Org. Agr.
https://doi.org/10.1007/s13165-020-00288-1

Food from 458 m^2—calculation for a sustainable, circular, and local land-based and landless food production system

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Received: 22 February 2020 / Accepted: 16 March 2020

Abstract Four hundred fifty-eight meter square is the available cropland per person throughout Africa, if the population will increase 4 to 5 times towards 4.3 to 5.9 billion people in 2100, the maximum estimation of the UN 2019 (95% confidence interval). This space is not enough for food sovereignty, if the low African yields remain. Even with the global average yields, nearly 3 times higher than African yields, will not allow food sovereignty. Hunger, wars, diseases, and mass migration can be the consequences already long time before 2100. Nevertheless, food sovereignty is possible, but not in the way as it is done up to today by governments and development projects. In the future, intensification of (yields) and/or expansion (grassland, forest: LULUCF) of agriculture will not be able to produce enough, nutritious, and affordable food for everyone. But clever combining of land-based and landless food production can be a solution for a local, sustainable, and circular food security. Maize and soybeans are best for WFP minimum diets and have the best yields. Using insects and earthworms as protein source can deliver enough and nutritious protein, and local photoreactors can produce oil/and/or starch for food energy. Later can be large industrial and very small household scaled. This "out-of-the-box" system approach needs research and development. Every good research needs good questions and a concept with some simple calculations to assess the strengths, weaknesses, opportunities, and threats. Socio-economic aspects are often not considered enough in technical focused and far ahead R&D.

Keywords Africa · Food security 2100 · Organic farming · Reactor food · Food sovereignty · Circular · Economy

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The food production and consumption problem

Food security is a challenge for the global mankind, and not only for the critical countries and communities. In 2100, alarming forecasts are for nearly all countries in Africa and some countries in Asia (e.g., India, China, Indonesia, Bangladesh) (Table 1).

Increasing food production will be necessary to feed every human on the earth with enough, nutritional, healthy, and affordable food. In this paper, we assume that the SDG No. 2 (no hunger) will be not achieved and regional food insecurity will become worse after 2030, at least in whole in Africa and in some densely populated and low developed countries in Asia. Significant and much more ambitioning increase of food production with efficient food chains and sustainable consumption has to be developed and scaled-up as soon as possible.

Food requirements

Food is one of the core requirements and need of us: the *Homo sapiens* (humans). In principle, we are very

Published online: 15 April 2020

Table 1 Global and continental population, land availability, and space per person in 2100

	World	Africa	Americas	Asia	Europe	Oceania
Population (mio people):						
2015	7349	1186	992	4393	738	39
2050*	9735	2489	1188	5290	710	57
2100 (medium est.)*	10,875	4280	1171	4720	630	75
2100 (maximum est.)**	15,600	5878	1696	7027	896	102
Land use 2015 (mio hectare):						
Country area***	13,467	3032	4075	3198	2306	856
Agricultural area	4869	1133	1225	1664	467	379
Grassland****	3275	861	826	1082	176	331
Arable land	1426	235	371	496	276	47
Permanent crops	165	34	28	86	15	2
Agricultural area/total land (%)	36%	37%	30%	52%	20%	44%
Available space per person 2015 (m^2/p):						
Country area	18,324	25,564	41,080	7279	31,244	219,524
Grassland*****	4457	7260	8326	2464	2379	84,757
Cropland*****	2165	2269	4024	1325	3951	12,512
Available space per person 2100 (m^2/p):						
Medium est.*:						
Country area	12,383	7084	34,804	6775	36,625	114,280
Grassland*****	3012	2012	7054	2293	2789	44,123
Cropland*****	1463	629	3409	1233	4632	6514
Maximum est.**:						
Country area	8632	5158	24,025	4550	25,720	83,852
Grassland*****	2100	1465	4870	1540	1959	32,375
Cropland*****	1.020	458	2353	828	3253	4779

*Medium population est. 2050 and 2100 (UN 2019)

**Maximum population est. 2100 (UN 2019 medium est. +0.95 confidence)

***Including deserts, high mountains, ice covered areas

****Mainly low productive savannas, pampa, etc. (usually not suitable for cropping yet)

*****Cropland is sum of arable land plus permanent crops. Sum of grassland and cropland is agricultural area

Source: Rahmann et al. 2019

adaptive in diets and food sources. As omnivores, we can digest a wide range of plants, fungi, animals, and others, at least after processing and/or cooking (Gibbons 2007). Despite or because of this fact, it is difficult to find a "typical ration" for a "typical human" in kilogram of food per day. The need is defined on the basis of nutritional demand.

