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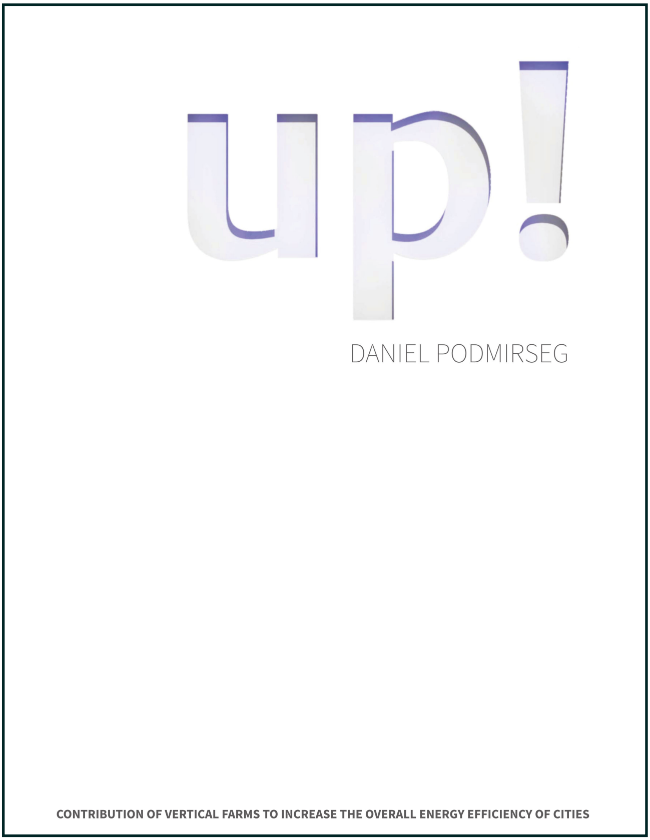
Contribution of Vertical Farms to Increase the Overall Energy Efficiency of Cities



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1. Introduction

Vertical Farming is defined as a highly industrialized year round cultivation method for food production, adaptable for multiple crop types, where the verticalized building typology, its programme and functions primarily focus on optimium plant growth. The building is seen as a structural element of the urban ecosystem. In addition to food production, the Vertical Farm must incorporate elements of the food sector which, at present, are spatially detached from each other on a global scale, something which has a severe impact on energy consumption and the environment. Form Follows Energy[1] for Vertical Farms in three ways: to grant optimum growing conditions for crops, optimized to follow the position of the sun all year round and guaranteeing energy flows, meaning phenomenologically, on the ground level of the city, or preferably, also vertically for public use. Primarily the development of the building itself must follow two main goals: Increasing the overall energy efficiency of a city and also attempting to bring about a considerable reduction in land use, as a result of the favorable comparison between vertically achieved yield and traditional agricultural practices.

Vertical Farming is a subject of controversial discussion. Throughout my last exhibitions, lectures and public presentations, the boundless fascination this theme unleashes among some audiences is as notable as the emphatic refusal it provokes from others. The typology of the Vertical Farm has deepened considerably since my diploma at the Academy of Fine Arts in Vienna, supported by Prof. Markus Schäfer. This progress is primarily due to the potential of the Vertical Farm to re-establish local social and economic interdependencies within the city on the one hand, while on the other, even if it does not seem to be the full solution at first sight, it at least presents a partial opportunity to relieve the burden on the current situation of conventional world agriculture practices and the dependency of the urban population on it.

Energy consumption, soil erosion, the conversion of natural land for farming use, especially using slash-and-burn methods in rain forests to make additional arable land available, i.e. the Neolithic Revolution, probably the biggest revolution of humankind in which hunters and gatherers became farmers, is now turning into a dystopia.

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1 CODY, B. 2012. „Form follows Energy - Beziehungen zwischen Form und Energie in der Architektur und Urban Design, DBZ Deutsche BauZeitschrift, Bauverlag BV GmbH, Gütersloh, p.48 ff.

