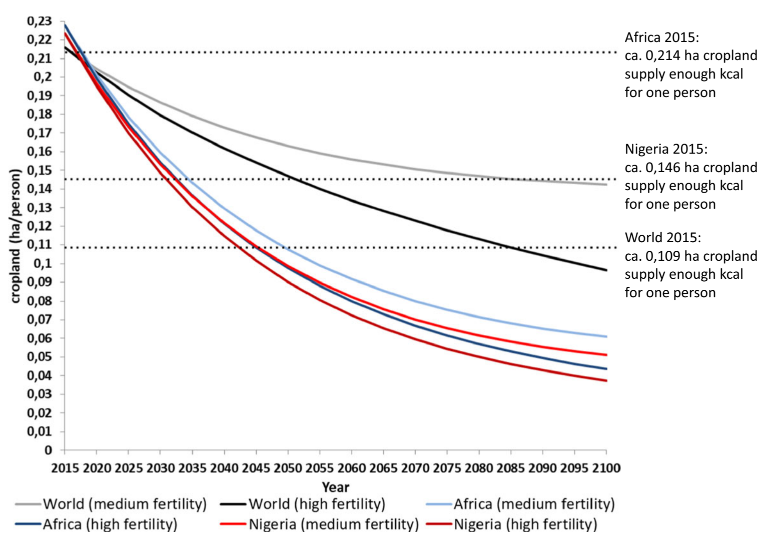

Table 2 Land availability in square meters per person in 2100 (medium and worst-case projections)

m^2/person in 2100	World	Africa	Nigeria	China	India	Germany
Medium case						
• Country area	12,010	6788[b]	1148	9373	2170	5070
• Agricultural area	4342	2536	895	5176	1187	2394
• Cropland	1421	607	504	1324	1115	1690
Worst case[a]						
• Country area	8113	4862[b]	841	6028	1378	3495
• Agricultural area	2933	1817	656	3329	754	1650
• Cropland	960	435	370	851	708	1165

Source: Compiled from data by UN 2017, FAOSTAT 2018

[a] + 0.5 children per woman above medium UN estimation

[b] Including deserts like Sahara and Namib (about 30% of total land in Africa)

Further challenges of sustainable food system development until 2100

Apart from population growth, several problems are challenging the global and African agricultural systems. Even though there is currently sufficient food production for everyone and an estimated 672 million adults in the world are obese, about 821 million people are undernourished (FAO 2018). While the number of overweight people (more than 30% of population) is increasing, the trend of decreasing world hunger of the last decades has been reversed in recent years (FAO 2018). Also, about 30–50% of food does not reach the consumer (Rahmann et al. 2017), largely due to spoilage but also due to biofuel production and because roughly a third of the produced grain is fed to the growing number of livestock (Godfray et al. 2010), as are other crops, such as soy. Since the demand for meat and other animal products is increasing worldwide, but in particular in developing countries, the portion of food that is used as feed is expected to rise (O'Mara 2012). In a large part due to this dynamic, food demand is growing faster than the population and is expected to increase by 100–110% by 2050 (Tilman et al. 2011). In Africa, food loss is to a large extent caused by an infrastructural deficit and by trade barriers, restricting farmers' access to national and international markets, storage facilities, fertilizers, pesticides, credits, and other commodities that improve economic opportunities (Rakotoarisoa et al. 2011). This is a major barrier for growth in the agricultural sector and restricts many smallholders to little more than subsistence farming (Harris and Orr 2014).

Partly caused by this lack of economic opportunity, many people in Africa move from rural to urban areas (Buhaug and Urdal 2013). Globally, the portion of people who live in cities is expected to rise from current 55 to 68% by 2050 (United Nations 2018). With only 43%, the share of people living in urban areas is still much smaller in Africa than in the rest of the world (United Nations 2018). However, by 2100, most Africans will also be living in urban environments and five of the ten biggest cities are predicted to be in Africa, Lagos becoming the world's largest city with up to 88 million people (Hoornweg and Pope 2017). Though such estimations "call for a fulsome measure of skepticism," as the authors themselves admit, the emergence of African mega-cities that dwarf modern-day giants like Tokyo or Mexico City seems certain. Given the dismal state of the infrastructure in most large African cities and the uncontrolled, rapid growth they are already experiencing, good concepts and swift action are necessary.