Life needs food for energy (calories, joule) and structural material for body growth and rebuilding, delivered as macro and micro-nutrients (carbohydrates, fats, fiber, minerals, proteins, vitamins) and water. Carbohydrates and protein deliver about 17 kJ (4 kcal) and fat 37 kJ (9 kcal) energy per gram DM. Vitamins, minerals, fiber, and water do not deliver energy, but are required as structural material, health components, and digestion. All food has at least some of the nutrients mentioned above. Not all food can be digested; therefore, the feces carry energy and structural material. Because it is so difficult to measure the food quantity per person per day, the energy and structural material (protein, etc.) is used for calculations.

The human food energy requirement is measured in kilocalories and Joule (1 cal is 4184 J), about 1 kcal per kg liveweight and hour as minimum energy without any activities (example: 70 kg man × 24 h = 1680 kcal × 4184 J = 7029 MJ). Adding activities, age, and sex is difficult, due to individual conditions, but roughly about 2500 kcal (10,460 MJ metabolizable energy ME) for men and 2000 kcal (8368 MJ ME) for women can be assumed as average daily need (FAO 2001).

Energy and ingredients density are different between all the different foods. Due to availability, the food baskets and food cultures are very different throughout the world. Despite the high variability, it can be assumed, that about 2 kg food as fresh matter (0.75 kg dry matter) are the daily need for an "adult average human" (30 years, normal activity, healthy, temperate climate) (without losses, usually 25% extra). The stomach of such an "adult average human" has a capacity of 1 to 1.5 l and can digest about 1 to 1.5 times filling a day (depends on digestibility of food). Therefore, the stomach can digest about 1 to 2.25 kg fresh matter food a day. Food must have a digestible nutrient density, that fits with the capacity of the stomach. The EAT-Lancet commission does recommend 2.500 kcal/p/year, but is focusing on global food production for 10 billion in 2050 (EAT-Lancet commission 2019). This is not a realistic scenario for challenging regions like Africa.

The World Food Programme (WFP 2019) does offer a food basket for emergencies and refugees with 2100 kcal (10–12% from protein and 17% from fat). A recommended WFP-standard ration is composed by wheat, maize or rice, lentils, soybeans, or other pulses, vegetable oil (fortified with vitamin A and D), sugar, and iodized salt. Additionally, 1 to 1.3 g crude protein xP per person and day should be available (WHO 2017). Of course, this minimum ration is not enough for adult and hard-working man or lactating woman, but much more than a young child or an elder person needs. Nevertheless, in a society, this minimum ration should be fine, if people share it in context to the individual demand (elder people, adults, children; hard or less hard working) (Table 2).

If we assume, that the WFP daily ration has 2100 kcal energy and 85 g protein, the minimum annual need per person is 767,000 kcal and 24 kg protein.[1] This has to be produced on available cropland or imported, if other option like landless food production is not considered.

[1] Protein: 1 g per day and kg liveweight of a person is needed, and the digestion rate (biological value) of crude protein (xP) in maize and soybeans is 75%. That would mean, 1.3 g xP per person and day is necessary. An average person of 50 kg liveweight would need 23.741 g xP per year.

Food production

Seventy thousand years was the collection of wild plant and hunting, the basis of food security. Till 10,000 BC, a maximum of 2 people per km^2 (50 ha per person) could find enough food and survive and only estimated 1 to 15 million pre-historic humans lived on the earth. With the invention of agriculture, about 12,000 years ago in Mesopotamia and adjacent areas (Bellwood 2005), humans have been able to produce more food per ha for increasing population densities (Puleston and Tuljapurkar 2008). In the year 1400, 500 mio humans used extensively 7% of the global land surface which have been used for farming (1.1 billion ha crop and grassland), respectively 2.2 ha per person. The year 1804 is seen as the first time when 1 billion humans lived on the earth.

Today, 7.6 billion humans use 4.8 billion ha crop and grassland intensively (0.6 ha per person). The global population density has raised towards 57 people per km^2 (USCB 2019). Most of our recent food comes from landlocked plants and livestock, only 10% from fishing and aquaculture. Thirty-six percent of the land surface (13.5 billion ha, excluding Antarctica) is used for crop and livestock production. Further encroachment into deserts, forests, mountains, and frosty areas is difficult and/or costly.

A "good" diet is a balance between different food to meet the demand, and there are many different staple foods creating a food basket of local diets and food cultures all over the world. In the last decades, a harmonization of food cultures took place. Today, only 3 food plants (wheat, maize, rice) contribute about 60% of human food intake, direct as plant food or indirect as meat, eggs, or milk (FAO 2019b).

Compared to rice and wheat, maize is the most important food product of the world (Table 3). This crop covers already 14% of the total global arable land. A lot of the global maize production is for animal feed. Additionally, to maize, soybean is best choice as pulse for a WFP minimum ration. This legume is more valuable for a WFP ration than others, due to high protein and fat content (Table 2). Today, 8.6% share of the global arable land is cultivated with soybeans, like maize mainly for livestock feed.

