Wissenschaftszentrum Weihenstephan für
Ernährung, Landnutzung und Umwelt

Assessment of the Ecological Sustainability of Foods – with a Main Focus on the Ecological Footprint

Master Thesis

In the Field of Sustainable Nutrition

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Declaration of Authorship

I, Kathrin Meinhold, herewith declare and confirm that the Master Thesis „*Assessment of the Ecological Sustainability of Foods – with a Main Focus on the Ecological Footprint*" has been my independent work, without help from others, and without using anything other than the named sources and aids. The texts, illustrations and ideas taken directly or indirectly from the various sources, quoted verbatim or paraphrased, have without exception been acknowledged and referenced.

Freising, 8th of February

Kathrin Meinhold

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Summary

The production and the associated consumption of our foods have substantial environmental impacts – in particular related to climate change and resource use. With the issue of sustainability gaining more and more importance in politics, society and also in the economy it is important that consumers, but also the producers and policy makers, know the status quo of different aspects of sustainability (for example resource consumption or amount of greenhouse gas emissions) for different food products.

Thus the analysis and evaluation of the ecological sustainability along the entire life cycle of various food products is a necessary first step. The number of appropriate assessment methods available in order to gather this kind of information is constantly increasing. By means of these assessment tools and indicators the main environmental impact categories (i.e. the input categories biotic/renewable and abiotic/nonrenewable materials, water, land area and air and the output categories waste, waste water and greenhouse gas emissions) of varying foods can be examined. However, the different assessment methods and indicators often only focus on one main aspect of the ecological sustainability. For example the Carbon Footprint is a well-developed indicator for greenhouse gas emissions, the Ecological Rucksack quantifies the amount of resources necessary for a certain food item and the amount of freshwater associated with a certain food can be measured by the concept of Virtual Water.

The indicator Ecological Footprint is a very promising and a more holistic approach for assessing the ecological sustainability of foods. The Ecological Footprint measures the amount of biologically productive land and water area which is required to produce all the resources a product, individual, population, country, etc. consumes, and to absorb the waste they generate. This area can then be compared with the earth´s actual biocapacity. Previously Ecological Footprint calculations have been carried out mainly on global and national scales, but nowadays they can be conducted on almost every level – including the food item level. In this piece of work a methodology was developed and applied to calculate actual Ecological Footprints of different foods by means of life cycle analysis databases and literature sources.

The results indicate mainly the high difference between animal-based and plant-based food items. Especially meat and highly concentrated foods like cheese have a high Ecological Footprint. Plant-based products in general have a very low Ecological Footprint, especially foods like fruits, vegetables or potatoes. This main outcome is supported not only by values from literature, but also the other reviewed tools and indicators for assessing the ecological sustainability all demonstrate this difference between plant- and animal-based foods. This phenomenon can be explained by the fact that animal-based food items require a lot more resources of any kind (for example biotic and abiotic resources, water, energy or land) and generate a lot more waste. The different indicators measure different parts of the resource consumption and/or waste generation and therefore show a difference between the plant-based and animal-based food items.

In general, therefore, the Ecological Footprint can be seen as a very appropriate indicator for the assessment of the ecological sustainability of foods. It covers some of the main environmental issues associated with food production, almost every food product can be assessed and it can be very easily communicated (for example to consumers). Nevertheless, the method is not fully developed yet and therefore leaves room for improvement. Major current constraints include the poor methodology standardization, the lack of appropriate underlying data and frequent methodology alterations. Furthermore one very important environmental aspect in the case of food production cannot be included up until now, that is greenhouse gas emissions besides CO_2. All these issues offer scope for a large number of future research applications. In the meanwhile a combination scheme with the Ecological Footprint and other indicators could serve as a comprehensive way for indicating the ecological sustainability of various food items. For example the “Footprint family”, e.g. the combination of the Ecological, Carbon and Water Footprint.

Zusammenfassung

Die Produktion und der Konsum unserer Lebensmittel hat erhebliche Auswirkungen auf die Umwelt – insbesondere im Hinblick auf Klimawandel und Ressourcennutzung. Daneben gewinnt der Nachhaltigkeitsgedanke nicht nur in der Politik, sondern auch in der Gesellschaft und in der Wirtschaft immer mehr an Bedeutung. Daher ist es wichtig, dass Verbraucher, aber auch Produzenten und politische Entscheidungsträger für verschiedene Lebensmittel den Status quo bezüglich verschiedener Aspekte der Nachhaltigkeit (z. B. Ressourcenverbrauch oder Höhe der Treibhausgasemissionen) kennen.

So ist die Analyse und Bewertung der ökologischen Nachhaltigkeit von verschiedenen Lebensmitteln entlang des gesamten Lebenszyklus ein notwendiger erster Schritt. Die Zahl der Bewertungsmethoden, die zur Verfügung stehen, um diese Art von Informationen zu sammeln, nimmt stetig zu. Durch diese Bewertungsmethoden und damit assoziierte Indikatoren können die wichtigsten umweltrelevanten Kategorien (d.h. die Input-Kategorien biotische/erneuerbare und abiotische/nicht erneuerbare Ressourcen, Wasser, Fläche und Luft sowie die Output-Kategorien Abfälle, Abwasser und Treibhausgasemissionen) verschiedener Lebensmittel geprüft werden. Jedoch konzentrieren sich die verschiedenen Bewertungsmethoden und Indikatoren oftmals nur auf einen Aspekt der ökologischen Nachhaltigkeit. Zum Beispiel ist der CO_2-Fußabdruck ein gut entwickelter Indikator für Treibhausgasemissionen, der Ökologische Rucksack beziffert die Höhe an Ressourcen, die ein bestimmtes Lebensmittel benötigt und mit Hilfe des Konzeptes „Virtuellen Wassers“ kann die Menge an Frischwasser, die einem bestimmten Lebensmittel zugeordnet ist, gemessen werden.

Der Indikator „Ökologischer Fußabdruck“ ist ein sehr vielversprechender und ganzheitlicher Ansatz für die Bewertung der ökologischen Nachhaltigkeit von Lebensmitteln. Der Ökologische Fußabdruck misst die Menge der biologisch produktiven Land- und Wasserflächen, die erforderlich sind, um alle Ressourcen, die ein Produkt, ein Individuum, ein Land, etc. verbraucht, zu produzieren und den Abfall zu absorbieren, der gleichzeitig entsteht. Diese Fläche kann anschließend mit der tatsächlichen Biokapazität der Erde verglichen werden. Bisherige Berechnungen zum Ökologischen Fußabdruck sind hauptsächlich auf globaler und nationaler Ebene

durchgeführt worden, aber sie können praktisch auf jeder Ebene durchgeführt werden - auch auf Lebensmittel-Ebene. In dieser Arbeit wurde eine Methodik entwickelt und angewandt, um Ökologische Fußabdrücke von verschiedenen Lebensmitteln zu berechnen.

Die Ergebnisse zeigen vor allem eine hohe Differenz zwischen tierischen und pflanzlichen Lebensmitteln. Vor allem Fleisch und hoch konzentrierte Lebensmittel wie zum Beispiel Käse haben einen hohen Ökologischen Fußabdruck. Produkte auf pflanzlicher Basis (bspw. Obst, Gemüse oder Kartoffeln) haben im Allgemeinen einen sehr geringen Ökologischen Fußabdruck. Dieses Ergebnis wird nicht nur von Werten aus der Literatur unterstützt, sondern auch die anderen betrachteten Indikatoren zur Beurteilung der ökologischen Nachhaltigkeit zeigen alle diesen Unterschied zwischen pflanzlichen und tierischen Lebensmittel auf. Dieses Phänomen kann durch die Tatsache, dass tierische Lebensmittel viel mehr Ressourcen jeglicher Art benötigen und mehr Abfall generieren, begründet werden. Die verschiedenen Indikatoren messen unterschiedliche Aspekte des Ressourcenverbrauch und/oder der Abfallerzeugung und zeigen somit die Differenz zwischen den pflanzlichen und tierischen Nahrungsmitteln.

Im Allgemeinen kann man den "Ökologischen Fußabdruck als einen sehr geeigneten Indikator zur Beurteilung der ökologischen Nachhaltigkeit von Lebensmitteln ansehen. Er umfasst einige der Haupt-Umweltprobleme, die mit der Nahrungsmittelproduktion in Zusammenhang stehen, fast alle Lebensmittel können evaluiert werden, und er ist ein sehr leicht kommunizierbares Instrument. Allerdings ist die Methode noch nicht voll ausgereift und lässt daher Raum für Verbesserungen. Gegenwärtige Schwächen sind bspw. die mangelhafte Standardisierung der Methodik, das Fehlen von geeigneten, den Berechnungen zugrunde liegenden Daten, und häufige methodische Veränderungen. Außerdem kann ein im Falle der Nahrungsmittelproduktion sehr wichtiger Umweltaspekt noch nicht berücksichtigt werden – nämlich Treibhausgasemissionen außer CO_2. All diese Schwachpunkte geben viel Raum für zukünftige Forschung. In der Zwischenzeit kann eine Kombination mit dem Ökologischen Fußabdruck und anderen Indikatoren zur umfassenden Angabe der ökologischen Nachhaltigkeit der verschiedenen Nahrungsmittel dienen. Zum Beispiel könnte die "Fußabdruck Familie", d. h. der Ökologische, der CO_2 und der Wasser-Fußabdruck kombiniert werden.

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List of Abbreviations

CED	Cumulated Energy Demand
CO_2e	CO_2 equivalents
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
GEMIS	Globales Emissions-Modell Integrierter Systeme
HANPP	Human Appropriation of Net Primary Production
IP	Integrated Production
IPCC	Intergovernmental Panel on Climate Change
IOA	Input-Output Analysis
ISO	International Organization for Standardization
IUCN	International Union for Conservation of Nature
LCA	Life Cycle Assessment/Analysis
MFA	Material Flow Analysis
MIPS	Material Input per Service Unit
NGO	Non-governmental Organization
NHS	National Health Service
NPP	Net Primary Production
PCA	Process Chain Analysis
PCF	Product Carbon Footprint
REAP	Resource and Energy Analysis Program
SPI	Sustainable Process Index
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environment Program
UNSD	United Nations Statistics Division
WCED	World Commission on Environment and Development
WWF	World Wide Fund for Nature

A) INTRODUCTION

1. Problem Statement

Currently the term “sustainability” seems to be omnipresent in politics, society and also in the economy. The environmental awareness in Germany is at a very high level – the majority of the population consider protection of the environment as a very important issue (Bundesministerium für Umwelt 2008). Nevertheless, usage of natural resources (including renewable and non-renewable materials, energy, water and land) and therefore environmental degradation are still increasing. Reasons for this development are the growing world population on the one hand and on the other hand the increasing per capita resource consumption in industrialized countries as well as emerging economies. Consumption is a key issue regarding sustainability and environmental damage, as the supply of goods and services is always linked to the use of natural resources (Burger et al. 2009a). It is estimated that between 30 and 50 % of the total environmental impact is caused by consumption activities of private households (Brunner et al. 2007). The case of food consumption is in some aspects very special. Unlike other products, food items can only be spared to a limited degree. The production and the associated consumption of foods have incredible environmental, but also social and economic consequences.

However, consumption can also be sustainable. By definition, consumption is sustainable if it contributes to meeting the needs of today´s generation without jeopardizing the chances for satisfying the requirements of future generations (Brunner et al. 2007; Schoenheit 2009). In the case of food consumption this is a vital requirement if for example issues like hunger and malnutrition should become a thing of the past. It has been shown that the willingness to accept sustainable consumption patterns in the German population is high (Bundesministerium für Umwelt 2008). However, a change in consumer habits which would promote sustainable development cannot yet be detected on a broad scale. There are different reasons for this gap between attitude and behaviour and therefore different possibilities of overcoming it (Eberle 2000; Schoenheit 2009). In this connection the issues of lack of (credible) information on the one hand and information overload on the other hand are of great concern. Consumers are not sure which products are sustainable. The increasing amount of more or less reasonable information and labels present on products has rather led to confusion than to more informed choices. But not only consumers need to be addressed – also companies and policy makers need to become involved. Companies need to develop and merchandize more sustainable products and politics need to set an overall framework favourable to sustainable production and consumption (Schoenheit 2009).

In order to reach the goal of sustainable consumption all three of these stakeholders (consumers, companies and policy makers) need to know the status quo of different aspects of sustainability, for example resource consumption or amount of greenhouse gas emissions, for different products. Only if these issues are known, will improvements be possible. Thus the assessment and evaluation of resource consumption, greenhouse gas emissions, etc. along the entire lifecycle of products is a necessary first step (Burger et al. 2009b). The number of assessment methods available in order to gather this kind of information is constantly increasing and methodologies are being permanently improved. Also the number of actual projects assessing different products is on the rise. This development (although certainly the right way) also contains some problems. First of all the applied methodologies are often not standardized, thus leading to incomparable results between different studies. Secondly, it is not always clear which assessment method is the most appropriate one for a certain goal. Last but not least the high number of (not standardized) methodologies can lead to a vast amount of sometimes contradicting results – this is highly problematic with regard to consumer education.

2. Research Objectives and Aims

After an introduction into the concept of sustainability and its connection with nutrition and our food system (**Section B**), two main objectives will be outlined:

The first of the two main objectives of this work is to provide the current state of research regarding the assessment of ecological sustainability of food items (**Section C**). The different assessment methods and associated indicators available which are suitable for analysing and evaluating food items will be explained and illustrated – wherever possible with examples from the food sector. One of the main focuses will be on the concept of the Ecological Footprint, since this seems to be a very promising tool for evaluating ecological sustainability. It is important to note that only the ecological dimension of sustainability will be taken into account. The main reason for this decision is the high complexity of the subject of sustainability. Dealing with all aspects is a very difficult task and therefore appropriate assessment methods and indicators are currently pretty rare. Besides, environmental issues are of great importance in the food sector and therefore deserve detailed analysis.

The second main objective is to develop and apply a methodology for Ecological Footprint calculations in the case of food items (**Section D**). Actual calculations of Ecological Footprints of different foods by means of Life Cycle Analysis (LCA) databases and other sources will be carried out and the results discussed with the appropriate literature.

After fulfilling these objectives a discussion will follow on which assessment methods and indicators respectively are suitable for assessing the ecological sustainability of foods (**Section E**). The focus will again be on the concept of the Ecological Footprint in general and in particular on the methodology developed in this piece of work. Current constraints of the Ecological Footprint will be identified and in this connection the role of the other assessment methods and indicators will be discussed.

The conclusion (**Section F**) will consider whether the Ecological Footprint and the developed calculation methodology qualify for the assessment of ecological sustainability. Recommendations and ideas for improvement will be presented.

B) Basic Concepts and Issues

3. The Concept of Sustainability

3.1. Defining Sustainability and Sustainable Development

Many definitions exist for the nowadays omnipresent terms “sustainability” and “sustainable development” – two often synonymously used expressions (Dresner 2004). The most common and widespread definition is given by the 1987 Brundtland report *“Our Common Future”*, defining it as the “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Munier 2005). Other definitions concerning sustainability include the following:

- The *International Union for Conservation of Nature* (IUCN), the *United Nations Environment Program* (UNEP) and *the World Wide Fund for Nature* (WWF) define sustainable development as "Improving the quality of human life while living within the carrying capacity of supporting ecosystems" (IUCN et al. 1991).
- *Friends of the Earth*, an international network of environmental organizations, stress that sustainable development meets the twin needs of protecting the environment and alleviating poverty (Chambers et al. 2007).
- Meadows et al. (1992) defines a sustainable society as one that behaves in such a way that it stays viable across all future generations.
- According to the *Global Footprint Network* sustainable human development will occur when all humans can have fulfilling lives without degrading the planet[1].