Urbanization is also one of many factors contributing to the loss of existing agricultural land. Globally, about 2% of existing cropland (30 million ha) is expected to be lost due to urbanization until the year 2030 (d'Amour et al. 2017). Since large cities are often situated in particularly fertile regions, the land that is going to be lost is about 1.77 times more productive than the average, in Africa even 3.32 times, so that ca. 3.7% of the current global and 8.9% of African crop production would be lost according to these projections (d'Amour et al. 2017). Also, 25% of agricultural land is already highly degraded, and globally, rates of erosion are estimated to be one to two orders of magnitude above the regeneration rate, which already leads to losses of billions of dollars annually (DeLong et al. 2015). Only 10% of cultivated soils worldwide are improving and 70% of agricultural soils in sub-Saharan Africa are degraded due to erosion (DeLong et al. 2015). In addition, about 1.5 million ha of cropland are lost globally every year due to salinization caused by irrigation (Foley et al. 2005). The loss of existing farmland is a driver of agricultural expansion into natural habitats, especially in Africa.

To compensate for this, agricultural areal efficiency must be increased. There is considerable potential for this, because the yield gap—the difference between potential and actual yields—is particularly large in Africa (Chamberlin et al. 2014). For example maize yields less than 40% of the world average (1.98 vs. 5.53 t/ha in 2015) (FAOSTAT 2018). This is often attributed to the fact that less agricultural inputs are used in Africa than in most of the world, which in turn is partly explained by how cheap it has been to increase productivity through agricultural expansion instead of intensification (Evenson and Gollin 2003; Fuglie et al. 2012).

Strategies for closing the African yield gap, such as laid out in the Comprehensive African Agricultural Development Plan (CAADP), aim at providing farmers with better access to "improved" seed varieties, machines, fertilizers, and pesticides and at increasing the area under irrigation and "sustainable land management" (NEPAD 2006). Since the 1960s, in what is now called, "The Green Revolution," such measures have played a crucial role in increasing yields and allowing countries such as India to feed rapidly growing numbers of people (Evenson and Gollin 2003; Fuglie et al. 2012). However, the future of this approach is unclear, not only because of negative effects on biodiversity, water, soil, and climate that are associated with it (Foley et al. 2005; Rahmann et al. 2017), but also because resources that are crucial for conventional agriculture, such as fossil fuels and, perhaps most importantly, phosphate, are increasingly rare. "Peak phosphate," the time when the mining of phosphate rock will be at its maximum, is expected to be reached by 2033–2034 (van Kauwenbergh 2010). After this "production will unavoidably decrease as the reserves are depleted," which will lead to rising prices of fertilizers (van Kauwenbergh 2010).

In the long run, through the depletion of phosphate, fossil fuels, soils, and water and loss of ecosystem services, the conventional agricultural approach in many ways undermines the foundation it is built on. For this reason, most stakeholders call for "sustainable intensification," which can generally be described as the goal of increasing yields while decreasing environmental impacts and dependency on inputs (Godfray et al. 2010). However, as is often the case in the development discourse, different stakeholders mean different things when using such a term (Cornwall 2007). For example, many perceive "green biotechnologies," especially the use of genetic engineering with novel tools such as CRISPR, as a means of sustainable intensification, while others are strongly opposed to this idea and call for purely "organic" intensification. Proponents of green biotechnologies highlight the potential for improving yields and resilience of crops to pests, droughts, and other environmental factors, while reducing the time it takes to react to such challenges and the amount of chemicals used in crop production (Gao 2018). But there are not only uncertainties concerning the environmental effects of genetically modified crops, as well as ethical arguments ("playing god") levered against the use of these technologies. Many people are also worried about the future and rights of smallholder farmers in the face of both, conventional intensification and green biotechnology. The concern is, to put it in layman's terms, that the adoption of these technologies will produce more losers than winners, and that the winners are more likely to be international corporations than African smallholders.

In a globalized world, African smallholders are already struggling with international competition and the influx of cheap food and feed from abroad (Rakotoarisoa et al. 2011). Studies have shown that returns from conventional agricultural intensification are too low to lift most smallholder farmers out of poverty, unless they are able to acquire additional land, though they could improve their food security (Harris and Orr 2014). In a time of rising prices of agricultural inputs, land, and food, smallholders are vulnerable to displacement by more powerful interest groups (Godfray et al. 2010; Rahmann et al. 2008). The lack of secure land rights in many African countries makes these concerns particularly serious.