Maize and soybeans have not only high nutritional and production yield advantages. These two plants grow in a wide climatic/weather range; high performance varieties for most of the earth are available. This does include GMO seeds, which are pest or herbicide resistant, and in the future, probably with higher water

Table 2 Nutrient content of maize, rice, wheat, and soybeans

Food name	Maize	Rice	Wheat	Soybean
Scientific name	*Zea mays*	*Oryza sativa*	*T. aestivum*	*Glycine max*
Water in FM (%)	14	14	14	14
kcal (per kg DM)	3840	3640	3640	4490
Protein (g xP per kg DM)	100	80	140	440
Fat (g per kg DM)	44	7	23	209

efficiency and salinity tolerance and, last but not least, high nutritional values (vitamins, amino acids, etc.). Because GMO are under ethical discussion (private business, patents, ecological and health risks), not invented for poor farmers but as expensive commodity, and the production costs with GMO are high (high input - high output systems) and therefore difficult for poor and remote small scale farmers, the ecological and socio-economic assessments of GM maize and soybeans have not been finalized yet.

Food insecurity can increase

The future food security is a global challenge and, for example, defined the United Nations Sustainable Development Goal SDG No. 2 (Zero Hunger) till 2030. Today, 240 (29%) of the global hungry 820 mio people live in Africa (FAO 2019a, b). It should not be forgotten, that never have been more people feed sufficiently on the earth (more than 6.5 billion), and obesity is a contradictory problem of hunger issues (1.2 billion people with BMI > 25). This is also the case for Africa. Nearly 1 billion people have enough food and 150 mio of them face obesity. Hunger is a problem of poverty, and a fair distribution of food does still not happening, despite enough food would be available for everyone and the UN has declared several programmes in the last decades (millennium and sustainable development goals).

The real challenge will appear after 2030. Most predictable, whole Sub-Saharan Africa and some countries in Asia (e.g., India, Pakistan, Bangladesh) will have severe food security problems in recent future, due to many factors. Ecological and soil degradation, water shortage, population growth, climate change, and socio-economic difficulties are already today observable, and the conditions for sufficient food production becomes worse in those regions, despite all efforts and developments of farming systems and food chains.

But, the main change and challenge will appear after 2050, particularly in dense populated and less developed areas of the world. For example, in Africa will be only 458 to 629 m^2 cropland per person available (Table 4). Increasing yields (very low) is difficult due to lack of knowledge and markets (farm inputs and outputs). Encroaching cropping on grassland and

Table 3 Production and yields per ha of maize, rice, wheat, and soybeans (2017)

Food name	Maize	Rice	Wheat	Soybean
Global land (mio ha)	197	167	218	123
Production (mio tons)	1135	770	772	353
Global average yields (tons/ha)	5.755	4.601	3.531	2.854
Lowest yields (continent average)	Africa	Africa	Africa	Asia/Africa
(Tons/ha)	2.073	2.444	2.604	1.371
Highest yields (continent average)	Americas	Oceania	Europe	Americas
(Tons/ha)	8.069	9.379	4.360	3.245

Table 4 Needed and available cropland in Africa under different scenarios

Cropland needed for WFP minimum ration: (m^2 per person):		Cropland available per person (m^2 per person):	
Global production yields*	489	4.3 billion people**	629
African production yields*	1216	5.9 billion people**	458

*Average production yields 2017: Global: maize 5.8, soybean 2.8 t/ha/year. Africa: maize 2.1, soybean 1.4 t/ha/year (FAOstat 2019).
**Population estimations (UN 2019)

nature areas is limited and difficult due to lack of water, infrastructure, capital, and land rights. Food import is also limited due to lack of money and/or competitive products for the world market. Food aid seems to be the only option for most of the countries.

Despite there will be not only food security problems in Africa, the following calculation will use this continent as an example to extrapolate the development. Comparable scenarios could be made for other countries and regions as well.

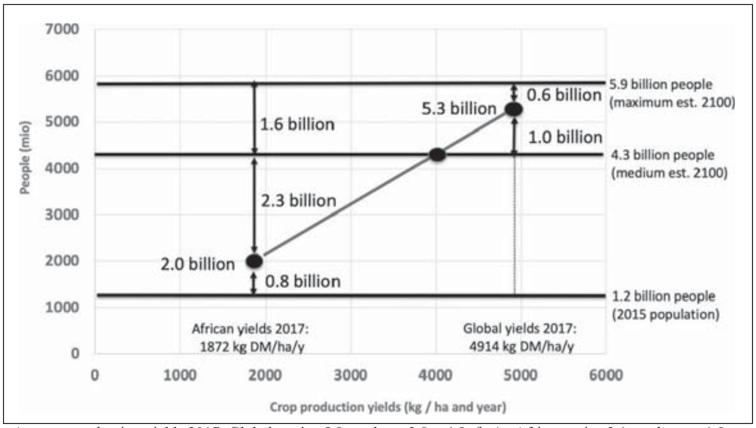
Till 2100, in 80 years, the African population will increase from 1.2 billion towards 4.3 or even 5.9 billion, and the continent will host about 50 to 60% of the global population. Already today, Africa is the continent of hunger and malnutrition (Rahmann et al. 2019). Land degradation, water shortage, and lack in agricultural infrastructures are obvious throughout the continent.