Besides the above mentioned examples many other definitions can be found in the prevalent literature. Despite differences among all these some basic principles share common ground and have gained widespread acceptance (Eberle 2000; Chambers et al. 2007):

- Human quality of life depends (among other things) on a healthy and productive environment which provides goods and services.

[1] See www.footprintnetwork.org

- The needs of the poor must be met. Thus a basic quality of life for all of the world´s population has to be provided.
- Future generations should have the same opportunity to utilize the world´s resources as the current generation.

Furthermore, the term sustainability generally indicates connections between the environment, the society and economic processes. The ultimate goal of sustainable development can therefore only be reached if these interrelations are taken into account.

3.2. The Origin of the Concept of Sustainability

Only a few decades ago sustainability was a relatively unknown expression. In the German language the origin of this term is closely connected to forestry. *Von Carlowitz* used it in the early 18th century in order to describe a forest management system which is characterised by not cutting down more trees in a certain time period than can re-grow in a certain time period. In the English language on the other hand the terms "sustainability" and "to sustain" were more broadly used in the general sense of maintaining something – possibly from the 13th century onwards (Eberle 2000).

The publication of the "*World Conservation Strategy*" in 1980 developed by the IUCN, the UNEP and the WWF and especially the Brundtland-report *"Our Common Future"* published by the *World Commission on Environment and Development* (WCED) in 1987 led to a widespread use of the terms sustainability and sustainable development. A growing environmental concern in the Western countries preceded and triggered these publications (Nagorni 1996; Eberle 2000).

The discussions prompted by these reports led to the *United Nations Conference on Environment and Development* (UNCED), often called the "*Earth Summit*", in Rio de Janeiro and the follow-up conference ten years later in Johannesburg (Brunner et al. 2007). The main goal of these conferences was to advance the recommendations given by the Brundtland-report to more legally binding policies (Jäger & Wiegandt 2007). For example the *Agenda 21* was signed (amongst other things) during the Rio conference – a global action plan outlining the sustainable development priorities for the 21th century (Dresner 2004).

Due to these two main conferences and many agreements (i.e. *the Agenda 21*, the *Kyoto Protocol* or the *Millennium Development Goals*) the concept of sustainable development has reached worldwide distribution and often forms the basis of local, national and international strategies (Brunner et al. 2007). Despite these, however, actual goals have not been met – poverty and resource consumption continue to increase – due to the often short-term political and economical practices (Jäger & Wiegandt 2007).

3.3. The Dimensions of Sustainability

Sustainability is often primarily associated with ecological issues. However, there is an increasing consensus that one should assume a three pillar concept covering not only ecological, but also economical and social aspects. These should be examined not only separately but also in their interrelations, conflicts and side-effects (Brunner et al. 2007).

The goal of the <u>ecological dimension of sustainability</u> is to increase human well-being by protecting resources required for human needs and by taking care that nature is not overburdened with the waste generated by humanity. To achieve this, the human population has to learn to live within the boundaries given by nature (van Dieren 1995). Ecological sustainability requires information and investigations concerning ecosystem services and how ecosystems have been and are influenced by man. Furthermore, principles of sustainable management of ecosystems need to be established (Brunner et al. 2007).

From the economic point of view nature is a scarce resource which can be used in different ways. Future generations should be able to realize at least the same benefits from this natural capital as today's generation. <u>Economic sustainability</u> is therefore often defined as the preservation of capital (van Dieren 1995). Different concepts exist to fulfill this economic sustainability. The concept of strong sustainability implies that the existing stock of natural capital must be maintained for future generations. This implicates that only renewable resources can be used. The concept of weak sustainability assumes convertibility between natural and human-made capital. Only the value of the total capital should be preserved. The concept of critical sustainability tries to compromise between these two extremes by using careful management schemes and safe minimum standards (Brunner et al. 2007).

The social dimension of sustainability covers aspects like satisfaction of the basic needs of all members of society, social security, equal opportunities, participation in decision-making, conservation of cultural heritage and cultural diversity, possibility of self-determined living based on one´s own work, gender justice, preservation and development of social resources, etc. Generally this pillar has played a minor role in the sustainability debate although it is of great importance not only to tackle above mentioned issues but also to raise acceptance for sustainable policies which could imply welfare losses (Brunner et al. 2007).

Besides these three main dimensions of sustainability sometimes additional ones are included. The political-institutional dimension does not cover substantive aspects of sustainability but rather deals with the question of how institutions and politics should adapt to and apply the principles of sustainability (Brunner et al. 2007). In the field of sustainable nutrition one can often encounter a health-related dimension of sustainability – a column otherwise attributed to the social dimension (von Koerber & Kretschmer 2000; von Koerber et al. 2004; Brunner et al. 2007). This composition was developed due to the dominance of health-related aspects in prevailing nutritional science. One can say that the concept of sustainable nutrition covering four dimensions of sustainability was formed by complementing traditional nutritional science with the environmental, economical and social dimensions of sustainability (von Koerber & Kretschmer 2000; von Koerber et al. 2004). This concept is illustrated in more detail in the following chapter.

4. Sustainability and Nutrition

4.1. The Four Dimensions of Sustainable Nutrition

As described above the science of sustainable nutrition can cover four dimensions – an ecological, economic, a social and a health-related one (von Koerber & Kretschmer 2000; von Koerber et al. 2004; Brunner et al. 2007). The most important aspects of each of these dimensions are described in the following chapters. The ecological dimension is described in more detail than the others due to its major importance in this piece of work.

4.1.1. The Ecological Dimension

Our food system as a whole has various effects on our environment.

First of all it is responsible for the emission of a significant amount of greenhouse gases and therefore contributes to climate change. Studies estimate the food systems share on total greenhouse gas emissions at approximately 20% (Niggli 2007; von Koerber et al. 2009). The most important single factor contributing to these emissions within the food system is agriculture (Niggli 2007). This is mainly due to the potent greenhouse gases methane and nitrous oxide (Garnett 2008). The *Intergovernmental Panel on Climate Change (*IPCC) estimated agriculture`s share on total anthropogenic greenhouse gas emissions in 2004 in terms of CO_2-equivalents at 13.5 % (IPCC 2007). Livestock keeping and the production of animal-based products respectively are the key issue in terms of food-related greenhouse gas emissions. The *Food and Agriculture Organization of the United Nations* (FAO) estimates that livestock activities are responsible for 80 % of total agricultural emissions or 18 % of total anthropogenic greenhouse gases (Steinfeld et al. 2006). A more recent study estimates its share even at 51 % (Goodland & Anhang 2009). Different system boundaries and assumptions lead to these varying results. For example, the IPCC accounts emissions caused by deforestation entirely to the forestry sector, while the FAO and Goodland and Anhang (2009) include deforestation for agricultural purposes to the agricultural/livestock sector (Steinfeld et al. 2006; IPCC 2007; Goodland & Anhang 2009). Besides agriculture, consumption-associated processes (for example cooling, cooking or shopping trips by car) also contribute a significant amount to the food systems greenhouse gas emissions (von Koerber & Kretschmer 2006).

A second important impact our food system has on our environment is its enormous usage of resources, especially land. The land necessary in order to support our food system is largely agricultural land. Globally approximately 38 % of all land is available for agriculture – this is equivalent to nearly 5 billion ha. The vast majority of this land (69 %) is used for pastures, only 28 % for arable land. Besides the pasture land, also one third of the arable land is used for the production of animal feed. Therefore livestock associated land use accounts for approximately 80 % of all agricultural land available on our planet – besides the fact that animal-based foods amount to only 17 % in the global food supply (von Koerber et al. 2009). Other important resources used for sustaining our food systems are water and energy. More than 70 % of all available freshwater is used in world agriculture. In order to produce the food to feed one human each day requires more than 1600 l of water. Fossil fuels (finite energy resources!) are used in enormous quantities in industrial agriculture for such inputs as fertilizers, pesticides, the manufacture and operation of farm machinery, and the powering of irrigation systems (Pimentel & Pimentel 2006).

Biodiversity is also affected by our food system. Different aspects associated with the production and consumption of foods are in part responsible for the persistent loss of biodiversity. One of the major factors is habitat loss due to conversion of natural areas to agricultural land (World Wide Fund For Nature et al. 2008). For example the cattle sector is the key driver of deforestation in the Brazilian Amazon with cattle being responsible for about 80 % of all deforestation in the Amazon region (Greenpeace 2009). Other factors leading to biodiversity loss are overexploitation (especially of the world´s fishing grounds), pollution through pesticides and over-fertilization as well as the effects of climate change (World Wide Fund For Nature et al. 2008). Loss of biodiversity can be detrimental to our food system in the future as different plant, animal and microbe species carry out essential functions for agriculture, for example pollination of crops, soil formation, biological pest-control, and recycling of wastes (Pimentel & Pimentel 2006).

Above mentioned ecological problems are by far not the only ones caused by our global food system, but perhaps the major ones. Other aspects that should be mentioned include acid rain formation (due to ammonia and nitrogen oxides from livestock production and over-fertilization), pollution and eutrophication of water bodies, soil erosion and last but not least soil compaction (Brunner et al. 2007).

4.1.2. Economic, Social and Health-related Aspects

Besides above mentioned environmental issues related to our food system there are also several economic, social and health-related aspects which play an important role in the field of sustainable nutrition.

Agriculture plays an important economic role currently engaging approximately 2.6 billion people worldwide. Nevertheless, the contribution of agriculture to national gross domestic product has been steadily declining in all regions. This is especially disadvantageous for the world´s poor and hungry as they often live in rural settings and are directly or indirectly dependent on agriculture for their livelihoods. Wide fluctuations of prices for agricultural commodities and projections of a tightening of the world food markets with increasing market concentration in a few hands are further economic problems, especially for (already poor) small-scale producers and landless labour. However, according to the World Agriculture Report *“Agriculture at a Crossroads”* agriculture and the food system can make a significant contribution to alleviating poverty if certain strategies and principles are applied (IAASTD 2009).

From the social point of view one of the major problems in the global food system seems to be the prevailing social deprivation and inequity. Although food production has been increasing globally, major distributional inequalities exist – therefore hunger is still a major concern (Millennium Ecosystem Assessment 2005). An important factor for this inequity comes from feeding approximately one third of the world’s crop harvest to livestock in order to produce meat (-products), milk and eggs – mainly for industrialized countries (von Koerber & Kretschmer 2006). Other factors leading to inequality and poverty are the uneven distribution and/or the lack of access to different resources as well as the lack of fair markets for small-scale producers (IAASTD 2009). Another important social aspect regarding our food system is inhumane working conditions, especially child labour. Critical foods are mainly products from developing countries, for example coffee, tea, chocolate or bananas (von Koerber & Kretschmer 2006). An increasing consumption of convenience products and fast food also has detrimental social effects. Food is not just economic goods and a requirement for good health, but also a centrepiece of culture – an above described diet transition therefore contributes to the loss of certain cultural values (Millennium Ecosystem Assessment 2005).

Regarding health, two main issues are of importance. On the one hand a global epidemic of diet-related obesity and non-communicable diseases is emerging (Millennium Ecosystem Assessment 2005). Non-communicable diseases are diseases which are not infectious but may result from genetic or lifestyle factors. Examples include the typical nutrition-related illnesses like cardiovascular diseases, gallstones, gout or diabetes mellitus. According to the Millennium Ecosystem Assessment (2005) the reason for this development is the fact that increasingly urbanized people adopt diets that are higher in energy and lower in diversity in fruits and vegetables than traditional diets. On the other hand malnutrition and hunger still play a major role, especially in developing countries. It is estimated that approximately 852 million people were undernourished in the period 2000 to 2002 – despite the fact that the prevailing food production has been increasing globally and would be sufficient to meet everybody's needs (Millennium Ecosystem Assessment 2005; von Koerber & Kretschmer 2006).

It has to be mentioned that all dimensions in the field of sustainable nutrition are closely connected. For example the effects of climate change will also have strong economic and social consequences. Another example are the current food prices which do not include external costs for ecological damage or costs necessary for the treatment of nutrition-related illnesses. Due to these interrelationships one should try to keep all the dimensions in mind, even when focusing on only one of them.

4.2. Sustainable Food Consumption

In order to meet the demands of all the above described dimensions a sustainable diet needs to be suitable for everyday life, safe, health-promoting, socially and environmentally sound and adjusted to a person's requirements (Brunner et al. 2007). More practical implications for an overall sustainable diet are given by means of the following seven principles, arranged according to their environmental priority (von Koerber & Kretschmer 2006):

1. Preference for plant-based foods (predominant lacto-vegetable diet)
2. Organically produced foods
3. Regional and seasonal products
4. Preference for low-processed foods - plenty of fresh foods
5. Products packaged in an environmentally sound way

6. Fair trade products
7. Delicious and salubrious foods

By following these principles benefits concerning environmental, social, economic and health-related aspects arise. The Swedish Food Administration has recently also proposed environmentally effective and health promoting food choices (Livsmedels Verket 2009):

- Meat: Overall meat consumption should be reduced. Besides, local and/or organic meat (products) should be preferred.
- Fish: Fish/shellfish coming from stable stocks and/or carrying eco-labels, for example the Marine Stewardship Council label should be favoured.
- Fruits and Vegetables: Local and/or organic products should be preferred. As these are delicate products one should try to reduce waste by storing them properly and not buying more than used.
- Potatoes and Cereals: Local and/or organic products should be preferred. Rice should be substituted by other cereals or potatoes.
- Cooking fat: Rapeseed oil should be favoured, palm oil should be avoided.
- Water: Tap water or at least locally produced water should be preferred.

Great similarities between both sets of above mentioned guidelines are apparent. Both are certainly important tools for guidance towards general, basic food choices. However, qualitative differences between food items are not apparent with these principles. Further information is also necessary in order to be able to compare food items within a certain food group or food items produced by different companies. For this purpose detailed sustainability assessments of food items are necessary. The following section deals in detail with the different possibilities available for assessing the ecological sustainability of food items in order to gather this information.

C) Ecological Sustainability of Food Items

5. Requirements for Suitable Sustainability Indicators & Assessment Methods

Sustainability indicators and assessment methods are very closely related and connected subjects but should be distinguished nevertheless:

Sustainability assessment can be defined as a tool that can help decision-makers and policy-makers decide which actions they should or should not take in an attempt to make society more sustainable. Sustainability assessment has become a rapidly developing area with the numbers of tools available for assessing sustainability increasing continuously (Ness et al. 2007).

Sustainability indicators can be defined as information used to measure and motivate progress towards sustainable goals (Ranganathan 1998). More specifically, they are absolute environmental measuring tools which (on the basis of a comparison of the present and the sustainable situation) show to what extent the aims of sustainability are met (Ragas et al. 1995). The idea of using indicators is based on the need to simplify complex phenomena and quantify information (Halberg et al. 2005). This is due to the fact that indicators characterize a system by reduction of its complexity and integration of information (Lewandowski et al. 1999). They can be useful as analytical, explanatory, communication, planning and performance assessment tools (Shields et al. 2002). Indicators are a step beyond primary data as they allow analysis of trends and cause-and-effect relationships (Veleva & Ellenbecker 2001).