Overarching the challenges described above are the threat of climate change and the overexploitation of other food systems, such as fisheries (Godfray et al. 2010). Europe, the Americas, Oceania, and most of Asia do not seem to be in as great danger of losing food sovereignty and sustainable livelihood as Africa, and sub-Saharan Africa in particular. However, there are many uncertainties and trends, such as the increasing spread of agricultural pathogens and pests from the equator towards the poles and evolved resistance to pesticides (Bebber et al. 2013) that challenge even those regions of the world where food security does not currently seem to be threatened.

Actions for achieving food security in the twenty-first century

In the following paragraphs, we transform the challenges described above into actions for building a sustainable and resilient food system. In our opinion, the actions 1–5 need to be tackled immediately, so that satisfactory results will be reached until 2050, while actions 6–10 are of less immediate necessity, though their execution is necessary until 2100. Some of these areas are already being researched and implemented, but ideally, all these areas should be tackled immediately and strengthened significantly.

Five actions that need more efforts until 2050

Action one: gain better understanding of human dietary needs

The agricultural system has to provide all nutrients that are required for a healthy human diet. However, what such a diet consists of is still unclear and can vary between individuals. Past attempts at making science-based dietary recommendations, such as the food guide pyramid, had to be revised in the face of new evidence but are still subject of controversial debates and criticism, drawing connections to obesity and other health-related issues (Gao et al. 2006). It is necessary to gain a better understanding of the real dietary requirements of humans to make adequate agricultural policy decisions, avoid overproduction of certain crops, and allow for improved selective breeding and the integration of novel foods into the food system.

Action two: produce enough, healthy, and affordable food for 9 to 11 billion people

Global food production will have to at least double until 2050 if current dietary trends continue (Tilman et al. 2011). Sustainable intensification of crop production, livestock farming, and aquaculture can therefore not be postponed.

Action three: develop coherent, ecologically sound food chains from production to consumption

The fact that 30–50% of produced food does not reach the consumer (Godfray et al. 2010; Rahmann et al. 2017) exposes a big flaw in the current food system. Considering the ecological costs of agricultural production and of transporting food around the world, as well as world hunger, it is not tolerable to let a significant portion of food spoil (Neuhoff et al. 2014). The disconnect between retail prices of food and true production costs can make products produced and transported at great environmental cost, appear cheaper than sustainably produced goods. For example, high animal densities, which are associated with the decoupling of crop and livestock farming, are associated with deforestation for feed production in the tropics, as well as water pollution on-site (Bleken et al. 2005), neither of which is adequately reflected in the price of meat or dairy. Future food chains must be more efficient in the use of resources and energy, for example by producing more food and feed locally.

Action four: make food chains economically efficient and fair

Farmers, especially in developing nations, often have no influence over the prices for which they can sell their goods and make a fraction of the profit that the processors of agricultural products make, usually abroad (Rakotoarisoa et al. 2011). This means that little money can be reinvested where it is most needed. The poor are disproportionately affected by rising food prices, and small-scale farmers often have the lowest food security (FAO 2018; d'Amour et al. 2016). To make the food system more economically efficient and fair for everyone, the land-rights of small farmers must be protected, their access to markets and credits improved, trade barriers between nations and groups of nations reevaluated, and the formation of value chains in the developing world promoted.

Action five: define ethical and social standards for future food chains

Given how tightly the food system is linked to environmental and social issues, it is necessary to reach binding international agreements on ethical standards and to formulate laws that can effectively enforce these. Animal welfare should play a role in future food systems; however, questions about what constitutes animal welfare and how it can be measured must be settled. To protect natural habitats from agricultural expansion, it is necessary to find effective legal tools. Countries such as Ecuador have gone as far as to grant "nature" the legal status of a person, to more effectively defend the environment against economic interests (Hillebrecht et al. 2017). Though it might seem strange to give nature the status of a legal individual, it should not be forgotten that this is already the case for economic institutions like firms and trusts, which are not persons either. This concept could have the advantage of leading to more fair legal battels between society and economy "with nature as a non-passive actor" (Hillebrecht et al. 2017). Regardless of whether this particular policy is the way forward, it shows how changes in ethical considerations can have a strong impact when codified as a law. To keep up with the rapidly changing realities of the food system, it is necessary to have these debates and craft new, effective legislation that protects people, but also non-human entities.