Average production yields 2017: Global: maize 5.8, soybean 2.8 = 4.9 t/ha/year, Africa: maize 2.1, soybean = 1.9 tons/ha/year (FAOstat 2019). Cropland use: 71% maize and 29% soybeans. Population estimations (UN 2019): medium est. 4.3 billion; maximum est. 5.9 billion people. Assumptions: only maize and soybeans are produced, no post-harvest losses, no LULUCF, only WFP ration (2100 kcal/p/day): 190 kg maize and 60 kg soybeans per person and year.

Food sovereignty for Africa is only possible, if the population will not raise above 5.3 billion (Fig. 1), and that (a) not more than the WFP ration is consumed, (b) no post-harvest losses, (c) the global crop production yields are achieved, and (d) only maize and soybeans are produced on all 269 mio ha African cropland. If the production yields will remain low like today, only 2 billion can be fed, even 0.8 billion people more than today. That even this can be achieved can be doubted, because already today 240 mio (20%) of the people face hunger and there is already food import to Africa. The continent has imported 2016 about 20 mio tons of maize for 4.1 billion US$ (205 US$/ton) and 2 mio tons of soybeans for 812 million US$ (406 US$/ton) (FAOstat 2019).

It can be doubted that an increase of African crop production towards global yields (280% for maize, 200% for soybeans) throughout the continent (Table 6). To increase the production from today's low external input—low output production towards today's global medium input—medium output yields, the

Fig. 1 Number of people in Africa, which can be fed with a WFP minimum diet if global or African production yields achieved



Average production yields 2017: Global: maize 5.8, soybean 2.8 = 4.9 t/ha/y, Africa: maize 2.1, soybean = 1.9 tons/ha/y (FAOstat 2019). Cropland use: 71% maize and 29% soybeans. Population estimations (UN 2019): medium est. 4.3 billion; maximum est. 5.9 billion people. Assumptions: only maize and soybeans are produced, no post-harvest losses, no LULUCF, only WFP ration (2,100 kcal/p/d): 190 kg maize and 60 kg soybeans per person and year.

production costs, for example, for maize and soybeans would increase by roughly 300 US$/ha/y (e.g., 100 US$ for improved seeds, 75 US$ for fertilizer, 75 US$ for pesticides), even if there are no increase of costs for labor, machines, capital, and land (this would probably need 300 US$ more per ha and year). If we calculate this per person, only 14.66 US$ would be necessary per year. This seems to be a little, but extrapolated for all 269 mio ha cropland in Africa, that would be about 80.718 billion US$ per year, or 3.3% of the 2.45 trillion US$ of Gross National Product of the continent (2019).

If the production yields in Africa will remain low, 53 to 66% of the required minimum food has to be imported (Fig. 1). That would be between 413 and 737 mio tons of maize and 136 to 233 mio tons of soybeans every year (Table 5). If the food is produced for example in the Americas (highest continental yields with 8 tons per ha maize and 3.2 tons per ha soybeans), between 82 and 169 mio ha arable land would be needed to produce for food export to Africa. This would be about 5% and 10% of the global arable land today (2017).

Using the prizes of 2016 ("cost include fright" -cif-Africa: 205 US$ per ton maize and 406 US$ per ton soybeans; FAOstat 2019), the value of the African minimum food import in 2100 would be between 144 and 246 billion US$, every year. That would be between 34 and 42 US$ per person and year for food import to Africa (Table 5). The question will be: who will pay this? Probably, Africa will not have enough money to afford it, and food aid would be necessary.

Not only the production, but also the food distribution will be challenged. While rural people can produce their food on their own (subsistence), urban people have to buy food (market). Already today more than 50% of the African population lives in urban areas, and Africa's cities will grow very fast in the future. Today, none of the global biggest 10 cities is in Africa, but in 2100, five of them and all are meta-cities with more than 20 mio inhabitants: Lagos (88 mio; biggest city of the world), Kinshasa (83 mio, no. 2), Dar Es Salaam (74 mio, no. 3), Khartoum and Niamey (56 mio each, nos. 6 and 7) (Hoornweg and Pope 2017).

Solutions to reduce food insecurity

In context to the above worst-case scenarios for Africa, that not all needed food can be produced on limited local cropland, other options are needed:

- Global: increasing of global food trade (from high productive towards high demand areas) and/or
- Local: to produce it locally land-based (e.g., intensive gardening) and landless (balcony, indoor, roof, vertical, container, reactor food, etc.).