Generally, both indicators and assessment methods concerning ecological sustainability should cover the main environmental categories and the most pressing environmental problems. The 6th *Environmental Action Program* of the EU lists the environmental issues natural resources, waste, soil, forestry, air, climate change, water, biodiversity and land use as policy priority areas. Comprehensive indicators for products should cover the input categories biotic (renewable) and abiotic (non-renewable) materials, water, land area and air and the output categories waste, waste water and greenhouse gas emissions. These categories capture the main environmental topics: scarcity of natural resources (non-renewable materials, renewable materials and water), land use change and deforestation, extensive energy use, waste and climate change (Burger et al. 2009a).

A range of other important criteria should be fulfilled by indicators and assessment methods for measuring environmental sustainability of products (Giljum et al. 2006; Burger et al. 2009a):

- The main environmental impact categories (as shown above) should not only be covered but also presented in appropriate ways. Information on the sustainability performance of a product has to be provided.
- The indicators and assessment methods should be applicable for a large range of products and product categories. Additionally they should imply a life cycle wide assessment of the environmental effects of these products.
- The resource use caused by the production and consumption of a product should not only be quantified in absolute numbers but also in relation to the scarcity of all natural resources.
- Information for improving the resource-efficiency of a product and reducing its environmental effects should be allowed to be identified.
- The compatibility with national sustainability accounts should be given so that the results can be put in relation to national and international environmental targets.
- Transparent accounting schemes, system boundaries and data sources should be used in order to increase objectivity and credibility.
- Indicators should be easy to communicate, in order to provide relevant information not only to a small group of experts, but to the general public.
- Indicators should find a balance between aggregation and disaggregation of information. Aggregation of statistical information into a few categories or even one number increases the communicability, but decreases scientific soundness and methodological consistency.
- Assessments should be feasible within an adequate effort in terms of time and costs.

In short, indicators and assessment methods need to be transparent, inclusive, testable, complete, relevant, adequate for the sustainability context, accurate, neutral, comparable, clear and on time (Global Reporting Initiative 2002).

6. Assessment Methods & Indicators for the Ecological Sustainability of Foods

Due to a growing interest in sustainability issues an increasing number of assessment methods and indicators relating to these have been developed in the last decades. Some of these can also be used for assessing the ecological sustainability of foods. These chosen assessment methods and indicators are presented below, grouped according to their main environmental impact category (i.e. energy use, emissions, material and area demand, water usage and transportation). Possible future methodologies are also discussed. The following table (table 1) shows an overview of the assessment methods and indicators reviewed in this piece of work.

Table 1: Assessment Methods and Indicators reviewed in this piece of work

Reviewed Assessment Methods and Indicators		Chapter	Page
Assessment Methods & Indicators concerning Energy Use and Emissions	Input-Output Analysis	6.1.1.1.	16
	Process Chain Analysis	6.1.1.2.	16
	Hybrid Analysis	6.1.1.3.	17
	Life Cycle Assessments	6.1.1.4.	17
	Cumulated Energy Demand	6.1.2.1.	20
	Concept of *Emergy*	6.1.2.1.	21
	Carbon Footprint	6.1.2.2.	22
Material-based Assessment Methods and Indicators	Material Flow Analysis	6.2.1.	26
	Ecological Rucksack	6.2.2.	27
	MIPS Concept	6.2.2.	27
Area-related Assessment Methods and Indicators	Direct Land Requirements	6.3.1.	29
	Sustainable Process Index	6.3.2.	31
	Ecological Footprint	7.	39
Miscellaneous Assessment Methods and Indicators	Water Footprint and Virtual Water	6.4.1.	34
	Food Miles	6.4.2.	36
Possible Future Assessment Methods and Indicators	Human Appropriation of Net Primary Production	6.5.1.	37
	Resource and Energy Analysis Program	6.5.2.	37

6.1. Assessment Methods & Indicators concerning Energy Use and Emissions

Energy use and emissions emitted, especially greenhouse gas emissions can be regarded as one of the most important environmental impacts. Therefore different analytical tools and indicators have been developed in order to measure and demonstrate these.

6.1.1. Analytical Tools for Assessing Energy Use and Emissions

Energy consumption and emissions emitted can be assessed in various ways. The most common methods are briefly presented in the next chapters.

6.1.1.1. Input-Output Analysis

Input-Output Analysis (IOA) is originally an economic tool used for describing interdependencies between economic sectors (Jungbluth 2000). The bases for IOA are input-output tables which contain the transactions between economic sectors in financial units (Kramer et al. 1999; Jungbluth 2000).

However, IOA can also be applied for assessing different environmental impacts in various economic sectors, for example greenhouse gas emissions, emissions to water, or embodied energy (Engström et al. 2007). This is accomplished by relating environmental impact intensities to the monetary flows in the input–output tables (the exact methodology varies with the environmental impact category in question). Thus the environmental impact can be quantified along the entire chain of intermediate transactions from industry to industry up to the point where households purchase the product (Kerkhof et al. 2009).

IOA is a top-down approach (Lenzen et al. 2003), faster to conduct than the process chain analysis described below, but also less detailed (Kramer et al. 1999).

6.1.1.2. Process Chain Analysis

Process Chain Analysis (PCA) is an instrument for determining the greenhouse gas emissions and the embodied energy during the life cycle of a product (Voorspools et al. 2000). The approach is relatively similar to life cycle analysis: energy demand and/or greenhouse gas emissions are analysed for the different process steps in a life cycle and subsequently summed. These results are then related to a certain product or service (Jungbluth 2000; Voorspools et al. 2000). Compared to IOA, PCA is more detailed, but also more laborious (Kramer et al. 1999).

6.1.1.3. Hybrid Analysis

Hybrid analysis combines PCA and IOA in order to assess environmental impacts (most commonly embodied energy and/or greenhouse gas emissions) of products in a more precise way. For this purpose information from both these approaches are linked. In a first step, a PCA is conducted for the whole life cycle of the product in question with a focus on activities which are relevant for emissions and/or the cumulated energy demand (CED). A distinction is made between basic goods (the raw materials of a product), packaging materials, capital goods (i.e. machines or buildings), residual goods (production inputs which cannot be allocated to the other input categories), direct energy usage and greenhouse gas emissions and last but not least transport and waste treatment processes. In a second step a mass balance is carried out in order to check the results of the PCA. After this a monetary balance in conducted in order to estimate the overall costs of the residual goods because these cannot be expressed in physical units. The overall costs of the residual goods are subsequently multiplied with the energy intensity of these (which in turn was previously estimated by IOA) in order to calculate the energy demand of the residual goods. By adding all the individual energy demands and/or the related emissions of the different goods/activities together, the total CED and/or the total greenhouse gas emissions are calculated for a given product (Jungbluth 2000; Taylor 2000).

6.1.1.4. Life Cycle Assessments

<u>Overview of the Method`s Concept</u>

Life Cycle Assessment or Analysis (LCA) is a method for capturing the environmental impacts of a given product throughout its entire life cycle, in other words: 'from cradle to grave' (Andersson et al. 1994; Jungbluth 2000). The procedures of LCAs have been defined by the norms of the *International Organization for Standardization* (ISO) number 14040 and 14044 in order to consolidate the workflows of LCAs (Roy et al. 2009). Nevertheless, this method is not completely standardized, leading to difficulties when comparing different studies (Jungbluth 2000; Chambers et al. 2007).

Generally, LCAs for products consist of four main phases (Heijungs & Guinée 1992; Jensen et al. 1997; Jungbluth 2000):

- *Definition of goal and scope:* in the first phase of a LCA the goal and scope of the study in relation to the intended application is specified. Reasons for the study in question, the target groups, the exact methodology which is going to be used, the system boundaries and the functional unit are defined.

- *Life cycle inventory:* in the second phase all the data relevant to environmental issues within the study boundaries are collected by means of input-output-tables and related to the defined functional unit. For this purpose a process chart for the whole product life cycle has to be compiled first.
- *Life cycle impact assessment:* in this phase the collected data are classified to different impact categories, for example greenhouse effect or depletion of biotic raw materials. Different methods exist to weigh these different impact categories against each other, making comparisons between them possible.
- *Interpretation:* in the last phase of a LCA the information obtained from the two previous steps is evaluated in the sense of the study goal. This usually involves comparison of different products and/or the identification of optimization possibilities (for example within the production chain).

Nowadays, a growing number of databases and LCA software applications are available in order to assist in these labour intensive assessments (Jensen et al. 1997).

<u>LCA and Food Products</u>

The underlying reasons for a LCA in the field of food products can be very diverse. For example an environmental improvement of a certain production system, the identification of environmental "hot spots" in the life cycle of a product, a comparison with products from business competitors or the wish to give consumers guidance for purchasing decisions are possible motivations (Jungbluth 2000). Despite the definition of LCAs, studies often focus only on specific stages of the life cycle of a product – in the case of foods mostly the agricultural or industrial processing step (Jungbluth 2000; Roy et al. 2009).

LCAs alone can give a lot of information regarding the sustainability of food items without being aggregated to a specific indicator. In the following paragraphs a selection of results of more comprehensive LCAs gathered by Roy et al. (2009) and relating to various food items from different food groups are given:

Bread: it has been shown that a scenario combining organic production of wheat, industrial milling and a large bread factory would be environmentally the best option for producing bread. For most impact categories the primary production and transportation stages are the most important phases; for energy use the processing step (the baking) is significant.

Tomatoes: especially the method of cultivation (greenhouse or open field, organic or conventional, and hydroponic or soil-based), but also the tomato variety, the location of cultivation, and packaging and distribution systems affect the environmental load of tomatoes.

Tomato ketchup: the environmental hotspots in ketchup production were found to be packaging and food processing. Regarding energy consumption the storage in the fridge of the consumer has a considerable impact.

Milk: in the life cycle of milk (and also of semi-hard cheeses) the agricultural phase was reported to be the main hotspot. Packaging, waste management and cleaning processes have lesser impacts. A high amount of improvement strategies for all the different stages in milk production are available.

Meat: also in meat production the agricultural phase is from an environmental point of view the most critical. Chicken and pork can be considered environmentally more efficient than beef, possibly due to the greater feed conversion ratio of cattle. In livestock and especially in beef production greenhouse gas emissions are typically one of the most important impact categories.

Generally, the above mentioned results indicate that different foods possess different environmental hotspots in their life cycle. The results can therefore also demonstrate where certain environmentally friendly measures would have the greatest impact for a given product, i.e. whether alternative production, processing, packaging, distribution or consumption patterns would reduce the associated environmental load best.

<u>Suitability of LCA for the Assessment of Foods</u>

Generally, LCAs can detect various (hidden) environmental impacts associated with products along their whole life cycle. This method can give directions for improving the sustainability of food products in the sense of reducing their environmental load. Nevertheless, some disadvantages are associated with this method:

- LCAs, although very comprehensive, do not (yet) integrate all ecologically important aspects of a product, some of which are highly relevant for agricultural products. Examples include aspects of erosion, overuse of biotic resources or water, biodiversity or noise pollution. However, efforts are undertaken in order to include some of these issues (Jungbluth 2000).

- LCAs provide detailed descriptions of impacts – this is accompanied however with interpretation difficulties and a lack of clearness. In order to overcome this problem results are sometimes aggregated (Chambers et al. 2007). For example the so-called *Ecoindicator 99* quantifies impacts on human health, ecosystem quality and resources in a single score per product (Huijbregts et al. 2008).
- Last but not least difficulties arise due to the as yet incomplete standardization of LCA procedures (Jungbluth 2000; Chambers et al. 2007).

6.1.2. Indicators concerning Energy Use and Emissions

Possible indicators regarding energy use are the cumulative energy demand and the lesser known emergy concept. Nowadays the Carbon Footprint is already a very well-developed indicator for greenhouse gas emissions.

6.1.2.1. Cumulated Energy Demand and the Concept of *Emergy*

The cumulated energy demand (CED), also known as embodied energy, is a measure for the total amount of (primary) energy which was required for the production of a certain product or service (Öko-Institut e.V. 2008). It can easily be used to compare and to evaluate different foods. LCA databases – for example the software GEMIS (*Global Emission Model for Integrated Systems*) developed by the German *Öko-Institut* – can be used for calculating the CED of a certain product, as LCAs provide all the necessary data.

The following table (table 2) shows the CED of some chosen food items, calculated via *GEMIS*. The values include all the process steps up to retail; successive steps (e.g. cooking processes) are not included. Generally meat, meat-products and highly processed milk products like butter or cheese are fairly energy-intensive in production, while most plant-based foods require low amounts of energy. The more process steps are required to make a product, the more energy is needed. For example, potatoes only require 2.37 MJ/kg, deep-frozen French fries however 79.22 MJ/kg. In most cases organically produced foods need less energy than conventionally produced foods – although the raw agricultural materials for the former usually have lower yields. The reason for this outcome is mainly the usage of energy-intensive chemical fertilizers in conventional, but not in organic agriculture.

Table 2: Cumulated energy demand in MJ/kg for chosen food items, data obtained from GEMIS (Öko-Institut e.V. 2008)

Food item		**Cumulated Energy Demand** [MJ/kg]	
		organic	conventional
Fruits and vegetables	Fruit mix (fresh)	-	6.0
	Fruit mix (deep-frozen)	-	6.2
	Vegetable mix (fresh)	2.0	2.1
	Vegetable mix (deep-frozen)	5.6	5.7
	Tomatoes (fresh)	1.6	2.8
Other plant-based food	Potatoes	2.1	2.4
	French fries (deep-frozen)	78.5	79.2
	Margarine	28.4	28.0
	Sugar	17.1	30.3
	Wheat flour	4.1	4.8
	Bread	8.2	8.7
Meat and meat-products	Chicken (deep-frozen)	58.4	50.8
	Beef (deep-frozen)	36.2	66.8
	Pork (deep-frozen)	37.5	45.4
	Sausages	32.4	40.4
Other animal-based food	Milk	3.0	4.3
	Yoghurt	4.3	6.0
	Cheese	18.4	31.0
	Butter	29.4	67.7
	Eggs	12.3	14.2

CED can be applied to foods in a relatively easy way, due to the growing availability of LCA-data. It has to be kept in mind though that only the aspect of energy consumption is considered, aspects like land and resource usage, pollution of water bodies, toxicity, etc are neglected. Nevertheless, energy demand is an important factor regarding sustainability and the CED can therefore give consumers directions for a more sustainable consumption.

A concept based on energy but with a wider scope has been developed by Odum, the concept of emergy (Hau & Bakshi 2004). Emergy can be defined as the available solar energy used up directly and indirectly to make an activity, service or product, i.e. it shows how much energy would be necessary to do a particular task if solar radiation were the only input (Hau & Bakshi 2004). It is calculated by translating each form of energy, but also raw materials or even labour in a certain system into their solar energy equivalent (Brown & Buranakarn 2003; Chen et al. 2006). Therefore a lot more factors are taken into account and environmental impacts can be assessed more precisely than with just CED alone.