World total primary energy supply (TPES) in 2014 was around 550 Exajoule (EJ).[1] A third of it is used by the food sector.[2] On a global scale, for every calorie we need to cover our daily energy requirement, we consume nearly six calories of total primary energy. One percent of the global landmass is defined as built-up land, where with the exception of a small percentage of indigenous populations, more than 7 billion people live. The area required to supply world population with food is ten times higher. Countries with emerging economies and above all the developed countries require and have established a food production network over the past few decades, which has reached a global scale and is completely dependent on hydrocarbon energy.

The world population will continue to grow within the next decades, reaching a plateau in 2075 of 9.22 billion people before it starts to decline.[3] This work aims to contribute to the discussion on whether Vertical Farming entails the potential to increase the overall energy efficiency of cities.

The architectural interest in how this typology could be interwoven into the city fabric first needed to be reset before fundamental questions could be answered, at least in part. There is no doubt, even without simulating the energy demand of a verticalized food production entity that this must be higher than it is on the field. In addition, the building is not planned as a principle for humans who have completely different requirements regarding the indoor climate. Light is perceived differently, humidity and temperature must be in a different relationship. What does a crop plant actually need to turn light into sugar to be a relevant deliverer of calories and nutrients for human consumption? These questions led to the decision to start an excursion through plant physiology and quantum physics for the development of parametric Vertical Farm models and to develop an aligned simulation tool especially for this calculation.

Throughout this research work, however, a number of limitations must be made, for reasons of time and complexity. The parametric Vertical Farm primarily attempts to find answers to the influence of different orientations or, more precisely, to find guidelines for future typological developments, especially in the context of the zoning of the building and the building depth. Water evaporation from the plants was not considered, although this clearly has an impact on heating demand. Plant growth, especially growth in height has a strong impact on the lighting demand. Although techniques are being developed by the author of this thesis to simulate the autoshading of the plants themselves, this emerging research did not find a place in this work by the time the dissertation was completed.

1 http://www.iea.org/publications/freepublications/publication/KeyWorld2013.pdf, retrieved 05.04.2014

2 FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO, p.10

3 http://www.un.org/esa/population/publications/longrange2/WorldPop2300final.pdf, p.1, retrieved 10.09.2015

STATE OF DESIGN

There are already plenty of design proposals for Vertical Farming with most of them unfortunately stopping at the design level. Over the past few years, since my diploma in 2008, some prototypes and research entities of Vertical Farms have now been built or are about to be built ranging from Suwon in South Korea to Paignton Zoo in Devon, or the exciting “Vertical Harvest” project in Wyoming, USA, and above all the strong architectural statement that has been made in Linköping, Sweden, where Plantagon had its ground breaking ceremony in 2012.

STATE OF RESEARCH

In most cases, academic research papers, dissertations or master theses dealing with Vertical Farming are an attempt to frame the state of (research)design, touching as raw assumptions the widely discussed topics on (Vertical) farming, namely water, land use and energy consumption. Vertical Farming is complex and current speed of growth of companies, industries, plant physiologists, horticulturists, urbanists and architects dealing with this topic makes it necessary to accept that the practice of stacking the cultivation area is still in a state of infancy.
On a qualitative level, Gordon Graff‘s thesis has to be mentioned here.[1] His work highlights the necessity of reading the Vertical Farm-building as an integrative part of the city‘s metabolism. A work which delivers quantitative values was written by Chirantan Banerjee.[2] The market analysis of a Vertical Farm elaborates predictions in energy and investment costs.
Basic research data for crop production in controlled environments delivers, above all, the National Aeronautics and Space Administration.[3] Abundance of activity in research on high-tech greenhouses is noticeable especially in the Netherlands[4] and Germany[5] as well as in the US[6]. Recommendations for literature can be retrieved from the bibliography of this work. The quickly growing interest on agriculture within controlled environments within the last years makes it understandable that the list on this page must be considered as incomplete.