Both options have advantages and disadvantages, and both will remain in the future and need to be developed into the direction to solve future food challenges.

Table 5 Annual volume and value of food import needs in Africa for 4.3 or 5.9 billion people, if production yields remain low in the continent (African yields 2017: maize 2.1 t/ha/year, soybeans 1,4 t/ha/year

	Units	Maize** (71%)	Soybean** (29%)	Total (100%)
4.3 billion people (53% of food imported):				
Import need	mio tons/year	431	136	567
Import value***	billion US$/year	88	55	144
Volume/person	kg/p/year	101	32	133
Value/person	US%/p/year	20.64	12.91	33.55
5.8 billion people (66% of food imported):				
Import need	mio tons/year	737	233	970
Import value***	billion US$/year	151	95	246
Volume/person	kg/p/year	125	40	165
Value per person	US$/p/year	25.71	16.08	41.78

**Standard WFP ration: 2100 kcal/p/day, 12% from protein, 17% from fat = 71% maize and 29% soybean in cropland use

***Import figures Africa 2016: maize 20 mio tons for 4.1 billion US$ (205 US$/ton) and 2 mio tons soybeans for 0.812 billion US$ (406 US$/ton) (FAOstat 2019)

Let us have a short view on the global option. Despite all the impacts and effects, the globalized food chain has brought, significant problems and risks cannot be ignored. The main problems are private- and profit-related global food chains, market difficulties (transport and processing disruptions, food demanding areas are not able to pay for imported food, and aid is needed), degradation, and contamination (pesticides, nutrients in water, drug resistant germs) of natural resources (soil, water, biodiversity, air, landscape). On the other side, the global land-based food is not free from risks like natural calamities (more frequent and damaging storms, droughts, floods) and last but not the least, political risks (e.g., wars, protection, embargos, terrorism). Therefore, global food chains have done a good job, but the impact has negative impacts as well. Several food system changes try to reduce the impacts, for example, organic agriculture with globally already 1.6% farmland share (IFOAM 2019), but this is not scaled-up enough, probably not good enough for the real future challenges, because the production yields are not high and the ecological impacts are not low enough (Rahmann et al. 2008, 2009, 2017) (Table 6).

Let us spend some thoughts regarding local option. Food sovereignty in very densely populated and low developed areas/regions is becoming less secure and safe in very dense populated and low developed areas/regions. Not only productive farmland is becoming more and more scarce, but also enough and clean water, necessary nutrients, productive and healthy seeds, renewable energy and—very important—better knowledge of all actors in improving food systems sustainable (from production to consumption). For such conditions, we proposed a combination of land-based and landless food production for a local, circular, and sustainable food chain (Rahmann et al. 2019).

Space efficient food production

Maize and soybean are the most space efficient crops to produce a WFP ration. In the case of Africa, 489 m^2/person would be necessary (Table 7), if global average yields can be achieved in Africa in the next decades, no food losses and only maize and soybeans are produced.[2]

[2] Alternative WFP rations composed by "rice (*Oryza sativa*) and soybean" would need 19% (580 m^2/p) and "wheat and soybean" 42% (695 m^2/p) more space. Other legumes than soybeans, like horse bean, lentil, or white beans, have much higher space demand and do not contain enough oil for WFP minimum criteria for rations.

If the production yields will remain low like today, 1216 m^2/person crop land would be needed, and—vis-a-versa—with the highest continental yields of Americas, 22% could be saved (382 m^2/person). This shows, there would be a chance to achieve food sovereignty, but only in the case of very high yields.

With the assumptions in Table 5, we can calculate, that 28 to 36 US$ per person and year are the threshold for the landless production to substitute 118 to 210 kg imported food. This would cost roughly 0.20 US$/kg (maize import -cif- Africa: 205 US$/ton) and would be very low, compared to production costs of recent photo-reactors, which produce high quality products for cosmetics and food additives for 10 to 50 US$/kg dry matter.

Of course, these model calculations of minimum diet and minimum cropland space (Table 1) do not consider all aspects. Some other crops (e.g., potatoes, white beans) do have comparable high yields and product qualities; some areas allow more than one harvest a year; maize and soybean cannot produced everywhere. On the other side, food chain losses and nutritional and food culture needs are not considered. For this paper, these factors are not considered.

Local, circular, and sustainable food chains

If food is insecure and import and aid not possible, local food systems have to be developed. A local, circular, and sustainable nutrient, energy and food chain was designed (Rahmann et al. 2019). As shown in Average African production yields 2017: maize 2.1, soybean = 1.9 tons/ha/year (FAOstat 2019). Assumptions: only maize and soybeans are produced with a land use relation of 71% maize and 29% soybeans, no post-harvest losses, no LULUCF, only WFP ration (2100 kcal/p/day): 190 kg maize and 60 kg soybeans per person and year.