These five actions are already ongoing. Solutions are usually found in concepts of "sustainable food production systems" (new green revolution, conservation or climate smart agriculture, precision organic farming, agroecology, ecological intensification, food sovereignty). However, they are only intermediate solutions, until approximately 2050, and will not suffice to solve the core question: How to make enough food with increasingly scarce but crucial resources (farm land, fossil fuel and raw nutrients, as well as knowledge and skills). Only some actions and research activities have addressed the problem of farm land scarcity and ethical issues (animal welfare, right to food, environmental protection) recently. Among these are urban agriculture (all different forms of city farms and branches like roof-, terrace-, vertical-, balcony-, hydro-, in-house-, and container-farming, as well as aquaponics), novel foods (insect food, jellyfish food etc.), artificial food experiments (in vitro meat, analog cheese, molecular food, functional food), changing food habits (veganism, vegetarianism, regional food, etc.), and even space farming (Biosphere 2 experiment, "greenhab" at the Mars desert research station, the NASA "plant habitat").

Many of these actions are still in the developmental or, like the concept we present here, in the theoretical stage. Some of them could make important contributions to the food system, while others can be seen as ideologically biased or unrealistic. Altogether, they do not provide a comprehensive, realistic solution for all the challenges after 2050. To meet these, further actions are needed.

Five additional actions needed to meet the challenges after 2050

Action six: invent and explore novel food sources

The integration of new organisms into the food system, or an increased cultivation of organisms that currently only play a small role, could make agricultural production more sustainable, efficient, and healthy. For example, 1900 species of insects are eaten worldwide, but despite better feed conversion ratios and less greenhouse gas emissions compared to livestock, they have a neglectable market share (van Huis 2013). Likewise, mushrooms, which can be cultivated on agricultural waste and are of comparable nutritive value as meat, could be used to much greater benefit than is currently the case (Grimm and Wösten 2018). Microbial protein could be an alternative to soy as feed (Pikaar et al. 2018). Algae, water lentils, and other plants, as well as marine organisms such as jellyfish, also have potential as future food and feed. The use of a more diverse set of organisms would open new possibilities for nutrient circulation and make food systems more resilient. Effective large-scale production methods for these organisms must be researched and designed.

Action seven: develop less/no livestock food systems

Livestock is one of the main causes of greenhouse gas emissions and food waste in agriculture (Godfray et al. 2010; Warnecke et al. 2014). Many smallholders are dependent on animals because they provide fertilizer and muscle power, and some areas of the world can only be used for agriculture by using livestock. But also, global demand for meat and dairy incentivizes farmers to rear livestock instead of focusing on crop production. Ways must be found to restrict the increase in the demand for animal products and to lessen the economic dependency of farmers on livestock.

Action eight: education and training in real sustainable food culture and consumption

In free market societies, consumer demand largely dictates what the food system provides. Therefore, education, especially of young people, is an effective tool for promoting a more sustainable consumer culture (Rahmann et al. 2017). For example, increased consumer awareness of environmental issues and animal welfare has led to an increased market share of organic food throughout the world (Bonti-Ankomah and Yiridoe 2006). In particular, the unsustainable consumer habits of the western world need to change, while trends towards similar dietary habits in developing nations should be confined.

Action nine: protect and develop sustainable local staple food systems

Local production and consumption of staple crops are not only more environmentally friendly than import-dependency, they also increase the food sovereignty and thus economic and political independence of nations and make them more independent from potentially unreliable supply chains. Supply shortages in staple crops are particularly severe for the poor (d'Amour et al. 2016). Though a diversification of imports can be part of the solution, the most important step towards food security is to increase food sovereignty, especially in Africa, by protecting and developing local staple food systems.

Action ten: develop sustainable landless food production systems

Landless food production can be used to compensate for land loss, to recycle nutrients from waste streams and to integrate urban areas, water surfaces, and deserts into the agricultural system. Some already existing landless food systems, such as aquaponics, provide an opportunity for using excess nutrients from aquaculture in crop production. The use of bacteria and microalgae in bioreactors bears particular potential in the recycling of polluted waste streams such as wastewater or household waste (Rittmann 2008; Abdel-Raouf et al. 2012). The high spatial efficiency of photobioreactors, with regard to biomass production, protein, carbohydrate, and oil content could be used to free cropland for more sustainable production. Through a combination of fermenters and photobioreactors, increased productivity could be reached while creating an added benefit: CO_2 mitigation. It is also possible to produce high-quality fertilizers from microalgae (Chew et al. 2017). Through a combination of these different usages, a crucial contribution to the food system in general could be made.