The doctoral thesis at hand is enlarging the research on energy consumption of Vertical Farming. By concentrating on tomatoes, *Lycopersicon Esculentum* (Mill.), it was possible to consider specific plant needs, to highlight parameters influencing pho-

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1 GRAFF, G. 2011. Skyfarming. Master of Architecture, University of Waterloo, Ontario, Canada.
2 BANERNJEE, C. 2012. Market Analysis for Terrestrial Application of Advanced Bio-Regenerative Modules: Prospects for Vertical Farming. Masterarbeit, Rheinische Friederichs-Wilhems-Universität, Hohe Landwirtschaftliche Fakultät.
3 https://www.nasa.gov/image-feature/space-farming-yields-a-crop-of-benefits-for-earth, retrieved 31.10.2015
4 http://www.wageningenur.nl/en/Expertise-Services/Research-Institutes/Wageningen-UR-Greenhouse-Horticulture.htm, retrieved 31.10.2015
5 http://www.zineg.net/ZINEG_E/, retrieved 31.10.2015
6 http://ag.arizona.edu/ceac/, retrieved 31.10.2015

tosynthesis in more detail and to integrate them into a parametric simulation model. The simulation method, especially developed for the thesis, unlike simulation software widely used for building simulations, evaluates year round solar radiation in WPAR within a Vertical Farm by using specific climate data. The simulation model was built up in a way so that parameters such as plant needs, climate data and building geometry can easily be substituted and therefore help to optimize future studies on an architectural level and will facilitate predictions relating to energy consumption of specific crops cultivated in Vertical Farms in specific climate zones.[1]

The integration of agriculture into discussions about architecture and urbanism is actually experiencing a revival. Concepts on (horizontal) urban farming from Ebenezer Howard to Frank Lloyd Wright and Le Corbusier are well known and documented. Vertical Farming as a substitution of traditional soil based agriculture or a supplement in food production is increasingly becoming an integral part of research works, theses, design projects and competitions dealing with urbanism in general[2 3 4], smart cities[5], „productive cities“[6 7] or „Hyperbuilding cities“[8].

Vertical Farms as buildings or elaborated design proposals can be retrieved from the world map on page 128.

1 CODY, B. 2012. „Form follows Energy - Beziehungen zwischen Form und Energie in der Architektur und Urban Design, DBZ Deutsche BauZeitschrift, Bauverlag BV GmbH, Gütersloh, p.48 ff.

2 VIE:BRA - Vienna-Bratislava-City, urban strategies: http://www.dieangewandte.at/jart/prj3/angewandte/main.jart?rel=en&reserve-mode=active&content-id=1234966513566&Akt-Id=4493, retrieved 31.10.2015

3 http://www.braincitylab.org/, die angewandte, Coop Himmelb(l)au, retrieved 31.10.2015

4 http://milliardenstadt.at. University of Technology, Vienna. Project initiator: Lukas Zeilbauer

5 LIM CJ, ED LIU. 2010. Smartcities + Eco-warriors. Oxfordshire (first published), New York. Routledge.

6 NELSON, N. 2009. Planning the productive city. Available: http://www.nelsonelson.com/DSA-Nelson-renewable-city-report.pdf. Delft Technical University, Wageningen University and Research, NL

7 http://www.futurarc.com/index.cfm/competitions/2013-fap/. Addressing „adaptation of existing building typologies for agriculture (...) urban networks for production [and] distributions (...)

8 CODY, B. 2014. Form Follows Energy - Die Zukunft der Energie-Performance, energy2121, Bilder zur Energiezukunft, Klima- und Energiefonds, Vienna, omninum, p. 121 ff.