In Fig. 2, the "green chain" displays the traditional nutrient and food chain: from cropping to human and livestock. Because this chain is not able to produce enough food, the "blue chain" has been added. Biomass from the "green chain," sewage, and waste-water from households are used for energy production and become homogenizing for a reactor-based and landless food production. Both chains together have to produce enough, healthy and affordable food for people in high populated regions and low development conditions.

Let us have some look to the two chains. The crop production of the "green chain" is the core of the system. If only 360 m^2 per person is available, an intensive

Table 6 Food security action assessment

Actions	Assessment	Impact
Expansion of crop production	- Difficult due to water shortage, low soil fertility, remote, steep, rocky. - Grassland: largely only extensive grazing possible. - Protected areas (e.g., reserves) restricted for farming. - In many countries no additional cropland available.	Low
Intensification of crop production	- Deficits in infrastructure, agricultural competence, and capital. - Food hazards and ecological risks high. - Mainly not related to hunger reduction: difficult for small scale family farming, non-food, cash crops, and/or export oriented, ... - More impacted by soil degradation, plant diseases, climate change	Middle
Imports	- Imports have to be paid (hunger is a result of poverty) - Food aid for billion people difficult?	Low
Population growths control	- "Life happens" children are not only a result of family planning. - UN estimations on fertility is optimistic with 2.1 child/wife in 2100.	low
Migration	- Urbanization is on the go. - Intra- and international and intercontinental is increasing.	high
Nutrition change (habits and food)	- Livestock products become more important ("white meat")!	low
	- Food: post-harvest losses and misuse reduction?	high
	- Insects, mushrooms, algae, etc., for food?	high

production for a maximum of needed food has to be carried out. Maize and soybean are the best crops to meet WFP ration demands, plus cabbage as an example for vegetables with high production yields and valuable nutrients and taste. A cultivation scenario of these three crops shall show the potential and limitations of the "green chain" (Table 8).

The nutrient flow in Average African production yields 2017: maize 2.1, soybean = 1.9 tons/ha/year (FAOstat 2019). Assumptions: only maize and soybeans are produced with a land use relation of 71% maize and 29% soybeans, no post-harvest losses, no LULUCF, only WFP ration (2100 kcal/p/day): 190 kg maize and 60 kg soybeans per person and year (Table 9).

Table 7 Minimum food and cropland need for annual WFP ration

	Maize (71%)	Soybeans (29%)	Total
Food energy supply (kcal/p/day)*	1491	609	2100
Protein supply (g/p/day)**	33	54	87
Food demand (kg/p/year)	190	60	250
Cropland needed (m2/p/year):***			
Lowest continental yields (Africa):	796	420	1216
Global average yields (all continents):	287	202	489
Highest continental yields (Americas):	205	178	382

*2100 kcal/p/day, 12% of the kcal are coming from protein and 17% from fat (WFP 2019)

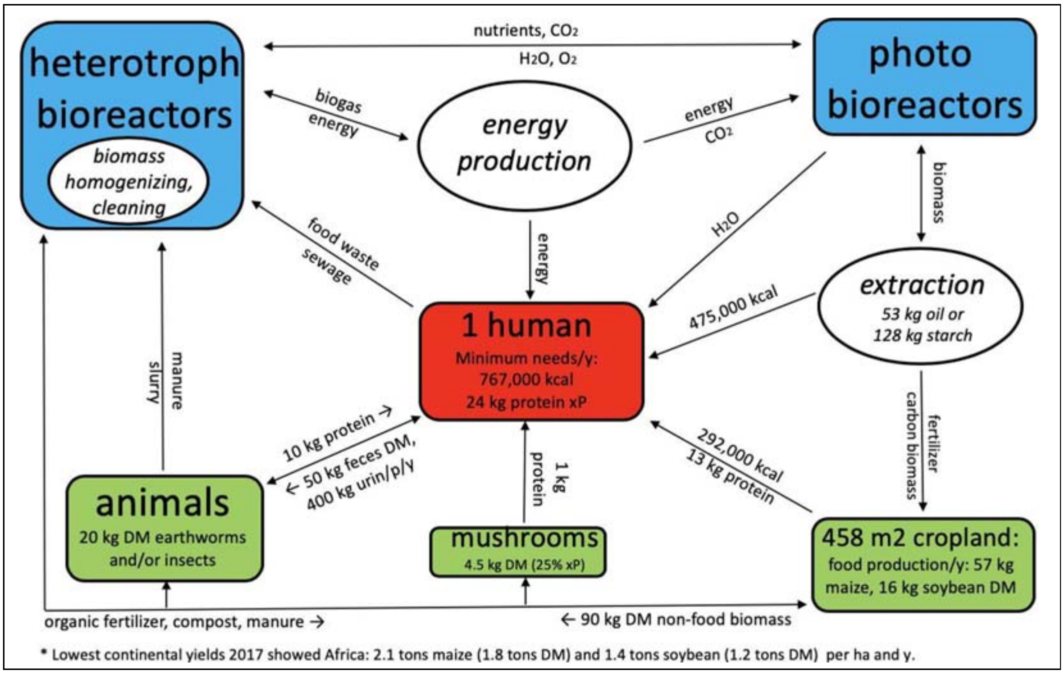
**1.3 g xP per kg liveweight to achieve with 80% digestibility