The actions 1 to 9 are already "on the radar" of scientists and policy makers, but not action number 10: develop sustainable landless food production systems. The high efficiency of microalgae with regard to biomass production is widely recognized, but usually, no connection to food security issues is made, because of comparably high production costs. In our opinion, however, action number 10 should be a crucial component of agendas to ensure food security. Costs of reactor-based food production can be reduced through improved technologies, selective breeding, upscaling, and through taking advantage of the many different benefits of photobioreactors, rather than focusing on one or few. Rising prices of land, resources and greenhouse gas emissions, would also have positive economic impacts on these systems. Last but not least, economic considerations are not the only or the most important considerations when it comes to technologies that can make important contributions to food security.

A concept for combing land-based organic with landless food production

The idea of LandLessFood was designed in 2015 by ISOFAR, at the first Organic EXPO in Korea, and a first, rough description can be found in Rahmann et al. (2017). As a result of discussions with stakeholders and key informants, the idea was refined, and the following conditions formulated:

Production of specific food ingredients (nutrient energy) instead of "full food"

In order to use waste streams like sewage for food production, it is necessary to exclude pathogens, heavy metals, antibiotics, and other pollutants from the end-product. For this reason, sewage and other polluted waste streams cannot be used in concepts like vertical farming or aquaponics, where whole parts of plants or animals are produced for consumption. By extracting only essential food ingredients, such as starch, oil, or proteins from microorganisms, such as microalgae or bacteria cultivated on waste water, this problem can be bypassed. So far, most research into bioreactor-based food production has focused on the extraction of lipids and proteins, as well as vitamins and other "high-value" micronutrients, rather than starch. Though bioreactors are an interesting option for producing protein-rich feed as well (Pikaar et al. 2018), the extraction of starch, for example from *Chlorella* species which contain up to 60% of this polysaccharide (dry weight) (Brányiková et al. 2011), would be of particular interest with regard to food security because most of the "edible energy" that is consumed in Africa and the world comes in the form of starch and sugars (Rakotoarisoa et al. 2011). The best-suited microorganisms for bioreactor-based production systems must be selected and bred for optimization, and facilities for the efficient and clean extraction of the targeted food ingredients must be developed.

One hundred percent "organic skills-based" production on farm land, with limited livestock and aquaculture based on feed from crop by-products

Food ingredients like starch and oils are important components of food, but not enough for a healthy diet. Only nature can provide all the nutrients, vitamins, and flavors that people need. However, by producing these ingredients in bioreactors, there would be less pressure to produce these components on agricultural land and in other food systems. This would benefit the spread of truly sustainable farming methods and would reduce the necessity to focus on cultivating mostly staple crops. Organic agriculture should be redefined by goals and assessed by clear indicators, which guarantee the permanent improvement of production and a closure of the yield-gap, compared to conventional agriculture (Rahmann et al. 2017). All technological, biological, and social options should be open for consideration, to achieve this goal. Conventional agriculture can learn from organic agriculture, but this is also true the other way around.

To restrict the use of land for unsustainable farming and mitigate negative social effects, land-right reforms might be necessary, which restrict the amount of private property that a single person or cooperation can own.

Reactor-based food production facilities should be public property and under public control. Reactor food should probably be a "free resource" for people. The production and processing facilities for reactor-based food should be established close to or in urban or devastated areas (Fig. 3).

The integration of photobioreactors into the agricultural system opens new pathways for nutrient circulation, food and fertilizer production, and a more effective and "clean" link between the agricultural and the sewage system. The methane (biogas) produced in anaerobic digestion can be burned for energy production, creating water and carbon dioxide which can be fed into photobioreactors to increase productivity. Carbon dioxide from aerobic digesters can be directly fed into photobioreactors. Suitably big photobioreactors could produce enough oxygen to provide oxygen-enriched air that can be fed into aerobic digesters, to increase productivity and possibly create a positive feedback loop. The integration of photobioreactors into the system has several potential main benefits: (1) spatially efficient food and fertilizer production, (2) extra cleaning step for sewage, and (3) carbon sequestration.

Landless food: potentials and open questions

The global decrease of available cropland per person, resulting from population growth and reinforced by unsustainable land use, particularly in Africa and several Asian countries, makes it imperative to increase the areal efficiency of agricultural production. However, it is uncertain whether it will be possible to further increase productivity or even maintain the average global productivity per hectare at the level where it currently stands until the year 2100. Landless food systems could be a solution to this problem. While vertical farming, aquaponics, and other existing concepts for landless food production have a potential role to play, they depend on similar inputs as conventional farms and have very little potential in recycling polluted waste streams like sewage. They can therefore not be used to capture the nutrients in polluted waste streams, to make them accessible to the food system again, in the form of food, feed, and fertilizers. Since most people will be living in urban areas in 2100, the amount of nutrients that will enter cities in the form of food will be enormous. Thus, the amount of nutrients that "escape" the cities, in the form of waste water or household waste, will also be very large.