2. Landuse, Biocapacity and Energy Consumption

2.1. Compiling a status quo model of traditional agriculture

Ever since agriculture became more and more structurally coupled with industry, especially the oil- and armament‘s industries[1] [2], agricultural production has not only completely changed in practice and scale, but also in its energy consumption patterns. From the Neolithic Revolution to the Green Revolution the only energy source for food production was direct solar radiation and human labor which was then supplemented increasingly by the use of electricity and, above all, by fossil fuels.
Agricultural production is becoming ever more energy intensive, if not altogether dependent on cheap and abundant oil and gas.[3] It is becoming a widespread concern that the reliance of the global food system on fossil fuel increases drastically.“[4] In fact there is an intrinsic factor of energy consumption in conventional food production that lies behind the structural coupling of the oil- and the food industries. Regarding future food supply, it is necessary to understand if Vertical Farming can make cities more energy independent, especially from hydrocarbon energy. At the present time one third of world energy consumption is accounted for the “nutrition” system (food sector), 25 % of this within the farm gate.

Beyond the production entity of the Vertical Farm although a significant reduction of hydrocarbon energy and CO2-emissions with urban Vertical Farming can be assumed. Substitution of natural sunlight with electrical power and heating demand for year round crop production however, might well increase energy demand in urban agglomerations. The question is if the reduction of energy consumption beyond the Vertical Farm gate (Vertical Farm-gate) can balance out the surplus in energy consumption for indoor crop production.

Before this question can be investigated with appropriate depth, a brief digression on the issue of energy consumption in the global food sector is appropriate at this

1 FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO

2 FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO. p.6

3 ibid. p.6

4 “It is this increased reliance of global food systems on fossil fuels that is now becoming cause for concern.” Energy-Smart” Food for People and Climate Issue paper, FAO, 2011, http://www.bigpictureagriculture.com/2011/12/fao-report-warns-about-fossil-fuel.html (19.05.2014)

point. The objective of this chapter is to investigate the current situation of world agriculture in terms of land use efficiency and to what extent it can be increased, while additionally presenting an all-round view of the limits to the current biocapacity of the earth for meeting future food demand. Investigations of landuse, energy consumption and biocapacity have the purpose of establishing the degree of pertinence Vertical Farming has gained in the face of this situation.

2.2. Land requirement for daily coverage of essential nutritional value for the human body

The human body, like that of every living being needs energy to sustain its biological functions and life. There are multiple calculation models to define the specific energy need per person. In addition to several prediction equations one of the most notable of these for calculating the Basal Metabolic Rate (BMR)[1] is the Harris-Benedict equation, created in 1919. This equation was revised in 1984 using new insights in biology. This was widely regarded and used as the best prediction equation until 1990, when Mifflin et al. introduced the Mifflin St. Jeor- Equation[2]. A simplification based on this equation will be used in this work to define the basal metabolic rate of the human body - which is „relatively constant among population groups of a given age and gender. (...)“[3]

- male: 1 kg of body mass consumes 24 kcal/day
- female: 1 kg of body mass consumes 24 * 0.9 kcal/day

BMR, broken down on organs and muscles of the human body, are divided as follows:

- liver 26 %
- muscles 26 %
- brain 18 %
- heart 9 %
- kidney 7 %
- other organs 14 %[4]

In addition to BMR, the Physical Activity Level (PAL) is of importance to calculate the total energy requirement. The Food and Agriculture Organization defines three ranges of values:

- sedentary or light activity lifestyle 1.40 - 1.69
- active or moderately active lifestyle 1.70 - 1.99
- vigorous or vigorously active lifestyle 2.00 - 2.40[5]

1 Basal metabolic rate (bmr), index of the general level of activity of an individual's body metabolism, determined by measuring its oxygen intake in the basal state—i.e. during absolute rest, but not sleep, 14 to 18 hours after eating. The higher the amount of oxygen consumed in a certain time interval, the more active is the oxidative process of the body and the higher is the rate of body metabolism. (...) http://www.britannica.com/topic/basal-metabolic-rate, retrieved 25.08.2015

2 http://ajcn.nutrition.org/content/51/2/241.abstract, retrieved 12.06.2014

3 http://www.fao.org/docrep/007/y5686e/y5686e07.htm, retrieved 25.08.2015

4 http://www.fao.org/3/contents/3079f916-ceb8-591d-90da-02738d5b0739/M2845E00.HTM, retrieved 25.08.2015

5 „PAL values higher than 2.40 are difficult to maintain over a long period of time.“, ibid.