To date, emergy analyses have been carried out for various systems (for example agricultural industries, such as ethanol production or crop production systems; Chen et al. 2006) and products (for example building materials; Pulselli et al. 2007). However, emergy assessments of foods have yet to be conducted.

6.1.2.2. The Carbon Footprint

<u>Overview of the Concept</u>

A Carbon Footprint can be defined as the overall amount of carbon dioxide (CO_2) and other greenhouse gas emissions (e.g. methane, laughing gas, etc.) associated with a product (European Commission 2007; Grießhammer & Hochfeld 2009). The Carbon Footprint is usually expressed in CO_2 equivalents (CO_2e), a unit which incorporates the different greenhouse gases according to their global warming potential.

Ideally, a Carbon Footprint should contain all the greenhouse gases emitted alongside the complete life-cycle of this product. This includes not only the supply chain (with the production and transport of raw materials and pre-products as well as the actual manufacturing and the distribution of the completed product), but also usage and end-of-life recovery or disposal processes (European Commission 2007; PCF Pilotprojekt Deutschland 2009a; Grießhammer & Hochfeld 2009). However, in Carbon Footprint assessments not always the full life-cycle of a certain product is chosen for the system boundary – therefore results of different studies should only be compared with care.

This problem has arisen, because there is not a consistent and internationally harmonised method available for calculating a Product Carbon Footprint (PCF; PCF Pilotprojekt Deutschland 2009a). However, efforts are under way in order to overcome this shortage. The ISO is working on an international norm concerning Carbon Footprints for products, which is estimated to be published in 2011 (PCF Pilotprojekt Deutschland 2009a; Grießhammer & Hochfeld 2009). At the moment the international standards for LCAs (ISO 14040/44) provide the basis for most Carbon Footprint calculations (European Commission 2007; PCF Pilotprojekt Deutschland 2009a). This is possible, because a Carbon Footprint can be seen as a subset of a full LCA or more precisely as a LCA with the analysis limited to emissions that have an effect on climate change (European Commission 2007). Carbon Footprints can therefore be calculated using data available in existing LCA databases, for example GEMIS.

Carbon Footprint Examples Concerning Foods

The food system as a whole is responsible for a high amount of greenhouse gas emissions, as demonstrated in chapter 4.1.1. However, between different food types the life cycle hotspot and the amount of greenhouse gases can vary considerably (Kramer et al. 1999; Fritsche & Eberle 2007; Garnett 2008). Generally meat (especially beef) and dairy products (particularly ones with a high fat content) have the highest impact, accounting for around half of foods` total greenhouse gas emissions (figure 1; Kramer et al. 1999; Garnett 2008). It has also been shown that organic products cause fewer emissions than conventional ones (Fritsche & Eberle 2007; Hirschfeld et al. 2008).

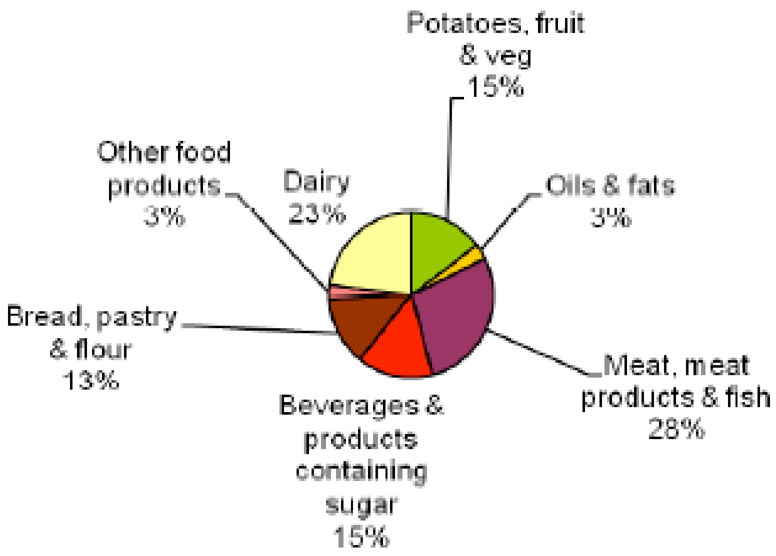

Figure 1: Contribution of different food product categories to total greenhouse gas emissions, in kg CO_2 equivalents, related to Dutch household food consumption (Kramer et al. 1999)

Specific Carbon Footprints for products can make these differences not only more clear for consumers, but also lower the negative climate effects in the food production and increase the competitiveness between food production companies

(Dialogue Forum Low Carbon Society 2008). In order to assess the Carbon Footprint of various specific products the project “*PCF Pilotprojekt Deutschland*” was launched in Germany. Among these products were four foods (organic eggs, strawberries, coffee and a pasta convenience meal), for which first results were published in early 2009 (table 3, PCF Pilotprojekt Deutschland 2009a). The results demonstrate that the Carbon Footprint varies strongly not only between different foods, but also between the different process-steps associated with the products. These findings can not only be used for informing consumers, but also for showing the producers where measures for the reduction of emissions would have the greatest impact (PCF Pilotprojekt Deutschland 2009a).

For the former, carbon emission labels have recently been launched in different countries, for example in South Korea or Japan, but first of all in Great Britain. There the “*Carbon Trust Carbon Reduction Label*” (figure 2) marks an increasing number of products, among them foods (e.g. orange juices, potatoes, or crisps; Dialogue Forum Low Carbon Society 2008; PCF Pilotprojekt Deutschland 2009a; Grießhammer & Hochfeld 2009). Other countries, for example Sweden and France are currently developing own Carbon Footprint labels. However, as there are still uncertainties and inconsistencies concerning the underlying Carbon Footprint methodology, it might be too soon for a product label (PCF Pilotprojekt Deutschland 2009a).

Figure 2: Carbon Trust Carbon Reduction Label (Dialogue Forum Low Carbon Society 2008)

Table 3: Carbon Footprints of various foods, assessed within the project "*PCF Pilotprojekt Deutschland*"; all results are given in g CO_2e per unit of food

Considered food	Carbon Footprints of the different process-steps						Total Carbon Footprint	Data source
	Production of raw materials	Main production	Distribution	Shopping trip	Product usage	Disposal		
Organic eggs[2] **(package of 6 eggs)**	32	693	183	47.3	200.7	20	1176	(PCF Pilotprojekt Deutschland 2009c)
Strawberries[3] **(500g package)**	0.8	182	140	65	-	54	441.8	(PCF Pilotprojekt Deutschland 2009b)
Coffee[4] **(one cup)**	33.0	3.9	1.3	1.9	17.9	1.2	59.2	(PCF Pilotprojekt Deutschland 2008)
Tagliatelle[5] **(500g meal)**	750	250	50	30	400	- 40	1400	(PCF Pilotprojekt Deutschland 2009d)

[2] Results refer to a package of six eggs, brand "*Naturkind*"; distributed through the company "*Tengelmann*".
[3] Results refer to a 500g PET-package of „*Best Alliance*"-strawberries, grown in Huelva, Spain, and distributed through the company "*Rewe*".
[4] Results refer to 1 cup (125ml) of "*Tchibo Privat Kaffee Rarität Machare*". The coffee beans were cultivated in Tanzania.
[5] Results refer to 500g of the deep-frozen, convenience meal "*Tagliatelle Wildlachs*" of the company "*FRoSTA*"

Suitability of the Carbon Footprint for the Assessment of Foods

The Carbon Footprint concept can be applied without much difficulty to food products. The growing availability of LCA-data will make these assessments even easier and faster to carry out. However, a standardization and optimization of the method has to be conducted in order to make results more comparable and reliable (PCF Pilotprojekt Deutschland 2009a).

The major drawback in the Carbon Footprint concept is that it can only address impacts on climate change - other important environmental impacts (e.g. land and resource usage, acidification of soils and water bodies, toxicity, etc) are neglected (European Commission 2007; PCF Pilotprojekt Deutschland 2009a). Additionally, consumers might have difficulty with the unit “CO_2-equivalents”. Therefore the sole use of the Carbon Footprint as an indicator of ecological sustainability for foods does not seem to be the right choice.

Nevertheless, the Carbon Footprint is a useful tool for leading consumers and producers to more informed choices (PCF Pilotprojekt Deutschland 2009a) and for assessing foods, as our food system is responsible for an important share of anthropogenic greenhouse gas emissions (Fritsche & Eberle 2007; Garnett 2008).

6.2. Material-based Assessment Methods and Indicators

Food production requires materials. Material-based assessment methods and indicators can quantify the amount of materials or resources necessary. Examples of these are material flow analysis, the Ecological Rucksack and the concept of *Material Input per Service Unit*.

6.2.1. Material Flow Analysis

Material flow analysis (MFA) has been established for quantifying the use of natural resources by different economic systems (for example countries, regions, economic sectors, businesses or households) and thus understanding the complex interactions between economic activities and the environment. MFA can identify key resources and can provide information about the overall resource flows as well as about unsustainable use of resources (Jungbluth 2000; Antikainen et al. 2005). However, MFA has difficulty accounting for qualitative aspects of material flows, such as the potential for specific environmental damage (Behrens et al. 2007).

Methodologically, a MFA follows the same steps as a LCA (definition of goal and scope, inventory, impact assessment and interpretation) – the procedure however is not yet standardized. The main difference between MFA and LCA is the application domain. While LCA focuses on the assessment of products, MFA is usually applied for product or material groups (Taylor 2000; Wiegmann et al. 2005).
For assessing certain food products, therefore, LCA is the more appropriate option.

6.2.2. The Ecological Rucksack and the MIPS Concept

The Ecological Rucksack and the concept of *Material Input per Service Unit* (MIPS) were both developed by Friedrich Schmidt-Bleek at the German *Wuppertal Institute for Climate, Environment and Energy*. Both of these closely connected ideas can be used to demonstrate environmental impacts of products (Schmidt-Bleek 1998; Ritthoff et al. 2002).

The Ecological Rucksack concept is related to MFA. It can reveal how many resources are necessary for a certain product. The Ecological Rucksack is calculated by summing the weights of all the material inputs necessary for the manufacture of a product, minus the product`s net weight. For all analysis, five resource groups are distinguished, namely abiotic resources, biotic resources, soil movements (mechanical earth movements or erosion), water and air (Schmidt-Bleek 1998; Ritthoff et al. 2002).

The methodology of the MIPS concept is very similar and based on the one of the Ecological Rucksack. The main difference between the two is that MIPS is more comprehensive than the Ecological Rucksack. It can be applied not only to products, but also to services, households, enterprises, regions and national economies. Additionally, the approach is life-cycle-wide, covering not only the production phases, but also the stages of usage, recycling and/or disposal (Schmidt-Bleek 1998; Ritthoff et al. 2002).

Attention has to be drawn to the fact that in literature MIPS-results are often displayed as “Ecological Rucksacks” due to the more easily understood imagery of this expression. In each case study and for both of these concepts the environmental impact potential is assumed to be less the fewer materials had to be used.

Studies applying these concepts to food groups could demonstrate that different food groups require differing material intensities (i.e. material inputs in relation to the particular unit of measurement; Ritthoff et al. 2002). Generally, animal-based foods require higher material intensities than plant-based foods (table 4). This can be explained by the preceding fodder production. Exceptions are highly processed products like sugar or plant-based fats (Loske & Bleischwitz 1996; Jungbluth 2000).

Table 4: Material intensities of different food groups in Germany (Loske & Bleischwitz 1996; Jungbluth 2000)

Food Group	Material Intensity [kg/kg]
Milk products	6.6
Eggs	4.2
Meat	16.7
Animal-based fats	16.7
Fish, shellfish	1.3
Cereals	3.7
Potatoes	2.0
Vegetables	1.4
Legumes	2.0
Fruit	1.4
Sugar	13.1
Plant-based fats, oils	12.1

Burger et al. (2009a) analyzed the Ecological Rucksack of different products, among them spinach and mineral water. The results (table 5) demonstrate that the main resource group which is necessary for producing both of these products is water. However, one kg of deep-frozen spinach needs approx. only half the amount of resources than fresh, baby-leaf spinach. Mineral water from recycled PET-bottles saves approx. 30 % of resources when compared to mineral water from new PET-bottles (Burger et al. 2009a).

Table 5: MIPS analysis for spinach and mineral water, according to Burger et al. (2009a), su = service unit

	Spinach [su = 1kg]		**Mineral Water** [su = 1l]	
	Deep-frozen	Baby-leaf	PET-bottle	Recycled PET-bottle
Abiotic Material [kg/su]	0.7	0.8	0.2	0.2
Biotic Material [kg/su]	1.2	1.0	0.03	0.04
Water [kg/su]	49.9	99.3	9.9	6.9
Air [kg/su]	0.5	0.4	0.1	0.06
MIPS [kg/su]	**52.3**	**101.5**	**10.3**	**7.2**

As seen in the above mentioned case studies, the concept of MIPS and the Ecological Rucksack can easily be applied to foods. However, the environmental impact of a certain resource does not have to be associated with its weight (i.e. the only value which is accounted for). Additionally, issues like toxicity or land usage are not covered within these concepts (Schmidt-Bleek 1998). Especially land usage is ecologically of particular importance in food production. A further drawback is that by definition Ecological Rucksacks only include the production stage and not the full life-cycle – although this can be counteracted by the MIPS concept.

6.3. Area-related Assessment Methods and Indicators

Food production causes environmental damage due to the high demand of land. Therefore area-related assessment methods and indicators can be used in order to evaluate the ecological sustainability of different foods. The most important of these – i.e. direct land requirements for foods, the Sustainable Process Index (SPI) and the Ecological Footprint – are described in more detail in the following chapters. The Ecological Footprint is described in detail in chapter seven and therefore not in this section.

6.3.1. Direct Land Requirements for Foods

Direct land requirements can be used for assessing various food items, as food production generally requires high amounts of (mostly agricultural) land. Gerbens-Leenes et al. (2002) developed a method in order to calculate the land required to produce individual food items. Information on yields, imports, food industry recipes and proportions of crops grown in the open air and in glasshouses respectively form the basis for these calculations. The results therefore include only agricultural land, other areas are neglected.

Table 6 shows several specific land requirements for different foods. Large differences can be observed between different food items. Especially meat, meat products, cheese and fats require high amounts of land whereas plant-based foods like cereals, vegetables or fruits require only very small amounts (Gerbens-Leenes et al. 2002). It has to be taken into consideration though that these outcomes all refer to the weight of a certain food item. Other studies assessed the land requirement per energy content of a certain food – with similar results (von Koerber et al. 2009). Especially beef requires huge amount of lands (20.9 m^2/kg and 31.2 m^2/1000 kcal respectively) – at least partially due to the low conversion efficiency of cattle (Gerbens-Leenes et al. 2002; von Koerber et al. 2009).