***Based on average yields found in FAO databank for the year 2017 (visited 2019)

Figure 2 shows that it is not possible to produce enough food with low African production yields. Not protein, but production of food energy (kcal) is the main deficit. Less than one-third can be harvested. Protein is also a challenge, but it can be enough produced, if mushrooms are cultivated on the 70-kg non-food biomass from cropping (0.1 kg mushroom/kg biomass DM with 2.5% protein) and earthworms and insects are used for animal protein (insects with 50% and earthworms with 60% protein).

Average African production yields 2017: maize 2.1, soybean = 1.9 tons/ha/year (FAOstat 2019). Assumptions: only maize and soybeans are produced with a land use relation of 71% maize and 29% soybeans, no post-harvest losses, no LULUCF, only WFP ration (2100 kcal/p/day): 190 kg maize and 60 kg soybeans per person and year.

If global yields would be achieved on 458 m^2 cropland, not all the space would be necessary for maize (50% of total cropland) and soybeans (25%) (Average Global production yields 2017: maize 5.8, soybean 2.8 = 4.9 tons/ha/year (FAOstat 2019). Assumptions: only maize and soybeans are produced with a land use relation of 71% maize and 29% soybeans, no post-



Average African production yields 2017: maize 2.1, soybean = 1.9 tons/ha/y (FAOstat 2019). Assumptions: only maize and soybeans are produced with a land use relation of 71% maize and 29% soybeans, no post-harvest losses, no LULUCF, only WFP ration (2,100 kcal/p/d): 190 kg maize and 60 kg soybeans per person and year.

Fig. 2 Subsistence food production for one person on 458 m^2 cropland under African yields scenario

harvest losses, no LULUCF, only WFP ration (2100 kcal/p/day): 190 kg maize and 60 kg soybeans per person and year Fig. 3). Up to 25% could be planted with vegetable and/or fruits. The system would be much more productive and efficient. Even chicken could be kept, fed with protein from mushrooms and crop production.

Average Global production yields 2017: maize 5.8, soybean 2.8 = 4.9 tons/ha/year (FAOstat 2019). Assumptions: only maize and soybeans are produced with a land use relation of 71% maize and 29% soybeans, no post-harvest losses, no LULUCF, only WFP ration (2100 kcal/p/day): 190 kg maize and 60 kg soybeans per person and year.

Table 8 Calculated production yields of selected crops per m^2 and year

		Maize	Soybeans
Food energy (kcal/kg DM)		3840	4490
Food protein (g/kg DM)		100	440
Production of food	Low yields*	0.18	0.12
(kg DM/m^2/year)	Average yields*	0.49	0.25
	High yields*	0.69	0.28
Production of food energy	Low yields	685	529
(kcal/m^2/year)	Average yields	1901	1102
	High yields	2665	1253
Production of protein	Low yields	18	52
(g xP/m^2/year)	Average yields	49	108
	High yields	69	123

*Global average, lowest and highest continent production figures 2017 (FAOstat)

Table 9 Calculation of food energy and protein production with maize, soybean and cabbage on 458 m^2 cropland plot under different yields