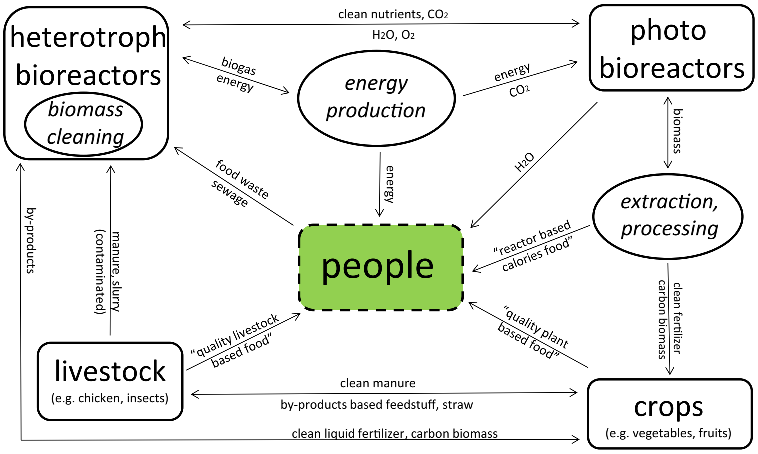

Fig. 3 Flow model of a circular sustainable land-based and landless food production system

For this reason, we propose to research and design bioreactor-based infrastructures, in which the process of water purification is coupled with food, feed, and fertilizer production. Water purification facilities already rely on heterotroph bioreactors, in which microbial communities, largely bacteria, are used to process waste. These systems could be improved and made more efficient by providing additional services with autotroph bioreactors. Several projects have shown that microalgae and cyanobacteria can be efficiently cultivated on sewage to produce biofuels, especially if solar radiation is high—as it is year-round in most of Africa, though temperature could be a problematic factor here. Microalgae and cyanobacteria grown in photobioreactors are several times more efficient than cereals crops in terms of energy capture (Gigajoule/ha × year), biomass production (tons/ha × year), and lipid and carbohydrate content (% of dry biomass) (Dismukes et al. 2008; Brányiková et al. 2011). The lipid fraction of some algal species is of higher nutrient quality than palm oil (Vanthoor-Koopmans et al. 2013). The cultivation efficiency of microalgae is significantly higher at increased CO_2 levels. Heterotroph bioreactors, as currently used in water purification and numerous processes in industry and food processing, produce large quantities of CO_2 and other greenhouse gases like methane and depend on high oxygen levels, which are provided through forced aeration at high energy costs. Instead of allowing the CO_2 produced in these processes to escape into the atmosphere, they could be captured and used to increase productivity in autotroph bioreactors, while the O_2 produced in autotroph bioreactors could be used to increase efficiency in heterotroph bioreactors. This could lead to positive feedback-loops, leading to increased productivity, at environmental benefit, in both systems. However, research on this is lacking.

Rising costs in agricultural production could make bioreactor-based food production more competitive, but it is also necessary to make technological improvements and cultivation efforts to create more productive organisms. An important factor contributing to the economic and environmental costs of photobioreactors is the downstream processing of algal biomass: The biomass needs to be dried and the extraction methods are often energy costly and require chemicals which can cause environmental problems (Vanthoor-Koopmans et al. 2013). If algae or other microorganisms are to be cultivated on waste water for food purposes, it is necessary to ensure that no harmful chemicals or organisms are contained in the end-product. This however can be accomplished, though considerable research is necessary.

Conclusion

Many aspects and components of bioreactor-based food systems are already known and even developed, but not in a comprehensive and coherent food-component production system from sewage via bioreactors to food and feed or fertilizers. To advance the creation of such systems, research in the next years should focus on: (i) the assessment of the biotechnological possibilities for producing food components like starch and oils and nutrients for fertilizers, like phosphorous, in phototroph bioreactors linked to the sewage system; (ii) technical concepts for extracting the target components with high food safety standards and HACCP (hazard analysis and critical control points) concepts; (iii) understanding the ethical and cultural impact and adaptation challenges of bioreactor-based food; (iv) designing infrastructures for landless food systems in selected cities in developing countries with high population growth.

To solve the problems of the global food system and offer a solution to overpopulated, poor regions of the world, ambitious research, and actions are needed. Therefore, the target should be to produce the same number of calories in 1 m^2 of bioreactor as on 1 ha of cropland.

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