This PAL-value is the factor multiplied by, BMR to obtain the needed daily energy requirement for the human body.[1]
With these figures we can now make an assumption about the daily energy requirement of an adult person, irrespective nationality or culture:

• adult male, 75 kg, sedentary: 75*24*1.5 = 2,700 kcal/day
• adult female, 65 kg, sedentary: 65*24*0.9*1.5 = 2,106 kcal/day

The total energy requirement of a sedentary male can therefore be assumed as

- 2,700 kcal or
- 11.30 MJ or
- 3.14 kWh or
- 0.30 OE[2].

The total energy requirement of a sedentary female therefor can be assumed as

- 2,160 kcal or
- 8.82 MJ or
- 2.45 kWh or
- 0.24 OE.

world population		FOOD REQUIREMENT / CAPUT						FOOD REQUIREMENT / CAPUT / YEAR			
7,325,965,000		kCAL	kJ	Wh	MJ	kWh	OE	kCAL	GJ	kWh	OE
3,787,523,905	male	3,200	13,397.89	3,721.64	13.40	3.72	0.36	1,168,000	4.89	1,358.40	131.76
3,538,441,095	female	2,300	9,629.73	2,674.93	9.63	2.67	0.26	839,500	3.51	976.35	94.71
7,325,965,000	fao average	2,750	11,513.81	3,198.28	11.51	3.20	0.31	1,003,750	4.20	1,167.37	113.24

Tab.1. World food energy content requirement estimation

1 It is explanatory, that there are additional variables throughout a human lifetime which cannot be considered here, such as pregnancy-periods, lactating women, the length of adolescence, etc. Additional information about the principles followed by the 1985 FAO/WHO/UNU expert consultations can be found on http://www.fao.org/docrep/007/y5686e/y5686e07.htm, retrieved 19.08.2015
2 http://www.aie.org.au/AIE/Energy_Info/Energy_Value.aspx, retrieved 09.09.2015: 1 l oil = 42 MJ, 1 kg of oil equals 37 MJ

This total energy requirement[1] (Tab.1) for the human body must be get provided through a continuously operating food supply system, at the beginning of which agriculture is to be found, with the exception of some very few aboriginal populations the provision is thus based on the cultivation care of fertile land.

By the end of the Paleolithic period, human societies made a sweeping change in their habits. „(...) [A]fter hundreds of thousands of years of biological and cultural evolution, human societies were able to make increasingly varied, sophisticated, and specialized tools, thanks to which they developed differentiated modes of predation (hunting, fishing, gathering), adapted to the most diverse environments.“[2]

Back then, with the emergence of a radical change in food provision, a single person would have needed between 40 and 150 ha to cover the total energy requirement of an estimated 3,960 kcal (75*24*2.2) per day, by hunting, fishing and gathering, depending on the fertility and topography of the land. That means a family of five would have required approx. 200 ha. „This estimate is based on an ideal ecosystem, one containing those wild plants and animals that are most suitable for human consumption.“[3]

We are entered the final period of prehistory, around 10,000 years ago. Several societies, among the most advanced ones of the time, enabled one of the most radical and influential changes in human history - the Neolithic Revolution.
„At the beginning of this change, the very first practices of cultivation and animal raising, which we will call protocultivation and proto-animal raising, were applied to populations of plants and animals which had not yet lost their wild characteristics.