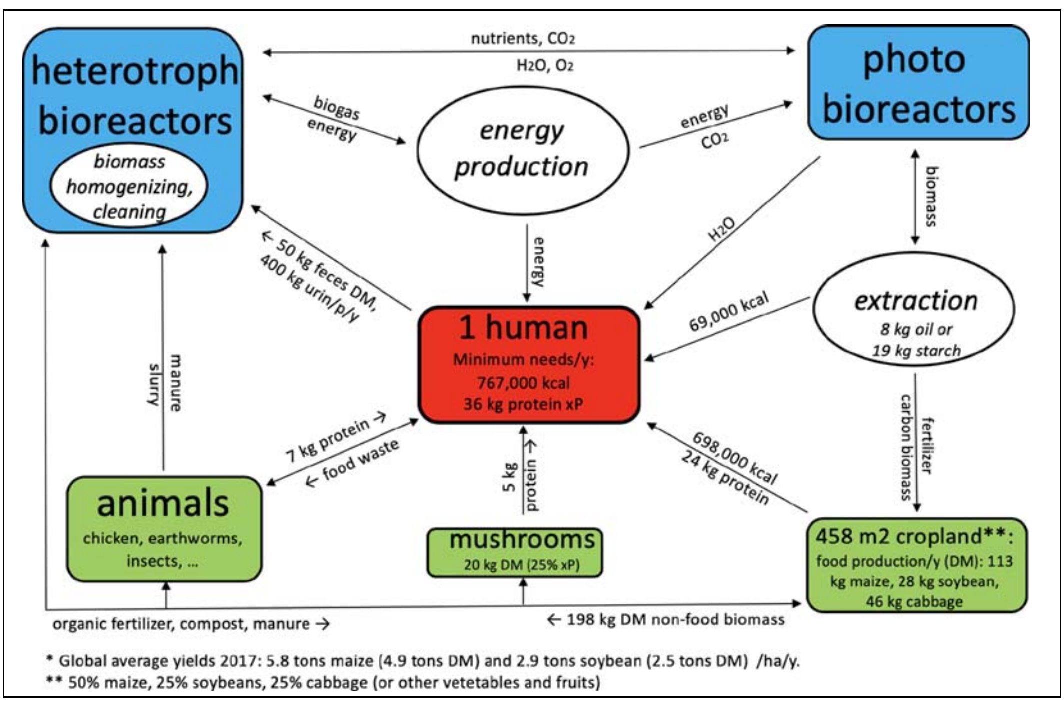
		Maize 320 m^2	Soybeans 138 m^2	Total 458 m^2
Total biomass** production	Low yields*	131	33	164
(kg DM)	Average yields*	364	68	432
	High yields*	511	77	588
Total food production*	Low yields	57	16	73
(kg DM)	Average yields	158	34	192
	High yields	222	39	261
Production of energy	Low yields	219,068	73,057	292,125
(kcal/year)	Average yields	608,170	152,082	760,252
	High yields	852,706	172,917	1,025,623
Production of protein	Low yields	5705	7159	12,864
(g xP/year)	Average yields	15,838	14,903	30,741
	High yields	22,206	16,945	39,151

*Global average, lowest and highest continent production figures 2017 (FAOstat)

**Total biomass production is food and non-food: relation for maize: 1:1.3 and soybean: 1:1

Landless food production

Landless food production is just scratched by some pioneers and inventors. Recent research is going for, e.g., artificial meat (Ireland 2019), roof/vertical gardens (Southey 2019), and container hydroponics (Sustainia 2019). They are all producing with highly sophisticated in technology, infrastructure, knowledge, and hygiene



Average Global production yields 2017: maize 5.8, soybean 2.8 = 4.9 tons/ha/y (FAOstat 2019). Assumptions: only maize and soybeans are produced with a land use relation of 71% maize and 29% soybeans, no post-harvest losses, no LULUCF, only WFP ration (2,100 kcal/p/d): 190 kg maize and 60 kg soybeans per person and year.

Fig. 3 Subsistence food production on 458 m^2 for one person cropland under global average yields scenario as well as capital intensive. Additionally, they are not linked to the land-and water-based food production nor the nutrient chains (e.g., human feces). Potential products targeting high price food chains. Therefore, all of them lacking the ability for solution of food insecurity in less developed areas/regions with very high population densities. Landless food production, using contaminated nutrients and produce for low/no price staple food for poor and fragile markets is an open research area. We initiated the project "LandLessFood" (https://www.thuenen.de/en/ol/by-specialist-disciplines/biodiversity/landlessfood/) as a conceptional model to cope with these defined pre-conditions and published it in Rahmann et al. (2019).

To ensure food sovereignty in Africa, photoreactor-based food production would have to deliver 475,000 kcal/person/year, if only 458 m^2 cropland per person are available and the production yields remain low like today. This could be 53 kg oil (9000 kcal/kg) or 286 kg starch (3700 kcal/kg), produced by algae or bacteria.

The reactor-based production costs of food energy must be low, e.g., 0.06 US$/1000 kcal, if the food import costs (cheapest is maize with 205 US$/ton cif Africa) is considered as economic benchmark. If the reactor food would be more expensive, the import of maize would be the better alternative (including the protein in maize), if available and payable. The market price for 1 kg of oil could not exceed 0.54 US$ and 1 kg of starch 0.22 US$, respectively. This would be 32 US$ per person and year, a very low price, but about 188 billion US$ for 5.9 billion people. Reactor food technology can be high-tech and industrial-like, but it would be much more suitable to have it low-tech, homebased, and robust. If algae or bacteria can be produced at home by people, some of the main costs in production can be ignored: buildings and labor. Simple and cheap technology for reactor-based production of oil or starch is a R&D challenge.

Funding Information Open Access funding provided by Projekt DEAL.

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