Table 6: Specific land requirements for different food items, data based on the Dutch production situation in 1990 (Gerbens-Leenes et al. 2002)

Food item		Specific land requirement [m^2×year/kg]
Beverages	Beer	0.5
	Wine	1.5
	Coffee	15.8
	Tea	35.2
Fats	Fats for frying	21.5
	Margarine	21.5
	Low fat spread	10.3
Meat	Beef	20.9
	Pork	8.9
	Minced meat	16.0
	Sausages	12.1
Milk products and eggs	Whole milk	1.2
	Semi-skimmed milk	0.9
	Cheese	10.2
	Eggs	3.5
Cereals, sugar, potatoes, vegetables and fruits	Flour	1.6
	Sugar	1.2
	Potatoes	0.2
	Vegetables (average)	0.3
	Fruits (average)	0.5

Based on the differing land requirements for various foods, different consumption patterns (for example in different countries or in different generations) also require varying amounts of land in order to sustain them (Gerbens-Leenes & Nonhebel 2005). Generally a diet requires more land with an increasing proportion of meat products (Gerbens-Leenes et al. 2002; Gerbens-Leenes & Nonhebel 2002; Gerbens-Leenes & Nonhebel 2005; von Koerber et al. 2009). Some food items have an extraordinary impact due to relatively high individual land requirements and high consumption levels. In the Netherlands for example, margarine, minced meat, sausages, cheese and fats for frying account for 43 % of the total Dutch household land requirement for food in 1990 (Gerbens-Leenes et al. 2002). Nutritional non-physiological requirements due to a nowadays wide-spread affluent diet claim a substantial part of the land area needed for food production (Gerbens-Leenes & Nonhebel 2002).

Direct land requirements for different foods are probably one of the easiest assessment methods for evaluation of the ecological sustainability of food items. As land use is one of the major impacts food production has on our environment, this indicator certainly also qualifies for an evaluation of foods sustainability. However, a lot of other important environmentally critical impacts concerning our food system are not considered with this method. Especially highly processed foods might appear to have relatively small impacts, as the stages after the agricultural phase are basically not considered. Therefore this tool should not be used on its own in the assessment of different food items.

6.3.2. The Sustainable Process Index

The Sustainable Process Index (SPI) was originally developed by Michael Narodoslawsky and Christian Krotscheck at the University of Graz. The concept shares some similarities with the Ecological Footprint – most importantly the fact that they are both area-based indicators of sustainability (Chambers et al. 2007).

The aim of the SPI is to assess the ecological impact of processes, which in this case are defined as providing a certain service (product). A life-cycle approach is aspired, taking into account the whole chain from raw material generation, production distribution and usage of the products (which thereby provide the service wanted) to taking care of the products and by-products after their use (Krotscheck & Narodoslawsky 1996).

A particular SPI is assessed by calculating the area which is necessary to embed an industrial process sustainably into the biosphere. This methodology implies summing up land areas required to provide resources and to assimilate emissions and wastes that are generated. Five different land categories are distinguished, all measured in m^2 (Krotscheck & Narodoslawsky 1996; Chambers et al. 2007):

- Area required to produce raw materials
- Area to provide process energy
- Area to provide the equipment for the process
- Area required for staff
- Area to accommodate products and by-products (including emissions and waste)

In order to allocate the different environmental impacts to areas, large numbers of assumptions (for example relating to waste absorption or toxicity) are necessary (Krotscheck & Narodoslawsky 1996). The SPI calculations can be carried out for example by using the software provided by the Institute for Resource Efficient and Sustainable Systems at the University of Graz.

The SPI has been applied to assess different foods (table 7). The results, which vary a lot between the different foods, indicate that animal-based products generally have a higher impact than plant-based products. Processed foods (e.g. bread) also have a higher impact than the same amount of their primary ingredients (e.g. wheat flour). There is also a big difference between organically and conventionally produced foods, whereby the organic produce generally has a lesser impact.

Table 7: The Sustainable Process Index of different food items[6]

Food item		**Sustainable Process Index** [m^2/kg]	
		organic	conventional
Fruits and vegetables	Apples	-	87.1
	Pears	-	128.4
	Tomatoes	25.3	32.0
	Mixed Vegetables	0.40	0.44
Other plant-based food	Potatoes	12.3	21.3
	Wheat flour	62.4	110.3
	Sugar	-	11.5
	Honey	-	326.6
	Soy bean oil	288.8	358.2
	Bread	487.7	530.7
Meat	Chicken	371.5	803.5
	Beef	250.5	4067.1
	Pork	166.3	300.0
Other animal-based food	Milk	100.9	355.5
	Yoghurt	119.5	339.0
	Cheese	1449.3	3957.4

In conclusion, the SPI is a very suitable indicator for the assessment of foods, as a lot of impact factors are accounted for – throughout the complete life-cycle of a product. When compared to the Ecological Footprint, the SPI can generally be considered to be a more sensitive method as it covers more impact factors (Chambers et al. 2007). However, this comes with a larger number of necessary assumptions (Krotscheck & Narodoslawsky 1996), which is the reason why the SPI cannot document which portion of the biosphere´s capacity is appropriated for a certain process. This is something the Ecological Footprint can do (Chambers et al. 2007).

[6] Data obtained from the webpage of the *Institute for Resource Efficient and Sustainable Systems*, University of Graz (http://spionexcel.tugraz.at/)

6.4. Miscellaneous Assessment Methods and Indicators

The assessment methods and indicators described above are not the only available options, but probably the most appropriate. Nevertheless, they often miss out on certain aspects, for example the issue of water. Therefore the concepts of the Water Footprint and Virtual Water have been developed. In the debate about sustainability of foods the aspect of food miles is also often discussed. The following chapters therefore deal with these two special aspects.

6.4.1. The Water Footprint and Virtual Water

The concepts of the Water Footprint and Virtual Water are closely related (similar to the concepts of the Ecological Rucksack and MIPS); the main difference is in the application possibilities.

The Water Footprint can be applied for individuals, businesses or nations and can be defined as the total volume of freshwater that is used for producing the goods and services consumed by these individuals, businesses or nations (Chapagain & Hoekstra 2004). The underlying methodology is very similar to the one of the Ecological Footprint (Hoekstra 2009). Virtual Water applies to products, commodities or services and is defined as the volume of freshwater used to produce these. In order to calculate the Virtual Water content for a certain product, the water usages in the various steps of the production chain are summed up (Chapagain & Hoekstra 2004).

Three water components are distinguished in both of the above mentioned concepts: a green, blue and a gray component. The green water component refers to rainwater; the blue component to surface and/or groundwater and the gray water component is the amount of water which becomes polluted within the production processes (Chapagain et al. 2006).

For foods, the concept of Virtual Water is the appropriate one. Some examples are displayed in table 8. Generally, livestock products have higher virtual water contents than crop products, due to the fact that animals consume a high amount of feed crops, drinking and service water before producing any output. Furthermore, processed foods usually have a higher Virtual Water content than the primary products – for example potato crisps have an impact almost 4times higher than potatoes per kilogram (Chapagain & Hoekstra 2004).

Table 8: Virtual Water content (world average) of selected foods, according to Chapagain & Hoekstra (2004)

Food item		Virtual Water content [l/kg] or [l/l] respectively
Cereals and legumes	Rice	3419
	Wheat	1334
	Maize	909
	Soybeans	1789
Potatoes, vegetables and fruits	Potatoes	250
	Tomatoes	186
	Oranges	500
	Apples	700
Meat	Beef	15497
	Pork	4856
	Chicken	3918
Other animal-based products	Eggs	3340
	Milk	990
	Cheese	4914
Beverages	Coffee	1120
	Tea	140
	Beer	300
	Wine	960
	Orange juice	850
Processed foods	Bread	1333
	Potato Crisps	925
	Hamburger	16000

The virtual water content is commonly used and easily applicable for the assessment of food products. Of course it only addresses the issue of water – an issue, however, that is often ignored by other sustainability indicators (for example the Carbon or the Ecological Footprint concept). Attention also has to be drawn to the fact that these food assessments are not life-cycle-wide, but only cover the production stages.

6.4.2. Food Miles

Food miles are generally defined as the distance food travels from the producer to the consumer (Saunders et al. 2006; Desrochers & Shimizu 2008). They can be relatively easily calculated using statistic data-sets (Smith et al. 2005). Food miles have been proposed to be a major way to determine the environmental impact of a food, as the further food is transported the more fossil fuels are burned (Desrochers & Shimizu 2008). Food transports have significant impacts. For example, in 2002 food transports for UK market food items were responsible for 19 million tons of CO_2 emissions. Furthermore, the number of food transports is expected to increase (Smith et al. 2005).

Recently however, different studies have been carried out in order to evaluate whether food miles really are a good indicator for the environmental impact of a food. All these assessments concluded that a single indicator based on total food kilometers is an inadequate indicator of sustainability (Smith et al. 2005; Saunders et al. 2006; Weber & Matthews 2008; Edwards-Jones et al. 2008). Primarily two reasons are responsible for these conclusions. First of all, the differing impact loads of different transportation modes (e.g. the high impact of airfreight) are not considered in the food miles concept (Smith et al. 2005). Secondly, it has been shown that transportation processes are only responsible for a small amount of the total greenhouse gas emissions related to food (Saunders et al. 2006; Weber & Matthews 2008; Edwards-Jones et al. 2008). For example Weber and Matthews (2008) calculated using life-cycle inventories that 83 % of greenhouse gas emissions associated with food can be attributed to the production phase. Food miles only contributed 4 % to total greenhouse gas emissions – transportation as a whole 11 %. It can therefore be better in some cases to buy imported foods than local ones (Saunders et al. 2006).

In conclusion, food miles cannot be seen as an indicator of ecological sustainability of foods. Nevertheless, locally produced food might have important social and economic impacts.

6.5. Possible Future Assessment Methods and Indicators

New methods and indicators are continuously being developed. Two of these, the concept of human appropriation of net primary production and the Resource and Energy Analysis Program, are described in more detail below. Both approaches are not yet applicable for food items, but this is not excluded for the future.

6.5.1. Human Appropriation of Net Primary Production

The human appropriation of net primary production (HANPP) is an aggregated indicator that wants to reflect both the amount of area used by humans and the intensity of land use. Different definitions exist for HANPP. Most commonly and recently it is defined as the difference between the amount of net primary production (NPP) that would be available in an ecosystem in the absence of human activities and the fraction of NPP remaining in ecosystems after human harvest under current conditions. HANPP measures the combined effect of land use induced changes in NPP and biomass harvest. In order to be able to calculate HANPP it is necessary to assess three properties: first of all the NPP of the vegetation that would be assumed to prevail in the absence of human land use (the potential vegetation), secondly the NPP of the currently prevailing vegetation and thirdly the human harvest of NPP. Different methods are available to estimate these three properties, for example remote sensing or geographic information systems technologies (Erb et al. 2009).

According to the above mentioned definition, the global HANPP was estimated at 23.7 % (Erb et al. 2009). Studies have also been carried out for different countries, for example the Philippines (HANPP estimate: 60 % in the year 2003; Kastner & Kastner 2009) or the UK (HANPP estimate: 68 % in the year 2000; Musel 2009). Furthermore, studies have been able to demonstrate that an increasing HANPP comes with a decrease in species diversity (Haberl et al. 2004).

In future it seems possible that this methodology could also be applied for assessing the impact of the food sector in general and also of different food groups.

6.5.2. Resource and Energy Analysis Program

The Stockholm Environment Institute is currently developing the Resource and Energy Analysis Program (REAP), a resource-environment modelling tool. Three main methodologies are combined in this software: material flow analysis as a basis and greenhouse gas emissions and the Ecological Footprint for expressing the key environmental impacts. Together these three methodologies can provide information about the impact of consumption (concerning the categories energy, waste, housing, infrastructure, food and transport) at the individual, organisation, local authority, region or national level. Additionally, scenarios can be conducted in order to estimate future resource and energy consumption (Barrett et al. 2004).

REAP has already been applied to assess resource use, CO_2 emissions and Ecological Footprints in the UK and its regions, subdivided in consumption categories (World Wildlife Fund UK. 2006). In future REAP is expected to identify and compare the impact of various products and their supply chains (Barrett et al. 2004).

REAP seems to be a promising tool to evaluate and communicate sustainable consumption and production issues, as it combines different methods and can thus deliver more precise results. The future will show whether it is appropriate for evaluating food items.

7. The Ecological Footprint

In this piece of work *"Ecological Footprint"* always refers to the aggregated sustainability indicator developed by Mathis Wackernagel and William Rees at the *University of British Columbia* in the early 1990's. Nowadays a growing number of communities, governments (for example the ones of Wales, Switzerland, Finland or Japan) and Non-Governmental-Organizations (NGOs, for example Greenpeace or the WWF) apply the Ecological Footprint concept as a core indicator for sustainable resource use (Greenpeace 2008; Ewing et al. 2008a). Alongside this, an increasing amount of Footprint practitioners (for example the NGO *Global Footprint Network* or *Best Foot Forward*) are emerging, offering Footprint analysis for various systems. Working mainly through educational work the Austrian-based *Plattform Footprint* wants to create awareness, insights and political pressure in order to achieve sustainable changes.

The following chapters deal in detail with the basic concept of the Ecological Footprint, its calculation methodology and current appliances.

7.1. Overview of the Concept of the Ecological Footprint

The Ecological Footprint is a measure of human demand on the biosphere. It measures the amount of biologically productive land and water area which is required to produce all the resources an individual, population, country, etc. consumes, and to absorb the waste they generate. This area can then be compared with the earth´s biocapacity, which is the amount of productive area that is available to generate these resources and to absorb the corresponding waste (Ewing et al. 2008a).

Six assumptions form the basis of Ecological Footprint analysis (Wackernagel et al. 2005; Giljum et al. 2007; Ewing et al. 2008a):

- The majority of the resources consumed by people/activities and the corresponding wastes can be tracked.
- Most of these resources/wastes can be measured in terms of the biologically productive area necessary to supply/remove them. If measuring isn`t possible, the resources/wastes are excluded from the assessment.
- Areas with differing bioproductivity can be converted into the common unit of average bioproductivity, the global hectare (gha; see definition 1).

- Global hectares can be summed, because they represent the same amount of bioproductivity in any single year.
- Human demand (measured by Ecological Footprint accounts) can be directly compared to biocapacity as both are expressed in global hectares.
- The demanded area can exceed the area available (status of overshoot), which leads to diminished ecological assets.

Definition 1: Global Hectares

Ecological Footprint and biocapacity results are often expressed in global hectares, a hectare with world-average ecological productivity (Wackernagel & Kitzes 2008). Yield factors and equivalence factors are used to convert the actual physical hectares into the global unit.

Yield factors account for differences in productivity of a certain land type between a nation and the global average in this area type. Varieties in precipitation, soil quality, management practices, etc. lead to these productivity differences (Ewing et al. 2008b). For example German cropland is 2.1 times more productive than the world's average (Ewing et al. 2009).

Equivalence factors on the contrary translate a certain land category into a universal unit of biologically productive area (Ewing et al. 2008b). Thus it is possible to compare and add up different land categories.

A full Ecological Footprint analysis consists not only of the assessment of the actual Footprint (the demand), but also of the biocapacity (the supply; Giljum et al. 2007). Both of them can be expressed in global hectares and therefore be directly compared with each other. Additionally they are both estimated using different land categories (see definition 2).