WORLD FOOD REQUIREMENT / YEAR					
kCAL	**EJ**	**TWh**	**barrel oil eq.**	**% of world oil prod.**	**% of world TPES**
4,423,827,921,040,000	18.52	5,144.96	3,138,749,808.20	8.92	3.38
2,970,521,299,252,500	12.44	3,454.75	2,107,614,338.69	5.99	2.27
7,394,349,220,292,500	**30.79**	**8,599.71**	**5,246,364,146.89**	**14.91**	5.62

But, as a result of such practices, these populations acquired new characteristics, typical of domestic species, which are the origin of most of the species that are still cultivated or bred today.“[4]

1 Data retrieved for the extrapolation of Tab. 1: https://www.cia.gov/library/publications/the-world-factbook/fields/2018.html, retrieved 01.06.2015
http://www.fao.org/docrep/meeting/009/ae906e/ae906e35.htm, retrieved 01.06.2015
http://www.eia.gov/forecasts/steo/report/global_oil.cfm, retrieved 01.06.2015
http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=5&pid=53&aid=1&cid=ww,&syid=2010&eyid=2014&unit=TBPD, retrieved 01.06.2015
„The reference man and woman“, FAO, http://www.fao.org/docrep/meeting/009/ae906e/ae906e35.htm, retrieved 31.10.2015

2 MAZOYER, M. & ROUDART, L. 2006. A History of World Agriculture, London, Earthscan. p. 71

3 PIMENTEL, D. et al. 2008. Food, Energy and Society, third edition, CRC Press Boca Raton. p. 45-46.

4 MAZOYER, M. & ROUDART, L. 2006. A History of World Agriculture, London, Earthscan. p. 71,

Within this change of habits, the creation of new social organizations were possible, or necessary. To plant grains in an already prepared fertile ground, or to capture and raise wild animals is not the challenge that was faced here. The difficulties at this stage of evolution were the following:

- „To arrange a social organization and rules that make it possible for units (or groups) of producer-consumers to subtract from immediate consumption an important part of the annual harvest in order to save it as seed stocks“(...)[1]
- „To exempt from slaughter enough reproductive and young animals to make it possible for the herd to reproduce itself“ (...)[2]
- „To protect the fields planted by one group from the previously recognized right of other groups to ‚gather‘ in those areas and to protect the animals being raised from the right of those groups to ‚hunt‘ them.“[3]
- „Lastly, what is difficult is to ensure the distribution of the fruits of agricultural work among the producer-consumer of each group, not only every day, but above all (...) when the eldest die and when the group becomes too large and must be subdivided into several smaller groups.“[4]

Still it took four thousand years until the first state-governmental structures in Egypt arose, but by settling down permanently for the first time in human history it was possible to build the first fortified villages and towns. The surplus of density of people around agriculture land directly led „to the rise of cities and civilization because it allowed people to develop and concentrate on manufacturing, trading and other specializations (...) like advances in technology, art and other innovations.“ [5]

The natural landscape became divided in two cultured landscapes - land for agriculture and land for cities, spatially united - as the nucleus for further civilizations.

Approximately 50 million people lived on earth by the beginning of the Neolithic Revolution.[6] This revolution now started a steady and continuous growth of the world population. Several factors have been attributed to this:

1 MAZOYER, M. & ROUDART, L. 2006. A History of World Agriculture, London, Earthscan. p.71
2 ibid. p.71
3 ibid. p.71-72
4 ibid. p.72
5 MC.KINNEY, M. et al. 2012 „Environmental Science: Systems and Solutions“, Burlington, Logan Yonavjak Jones & Bartlett Publishers. p. 36
6 ibid. p. 35

- „Settlement on farms may have allowed women to bear and raise more children; freed from the nomadic lifestyle, women no longer had to carry young offspring for great distances (...)“
- Labor capacities of children can more easily used in agriculture than in gathering and hunting
- „Agriculture and domestication may have made softer foods available, which allowed mothers to wean their children earlier.“ More children a mother therefor could bear.
- Higher densities of people were possible, as a consequence of agriculture and domestication. „(...)[W]ith farming, one family or group of persons could raise more food than they personally needed.“

The upcoming developments of tools, achieved knowledge in plant culture, seed production and husbandry and especially the capacity in storing sun energy through feed and food storage for periods when nothing can be harvested because weather or seasonal conditions radically reduced the area needed to supply human beings with their daily energy requirements to guarantee a personal healthy life for the individual and on a communal level - maintaining social cohesion.