Definition 2: Land categories

For Footprint analysis different categories of ecological space are distinguished (figure 3; Wackernagel et al. 2005; Chambers et al. 2007; Ewing et al. 2008b):

- *Bioproductive land*, a combination of arable, pasture and forested land:
  - *Arable land* (or cropland) consists of areas used to produce food and fibre for human consumption, feed for livestock, oil crops and rubber.
  - *Pasture or grazing land* is land used for raising livestock for various products (meat, milk, hide and wool products).
  - *Forested land* refers to forests which yield timber and timber products. Other forest functions (e.g. protection of biodiversity, climate stability or erosion prevention) are not accounted for in this category.
- *Bioproductive seas/internal waters* (or fishing grounds) represent the area which is needed to support the fish caught for direct human consumption, for fishmeal production as well as bycatch.
- *Built-up land* consists of the area covered by human infrastructure (such as transportation, housing or industrial facilities).
- *Energy or carbon land* represents the amount of forested area required to absorb a given amount of carbon dioxide, effectively removing it from the atmosphere. This land category is only used for the actual Footprint and not for biocapacity calculations (Wackernagel & Kitzes 2008).
- *Biodiversity land* is the land needed to ensure the protection of the planet´s non-human species. This land category is often left aside in Footprint calculations, especially in recent ones (Giljum et al. 2007).

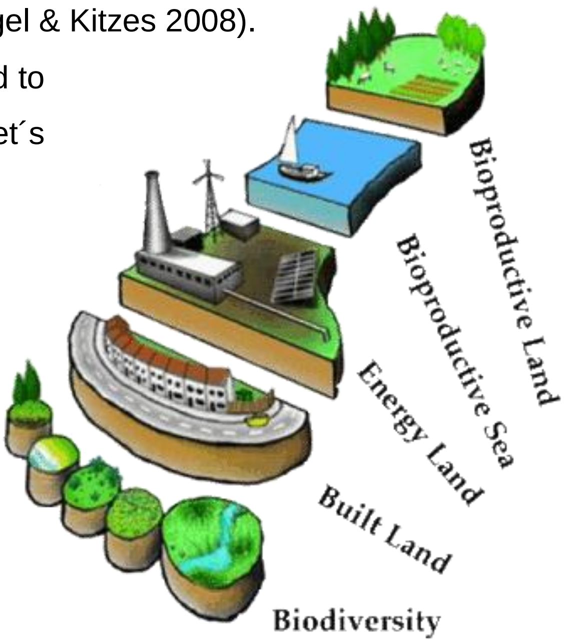

Figure 3: Land categories used in Ecological Footprint analysis (Chambers et al. 2007)

Biocapacity measures the ability of available terrestrial and aquatic areas to provide ecological services (Ewing et al. 2008a) and can be defined as the total usable biological production capacity in a given year of a biologically productive area (Wackernagel et al. 2005). Biologically productive areas are defined as land and sea areas with significant photosynthetic activity and accumulation of biomass. Therefore the earth´s deserts, deep oceans or ice caps are not included (Wackernagel et al. 2005; Ewing et al. 2008a). In order to calculate biocapacity, each of the different types of bioproductive areas – cropland, forested land, fishing grounds, pasture land, and built-up land – is multiplied by the appropriate equivalence and yield factor, so it can be expressed in global hectares (Ewing et al. 2008b). That way earth´s total biocapacity was estimated at 11.9 bn global hectares in the year 2006, equal to approximately a quarter of the planet´s surface (Ewing et al. 2009).

The Ecological Footprint measures how much of the above mentioned biologically productive area a certain system (for example a product, an individual, a city, a country, a region, or humanity) uses to produce the resources it consumes and to absorb the waste it generates, always assuming prevailing technology and resource management schemes (Wackernagel et al. 2005).

Due to the above mentioned principles only those aspects of resource consumption and waste production can be included in Footprint calculations for which the earth has regenerative capacity and where data exist that allow this demand to be expressed in terms of productive area (World Wide Fund For Nature et al. 2008). Thus many ecologically critical processes are not or only partially taken into account, for example the release of various toxic compounds (heavy metals, radioactive materials, pesticides, etc), land degradation (e.g. caused by erosion or salinisation), nuclear power or waste flows besides the one of CO_2 (Ewing et al. 2008a). Ecological Footprint results therefore always have to be regarded as underestimates.

For this and other reasons the Footprint concept has often been criticised (van den Bergh & Verbruggen 1999; Fiala 2008). Nevertheless it is a very useful, descriptive and particularly an easy to communicate tool for promoting sustainability (Giljum et al. 2007).

7.2. Methods of Calculation

Two complementary approaches are available for calculating Ecological Footprints, the compound and the component-based method. Each of these methods has its own advantages and disadvantages; therefore they are suitable for different kinds of Footprint calculations. Over the years the methodologies have been and still are constantly changing, due to better background knowledge and data availability[7]. This leads to increasingly robust and reliable results and a broader array of applications (Wackernagel 2009). Both of these approaches are briefly described below.

7.2.1. Compound Calculation (Top-Down Approach)

This methodology is used primarily for the most well-known Footprint calculations, the global and national Footprint accounts, and is under continuous improvement (Kitzes et al. 2009).

To assess the Footprint of a nation, the Footprints of all consumption activities within this country are calculated and then summed. Consumption activities are either products harvested directly from the four productive land categories (cropland, grazing land, fishing grounds, and forest land), the physical extent of built-up area, or carbon dioxide emissions released from any given activity. The global Ecological Footprint is calculated as the sum of all national Footprints (Wackernagel & Kitzes 2008).

In order to calculate the Ecological Footprint for any consumption activity the following equation is used:

$$\boxed{\mathrm{EF} = \frac{\mathrm{D}}{\mathrm{NY}} \times \mathrm{YF} \times \mathrm{EQF}}$$

Whereas *EF* is the Ecological Footprint of a given consumption activity (in gha), *D* is the annual demand of this activity (in tons per year), *NY* is the national yield for *D* of the country in which this activity was produced (in tons per hectare per year), *YF* is the yield factor (dimensionless), and *EQF* is the equivalence factor (in gha per hectare; Ewing et al. 2008b; Wackernagel & Kitzes 2008).

More precisely, for directly harvested products *D* is the amount of product harvested and *NY* the national average yield for this product. In 2009 Ewing et al. for example

[7] For example IOA has been combined with national Footprint calculations in order to allocate demand of certain human activities in more sophisticated ways (Wiedmann et al. 2006)

calculated the Footprint of 164 different crop categories for 201 countries. The Footprints of secondary products (e.g. flour) which are derived from primary products (e.g. wheat) are calculated by converting them back into primary-product equivalents (Ewing et al. 2008b; Wackernagel & Kitzes 2008). The Footprint of built-up land is calculated by using the area occupied by human infrastructure (in hectares) instead of *D* divided through *NY* and multiplying this with the yield and equivalence factors for cropland. This is based on the assumption that most built-up land occupies former cropland (Ewing et al. 2008b). The Footprint for CO_2 emissions uses the total mass of CO_2 emissions released from a given activity for *D* and the average rate of carbon uptake per hectare of forest land for *NY*.

It is important to note that these calculations result in Ecological Footprints of consumption, as for each country and consumption activity imports are added to a country's production and exports are subtracted (Ewing et al. 2008b). This enables it to detect impacts of different countries in a clearer way, because trading activities often shadow these impacts.

An overview of this calculation structure is also shown in figure 4.

Figure 4: Structure of calculating national Ecological Footprints, excluding secondary products (von Stokar et al. 2006)

7.2.2. Component-based Calculation (Bottom-Up Approach)

The component-based methodology is mainly used for the calculation of more specific Footprints, for example of institutions or products.

In this model an Ecological Footprint for a certain system is estimated by adding pre-calculated Footprint values of certain activities or components using data appropriate to the region under consideration. For example in order to calculate the Footprint of car travel per passenger-km first data on fuel consumption, manufacturing and maintenance energy, land-occupancy by roads, distance travelled, etc. have to be obtained for the region in question, then transformed into Footprint data and last but not least combined to a single value (Chambers et al. 2007). The typical Footprint land categories are retained, but often the results are not transformed into global hectares (due to the primarily local or regional relevance of these estimates).

Ideally the underlying data comes from life-cycle-inventories, but these are still not as widely available as desired. Further problems arise from the possible variability and reliability of these data sets, due to different measurement assumptions, methodologies and samples. Nevertheless, the component-based approach is usually easier to communicate and more instructive than the compound approach (Chambers et al. 2007).

7.3. Examples of Ecological Footprint Calculations (Focus on Nutrition/Foods)

Today Ecological Footprint calculations can be conducted on almost every level, depending on what kind of knowledge is requested. So far calculations have been carried out for different spatial scales (global, national, regional and local levels), for institutions, businesses and individuals, and last but not least for services and products. In the following chapters examples of these calculations will be presented for every category, in each case with a special focus on the aspects of nutrition and/or foods.

7.3.1. Global Level

To date global Ecological Footprint calculations have been carried out for over ten years with the latest data being published in the *Ecological Footprint Atlas 2009* (Ewing et al. 2009). This report uses international data generated up to the year 2006 mainly by UN agencies, for example the FAO or the *United Nations Statistics Division* (UNSD).

The main result of this calculation is that in the year 2006 humanity´s total Ecological Footprint was about 40 % larger than the earth's biocapacity. This means, that mankind would need approx. 1.4 earths in order to support its consumption. The main component of humanity´s footprint, accounting for approx. 50 %, is land needed for the uptake of CO_2. This component increased more than tenfold between 1961, the first year for which Footprint calculations are available, and 2006, while the other ones rose to much lesser degrees (figure 5; Ewing et al. 2009). It has been calculated using IPCC scenarios that humanity´s Footprint will increase even more drastically by 2050 (Ewing et al. 2008a).

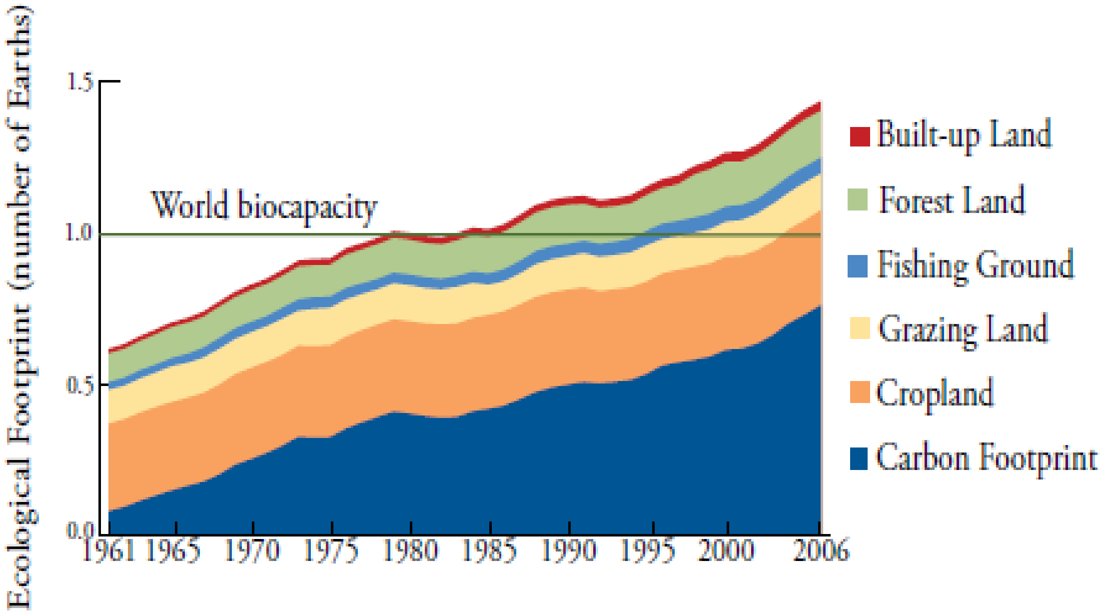

Figure 5: Humanity´s Ecological Footprint by component, 1961 to 2006 (Ewing et al. 2009)

Humankind can live in this state of overshoot for only a limited amount of time, but if this trend continues the different ecosystems will lose their productivity and their ability to regenerate.

This will be especially detrimental for the global food system, because for our food we depend entirely on the biosphere´s productivity. Global analysis of humanity´s food Footprint showed that in 1999 the food system required 40 % of the earth´s biologically productive area (figure 6) – an increase from 27 % in 1961 (Deumling et al. 2003). With the estimations of the yet growing human population and an increased demand for livestock products, this amount is likely to increase even more – meaning that the remaining biocapacity, which is necessary for other products and ecosystem services besides harbouring most of the earth´s biodiversity, will be reduced.

The food Footprint consists basically of four components (cropland, pastures, fisheries and energy; figure 6), which account for all the foods we produce.

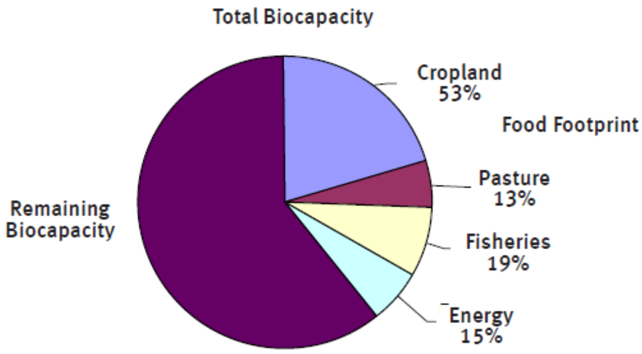

Figure 6: Proportions of food Footprint components on the earth´s biocapacity, 1999 (Deumling et al. 2003)

Cropland is responsible for more than half of the global food Footprint (Deumling et al. 2003) – although actual cropland accounts for only 28 % of the world´s total agricultural land (von Koerber et al. 2009). In order to calculate the cropland footprint, 90 different crop products were analysed (Deumling et al. 2003) - with wheat, rice and corn nowadays providing 60% of humanity´s food (Tilman et al. 2002). The total amount of cropland is estimated to increase due to the growing world population and a growing demand for livestock products. Cropland is not only the basis for products for direct human consumption, but also for animal feed. According to the FAO, animal feed production accounts for a third of all cropland available globally (Steinfeld et al. 2006). In the U.S. animals consume even two-thirds of all cereals (Deumling et al. 2003). As livestock production is projected to increase in the future (Steinfeld et al. 2006), this portion is likely to increase as well.

Pastures account for approx. 13 % of the global food Footprint. In terms of real agricultural area (not gha) pastures make up 69 % of all agricultural land (von Koerber et al. 2009). This high difference is due to the low bioproductivity of pasture land. Differences in bioproductivity are offset by the conversion into gha and therefore cannot be observed anymore in plain Footprint accounts (for example the above mentioned ones). The growing consumption of animal products has led and is leading to an increase in the amount of pasture land. However, this increase wasn´t as big as expected due to the trend to industrial livestock farming - i.e. intensive fertilization of pastures or feeding livestock from cropland production (Deumling et al. 2003).

The **fisheries** Footprint accounts for 19 % of the global food Footprint. The world´s high demand on fish already has strong impacts on different fish species and on ocean ecosystems in general (Deumling et al. 2003).

Energy`s share on the global food Footprint is estimated to be around 15 %. This energy is used in agricultural food production, for inputs contributing to this production (e.g. manufacture of fertilizers and pesticides) and post-production operations (i.e. processing, packaging, transport, storage and retail of foods). The latter category is by far the most important one, making up 80 – 90 % of the food´s system fossil fuel use (Deumling et al. 2003). Generally, the energy required for processing and packaging is much greater than the energy the food product contains (Heller & Keoleian 2003).

As demonstrated above, the global food systems take up a large portion of the earth`s biocapacity. Nevertheless these results should all be viewed as conservative underestimates, because other important impacts of food production cannot yet be calculated with the Footprint concept. Examples for these impacts are soil erosion due to intense agricultural practices, pesticide toxicity or methane release from the keeping of livestock or rice cultivation (Deumling et al. 2003).

7.3.2. National Level

Besides the global Ecological Footprint calculations the national ones are probably most well known. In 2009 Ewing et al. published the Ecological Footprints and the available biocapacity of 241 countries and showed which countries are ecological debtors or creditors (figure 7). Debtor countries have an Ecological Footprint greater than their own biocapacity; creditor countries have an Ecological Footprint smaller than their own biocapacity respectively. Overuse of own natural resources, import of resources from other sources and the release of CO_2 into the atmosphere are the reasons why it is possible for a country to acquire an ecological dept (Ewing et al. 2009).

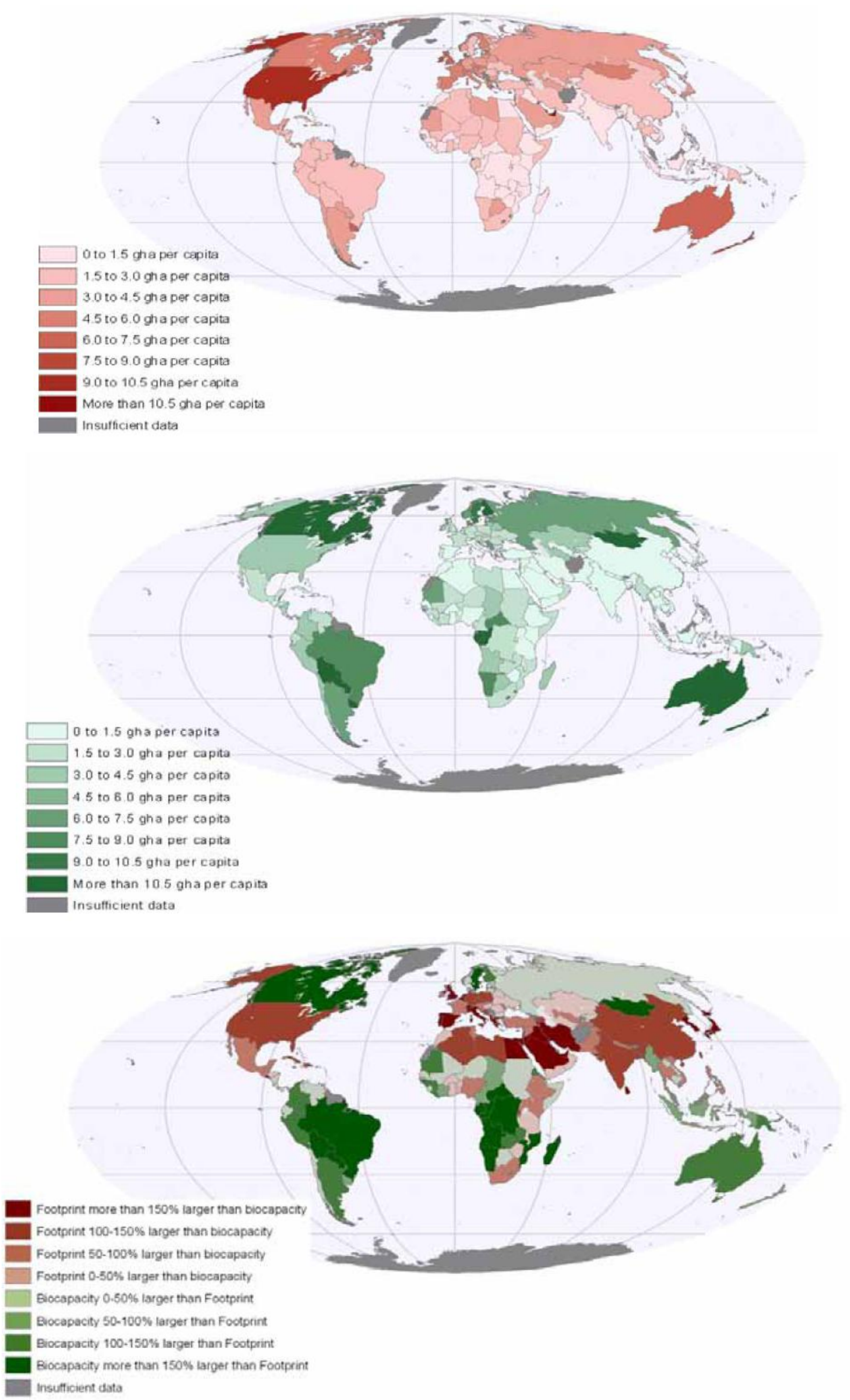

Figure 7: Ecological Footprint (top), biocapacity (middle) and ecological dept analysis (bottom) by country, 2006 data (Ewing et al. 2009)

The different countries have very varying impacts on the earth: industrialized, high-income countries have the highest impacts (for example the US have an Ecological Footprint of 9.0 gha/cap or Germany with 4.0 gha/cap), developing, low-income countries have the lowest impact, like Bangladesh with an Ecological Footprint of 0.5 gha/cap. An acceptable Footprint according to the earth´s biocapacity would be 1.8 gha/cap. This number is calculated by dividing the 11.9 billion gha of available biocapacity by the estimated world population of 6.6 billion in the year 2006 (Ewing et al. 2009).

The different countries also have very varying food Footprints, although the amount of energy every person requires from food is relatively similar. The global average food Footprint is approx. 1.9 gac./cap (equals 0.8 gha/cap), the US food Footprint however consists of 5.2 gac./cap (equals 2.1 gha/cap; figure 8) – which is already more than the acceptable Ecological Footprint of 1.8 gha/cap (Deumling et al. 2003; Ewing et al. 2009). Germany´s food Footprint consists of 1.5 gha/cap, which equals approx. 35 % of their total Footprint (Greenpeace 2008). In the UK every person needs approx. 1.14 gha for food corresponding to 21 % of their total Ecological Footprint of 5.4 gha/cap (World Wildlife Fund UK. 2006).

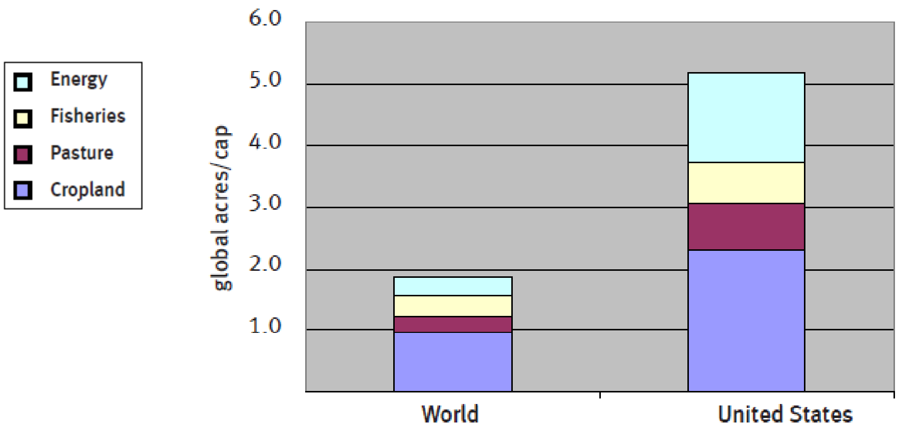

Figure 8: Food Footprint of the world and the US (Deumling et al. 2003)

Reasons for these differences among countries lie on the one hand in the different amount of calories per capita and on the other hand in the so-called diet impact ratio (White 2000). The diet impact ratio demonstrates the environmental impacts of various diets and can be depicted in generated Footprint per calorie. Regions where the diet contains a lot of livestock products (for example North America) have been shown to have a higher diet impact ratio than regions where the diet is mainly vegetarian – like in Africa or Asia (table 9; White 2000).

Table 9: Diet impact ratio by region expressed as footprint per 1000 kcal, data from 1995 (White 2000)

Region	Diet impact ratio [ha/1000 kcal]	Diet impact ratio [m^2/1000 kcal]
Asia	0.081	810
Africa	0.083	830
South & Central America	0.113	1130
Europe	0.120	1200
Oceania	0.145	1450
North America	0.153	1530
World	**0.095**	**950**

7.3.3. Regional and Local Level

A number of studies have been conducted in order to calculate the Ecological Footprint of different regions and districts, especially in the UK. This is important because Ecological Footprints differ not only between countries, but also between different regions within a country. For example in the UK the variation in Ecological Footprints across different regions is approx. 33 %, the highest values found in the wealthy south-east parts of the country (World Wildlife Fund UK. 2006). Furthermore, the results of these studies can help to direct policy-makers to more informed actions (Collins & Fairchild 2007).

Best Foot Forward, a company dedicated to Ecological Footprint analysis amongst other things, calculated these for different UK regions/districts, for example the South-West of England (Best Foot Forward Ltd. 2005), the Isle of Wight (Best Foot Forward Ltd. 2001) or the city of London (Best Foot Forward Ltd. 2002). In each of these studies the food Footprint was also specifically analysed. It was shown that animal-based products (especially meat and milk) contribute the most to the food Footprint. For example in London meat consumption is responsible for 28 % and milk consumption for 12 % of the food Footprint. Another important category in London is pet food which accounted for 15 % of the food Footprint (Best Foot Forward Ltd. 2002). In the South-West of England animal-based food makes up 77 % of the food Footprint - although twice as much plant-based food is consumed there (figure 9, Best Foot Forward Ltd. 2005).

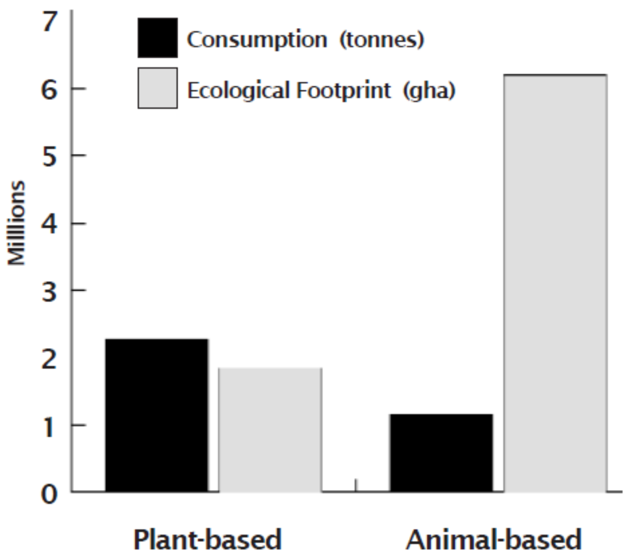

Figure 9: Ecological food Footprint of residents of the South-West of England compared with amount consumed (Best Foot Forward Ltd. 2005)

Collins and Fairchild (2007) estimated the Ecological Footprint of Cardiff, the capital of Wales, with a special focus on the food and drink component. Additionally they developed scenarios in order to see how the environmental impact of Cardiff's food and drink consumption could be reduced with certain dietetic alterations. A Cardiff' resident has an average food Footprint of 1.33 gha/cap which relates to a quarter of their total Ecological Footprint of 5.59 gha/cap. The Footprint of food associated waste (consisting mainly of paper, card and putrescibles, i.e. not consumed foods) is approximately 0.42 gha/cap – which is about a third of the total food Footprint (World Wide Fund For Nature Cymru 2005; Vale & Vale 2009). Reasons for the high food Footprint are mainly the consumption of a lot of animal-based products, a high amount of food associated waste, a high degree of eating out and a low portion (only 1.1 %) of organic foods. Food transport played a minor role regarding the food Footprint of a Cardiff resident (only 1.7 %). Collins and Fairchild further showed that small changes in the diet can lead to high changes in the food Footprint. For example a switch to an 87.97 % organic diet would reduce the food Footprint by approx. 23 %. With replacing the most critical food items from the diet with alternatives reductions between 18 % and 26 % can be achieved. A vegetarian diet would only lead to an approx. 6 % reduction, due to the fact that in the scenario the meat products were mainly replaced with other animal-based products with a high Footprint, for example cheese (Collins & Fairchild 2007).

7.3.4. Institutional and Business Level

Ecological Footprint calculations have also been applied to different kinds of institutions and businesses. For example *Best Foot Forward* calculated the Ecological Footprint of the *National Health Service* (NHS) in England and Wales. Per capita the NHS evokes an Ecological Footprint of 0.09 gha. The most important components contributing to this are products and waste the NHS creates (58 % of the total Ecological Footprint), travelling of visitors, patients and staff (22 %) and direct energy usage (17 %) – while food is only responsible for 2 % of the generated Footprint (Best Foot Forward Ltd. 2004).

Footprint calculations have also been carried out for universities. For example the Ecological Footprint of *Oxford Brookes University* was estimated at approx. 2800 ha – an area 80 times the size of the actual campus. The study further led to the production of a green commuter plan, due to the fact that commuting took the largest share of the total Footprint (Chambers et al. 2007).

Van der Werf et al. (2007) analyzed the Ecological Footprint of organic and conventional pig farms. The results showed that per hectare of farm surface the Footprint of the conventional farm is twice as big as the one of the organic farm. Per kilogram of pig (live weight) though the Ecological Footprint is almost 50 % higher in the organic farm compared to the conventional one. This is mainly due to the large amount of actual land required for organic farming (van der Werf et al. 2007).

Other studies estimated the Footprint of fisheries (Larsson et al. 1994; Folke et al. 1998; Warren-Rhodes et al. 2003). The results indicate that the current consumption of fish is not sustainable. Especially aquacultures have a high impact on the environment. Folke et al. (1998) for example calculated that fish farming in cages requires marine ecosystem areas as large as 10.000 - 50.000 times the area of the cages for producing the food for the fish.

7.3.5. Individual Level

People living in the same country can cause very differing Ecological Footprints depending on the individual lifestyle. Footprint calculators have been developed in order to visualize these differences and to demonstrate what kind of impact certain behavioural changes would have. These calculators are usually internet-based tools and provide an opportunity for everyone to estimate his or her personal Ecological

Footprint (examples can be found and tested at *www.mein-fussabdruck.at, www.ecologicalfootprint.com* or *http://footprint.wwf.org.uk*). Often recommendations for the reduction of the personal Ecological Footprint are also given.

The bases for the calculations are questionnaires which cover different consumption categories (food, housing, mobility and products) and the national average Ecological footprint accounts (Institut für Soziale Ökologie 2004). The individual Ecological Footprint is higher or lower than the average national Footprint depending on how much the consumption pattern diverges from the national mean. The results of these calculations should therefore be seen as rough estimates only.

7.3.6. Service Level

Services also generate a Footprint. This is a relatively new application of the Footprint methodology, therefore examples are relatively rare.

Vale and Vale (2009) calculated the Footprint of various ways of washing the dishes. They came to the conclusion that washing up by hand once a day is the best option (approx. 35 m^2/a), followed by a dishwasher used once a day (approx. 48 m^2/a). Washing up smaller amounts three times generates a Footprint of approx. 58 m^2/a – still better than using a dishwasher twice a day (approx. 96 m^2/a).