Before we come up with a concluding ratio in land use between hunters/gatherers and sedentary people, an important concept for food supply needs to be explained, the food balance sheets, as defined by the Food and Agriculture Organization.

2.2.1.Food Balance Sheets

Food balance sheets create a picture of the pattern of food supply of a specific country in a defined period. This information sketches the daily consumption of food items of a country both in terms of the amount (g/day) and the nutritional value (kcal). In addition FBS provide information about the quantity of imports and exports, items used for feed (livestock), used for seeds and for food losses or food waste. Apart from several weaknesses, e.g. they do not provide any information on differences in food supply within a country or seasonal differences, the FBS are (...) the only source of standardized data that permit international comparison over time.[1] FBS „do provide an approximate picture of the overall food situation in a country and can be useful for (...) nutritional studies. In addition FBS provide data to estimate future changes in food supply or, more correctly, food consumption, especially in countries with emerging markets.“[2]

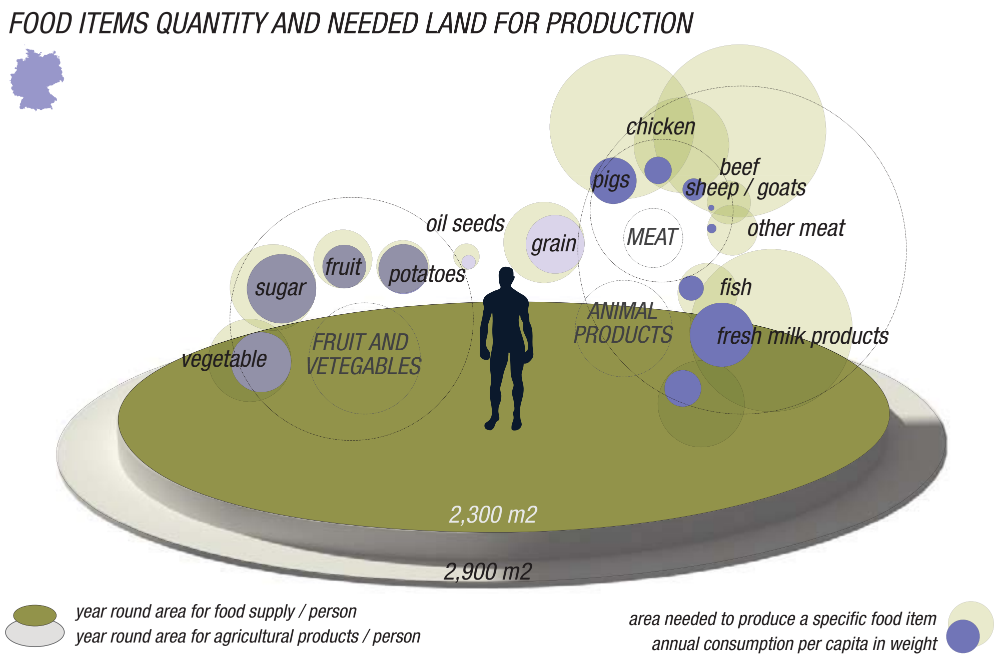

Fig.1. Arable land per person and food items consumption ratio (blue) and the related area needed (green) exemplary for Germany

As we have seen before in our two assumed examples, an average person needs around 2,500 kcal/day. By contrast with the data provided by FBS, this is data for food consumption, specifically the amount of energy a human being needs per day to sustain biological functions and life. Before food can be consumed, it must first be provided - this is defined as food supply. The values for this are always are high-

1 FOOD AND AGRICULTURE ORGANISATION OF THE UNITED NATIONS 2001. Food balance sheets. A handbook. Rome: FAO. p.4

2 ibid.