Keeping pets can also have a high environmental impact – especially if the pets in question are feed on a diet based on meat. A large dog, for example an Alsatian, can generate the same Footprint (approx. 0.36 ha/a) as driving a car for one year (based on 14.000 km/a; Vale & Vale 2009). This finding however might need to be reconsidered. Animal feed is made mainly from slaughterhouse waste – originating from livestock bred for human needs. Therefore animal feed has only a small share of the environmental impact of meat production. Nevertheless, pets are not negligible from an ecological perspective (Blawat 2009).

7.3.7. Product Level

These days product Ecological Footprints are still relatively rare (due to the fact, that the methodology for product Footprints is not fully developed yet), but are getting more and more popular. Footprints for specific foods are probably the most common application, but the analysis can be conducted for almost any kind of product, for example fuels (Holden & Høyer 2005) or pulp (Kissinger et al. 2007).

Specific food Footprints can be estimated with both calculation methods. The compound calculation method however gives only rough results and can only be applied to estimate the Footprint of food groups. Nevertheless these results already indicate the great difference between plant-based and animal-based products. In table 10 some Footprint values for different food groups are presented (Chambers et al. 2007)

Table 10: Ecological Footprint estimates for various food groups (Chambers et al. 2007)

Food	**Ecological Footprint** [gm^2/kg/a]
Roots & Vegetables	3 – 6
Fruit	5 – 6
Milk	11 – 19
Grains	17 – 28
Legumes	36 – 44
Fish (oceanic)	45 – 66
Meat	69 – 146

Collins and Fairchild (2007) estimated the Ecological Footprints of various foods by combining the classical Footprint methodology with environmental IOA (table 11). By this means narrower food groups can be analysed. The results demonstrate that animal-based and concentrated food items have a higher Ecological Footprint than plant-based foods – not only with respect to the weight of the foods but also with respect to the amount of calories contained (in this case the difference is, however, not as pronounced). The latter data was calculated by means of the nutritional information panels published by the *German Society of Nutrition* (Fröleke & Wirths 2002).

Table 11: Ecological Footprint estimates for various food items in gm^2/kg (Collins, Fairchild 2007) and $gm^2/1000$ kcal (own calculations, underlying data from Fröleke & Wirths, 2002)

Food		Footprint [gm^2/kg]	Calories[1] [kcal/kg or kcal/l]	Footprint[1] [$gm^2/1000$ kcal]
Milk and milk products	Whole & skimmed milk	14	565 (480 – 650)	25 (22 – 29)
	Yoghurt	17	595 (490 – 700)	29 (24 – 35)
	Ice-cream	43	2050	21
	Cream	61	3080	20
	Cheese	111	3120 (1270 – 3980)	36 (28 – 87)
	Butter	115	7510	15
Meat	Pork/ham/bacon	19	2210 (1030 – 6210)	9 (3 – 18)
	Poultry	32	1760 (1050 – 3420)	18 (9 – 30)
	Mutton & lamb	76	2260 (1120 – 3810)	34 (20 – 68)
	Beef & veal	157	1270 (920 – 2070)	124 (76 – 171)
Other animal-based foods	Eggs	19	1360	14
	Fish	32	1120 (660 – 2330)	29 (14 – 48)
Fruits and Vegetables	Potatoes	3	700	4
	Vegetables (fresh)	3 – 4	260 (110 – 870)	13 (4 – 31)
	Vegetables (processed)	5	-	-
	Fruits	5	520 (160 – 890)	10 (6 – 31)
	Fruit juices	11	470 (260 – 700)	23 (16 – 42)
Cereals & cereal products	Bread	5	2140 (1820 – 2580)	2 (2 – 3)
	Flour	7	3200 (2890 – 3320)	2
	Biscuits	14	4280	3
	Cakes	16	3140	5
Other plant-based foods	Margarine	66	7220	9
	Vegetable & salad oils	38	9000	4
	Sugar	7	3990	2
Beverages	Mineral water	1	-	
	Soft drinks	2	430	5
	Beer and lager	5	396 (370 – 420)	13 (12 – 14)
	Wine	22	727 (670 – 800)	30 (28 – 33)
	Spirits (e.g. whisky)	41	2260 (1790 – 2470)	18 (17 – 23)
	Tea (leaves)	35	1470	24
	Coffee (beans)	45	1800	25
	Cocoa/drinking chocolate	56	3430	16

[1]: In the case of multiple food items per food group (in the case of complex food groups?) the mean value and the range in brackets is given

With the component-based calculation much more specific food Footprints can be generated. Often life cycle inventories form the basis for these product Ecological Footprint calculations (Huijbregts et al. 2008). Generally the most important land types for all agricultural products are CO_2-uptake land and direct land occupation, while other products mostly rely on the consumption of non-renewable energy (Huijbregts et al. 2008).

One of the first studies about a product Footprint was carried out by Wada (1993), who compared the Footprints of tomatoes from two different cultivation methods (hydroponic and open field operations). He came to the conclusion that hydroponic operations have a 14 – 21 times higher Footprint than conventional open field agriculture to produce the same amount of tomatoes (Wada 1993). Other specific Footprints for various foods can be viewed in table 12. It has to be kept in mind though that each of these studies used different assumptions and system boundaries and therefore should be compared with each other cautiously.

Table 12: Specific product Footprints for various foods

Food	Footprint	Data Source
Tomatoes • Greenhouse • Open field	7.65 - 9.19 m^2/kg 0.43 - 0.56 m^2/kg	(Wada 1993)
Bananas • Conventional • Organic	0.77 m^2/kg 0,33 m^2/kg	(Giljum 1999)
Apples • Conventional • Organic	3.4 m^2/kg 0.8 m^2/kg	(Mamouni Limnios et al. 2009)
Spinach • Deep-frozen • Fresh baby-leaf	0.85 gm^2/kg 1.42 gm^2/kg	(Burger et al. 2009a)
Wine • Conventional • Organic	13.98 gm^2/bottle 7.17 gm^2/bottle	(Niccolucci et al. 2008)
Beef • Conventional • Organic	23.91 m^2/kg slaughter weight 115.09 m^2/kg slaughter weight	(Kratochvil & Dekker 2004)

Nevertheless, some important observations can be made. First of all the specific food Footprints are of the same order of magnitude as the Footprint estimates in table 10 and 11. According to Wolfgang Pekny (*Plattform Footprint*) one can be satisfied if the results do not deviate more than 15 % of each other[8]. Secondly, meat generates a much higher Footprint than plant-based food as it requires a lot more land, energy

[8] personal interview on 7/11/2009, Würzburg

and water resources. According to Deumling et al. (2003) crop-based food requires approx. 0.36 gha per gigacalorie of food, compared to 1.46 gha per gigacalorie of animal-based food. Last but not least it can be observed that the production methods have a high impact on the Footprint: Organic agriculture usually generates a lower Footprint than conventional agriculture per unit of product. Greenpeace (2008) estimates this difference for plant-based products at 20 %. Exceptions are organic meat products – these generate a higher Footprint than ones from conventional agriculture. Kratochvil & Dekker (2004) demonstrated that organic beef has a 5 times higher Footprint than conventionally produced beef. However, this study has some methodological errors. Therefore Wolfgang Pekny estimates that organic meat has only a 20 % higher Ecological Footprint than conventional produce[7]. The main reasons for this difference between conventional and organic are the extensive use of pastures and a lower productivity in organic agriculture (Greenpeace 2008; Kratochvil & Dekker 2004).

The LCA database *ecoinvent V2.01* offers Ecological Footprint values for a wide range of products, for example plastics, textiles, metals or agricultural products (ecoinvent Centre 2007). No data regarding actual food items can be found in this database. However, data for some basic agricultural resources which form the basis for a lot of food items are available. Figure 10 shows the Ecological Footprints for some agricultural crops at the farm level in Switzerland.

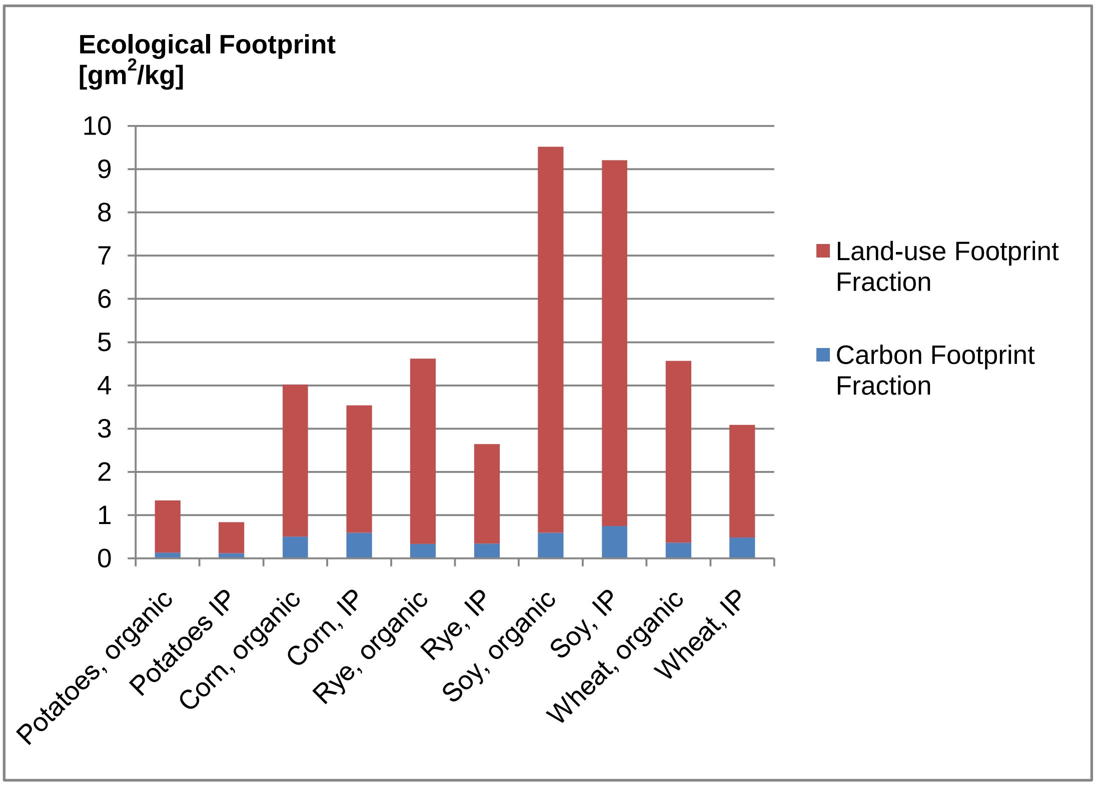

Figure 10: Ecological Footprint values (total, land-use and carbon fraction) of some agricultural crops at farm level in Switzerland, underlying data obtained from *ecoinvent V2.01*, (ecoinvent Centre 2007); IP = Integrated Production

It can easily be observed that soy has the highest Ecological Footprint per kg, followed by the different cereals and last but not least by potatoes. The arable crops originating from the integrated production system (a farming system which is more or less a bridge between conventional and organic agriculture; Boller 2004) all have lower Ecological Footprints than the crops deriving from organic agriculture. The reason is mainly the lower yields of these arable crops in Swiss organic agriculture.

D) FOOTPRINT CALCULATIONS

In this section the Ecological Footprints of different foods were calculated by means of LCA-databases and literature sources. Footprint values of different components were pre-calculated and then added - therefore the methodology equals a component-based or bottom-up approach (Chambers et al. 2007). The exact methodology is illustrated in the following chapter.
It is important to note that the calculated Ecological Footprints of food items include only the life-cycle steps up to retail (unless otherwise stated). This is due to the fact that data covering the entire life cycle of food products is hardly available.

8. Material & Methods

The conducted Ecological Footprint calculations are based on the assumption that only the land categories *arable land*, *pasture land* and *carbon land* are of importance in the case of food items. The land categories *built-up land* and *forest land* are therefore being neglected. However, this should not change the results in a significant way as for agricultural products these land categories only play a minor role (Huijbregts et al. 2008). The category *fishing grounds* is not included as fish products were not analysed due to lack of appropriate data.

The actual calculations were carried out in three steps: In the first step the portion of the Ecological Footprint solely due to the CO_2 emissions of a certain food item was calculated (Carbon Footprint Fraction Calculation, chapter 8.1). This covers the land category *carbon land*. Other greenhouse gases besides CO_2 were not taken into account as this is not possible in the current Ecological Footprint methodology (see chapter 7.2). In the second step the portion of the Ecological Footprint due to actual land-use was estimated (Land-use Footprint Fraction Calculation, chapter 8.2). Hereby the land categories *arable land* and *pasture land* are captured. The following two chapters explain these two calculation steps in more detail. In the last step the results of the two previous ones were added up in order to obtain the total Ecological Footprint value of a certain food.

8.1. Carbon Footprint Fraction Calculation

The production of a certain food is associated with CO_2 emissions. The emitted amount of CO_2 per unit of food can be obtained by means of LCA-databases. In this piece of work the LCA-database GEMIS was used in order to gather this information (Öko-Institut e.V. 2008). With the help of this database the associated CO_2 emissions per kilogram of a certain food item (for Germany) were obtained (see appendix, table 16, 18 and 20).

These values can be transformed into Footprint values by multiplication with the so-called *Footprint Intensity of Carbon*. This factor gives the Ecological Footprint value per ton of CO_2 emitted. It is calculated itself on the basis of the *Carbon Sequestration Factor* and the *Ocean Sequestration Percentage*. The *Carbon Sequestration Factor* estimates the annual carbon uptake of a hectare of world average forest land. The *Ocean Sequestration Percentage* reflects the percentage of global fossil fuel carbon emissions that are sequestered by oceans (Kitzes et al. 2008).

In literature different values for the *Footprint Intensity of Carbon* can be found. In this piece of work the most recent value of 0.28 gha per ton CO_2 given by the *Global Footprint Network* was used (National Footprint and Biocapacity Accounts 2006). This methodology was also applied in the study of Niccolucci et al. (2008), who calculated the Ecological Footprint of two Italian wines.

The result of the multiplication of the CO_2 emissions of a given food item with the *Footprint Intensity of Carbon* is the amount of gha associated with the CO_2 emissions of the considered food – subsequently named the *Carbon Footprint Fraction*.

8.2. Land-use Footprint Fraction Calculation

The *Land-use Footprint Fraction* of the total Ecological Footprint concerning a certain food was calculated by multiplying the direct land requirement for this food with the appropriate equivalence and yield factor. The used equivalence and yield factors were obtained from the latest edition of the *Ecological Footprint Atlas* (see table 13; Ewing et al. 2009). Due to the fact that most of the underlying data originates from Germany or neighbouring countries (for example Denmark or the Netherlands) the yield factors for Germany were applied.

Table 13: Equivalence and yield factors used in Footprint Calculations, obtained from Ewing et al. (2009)

Factor	**Land category**	
	Pasture land	Arable land
Equivalence Factor [gha/ha]	0.51	2.39
Yield Factor (for Germany)	2.2	2.1

The necessary data of direct land requirements for certain foods was gathered by means of the LCA-database *LCA Food* (Nielsen et al. 2003), the *Food and Agriculture Organization Corporate Statistical Database* (FAOSTAT 2010) and literature sources (Gerbens-Leenes et al. 2002; Seemüller 2000; Woitowitz 2007). All of these sources delivered information on the amount of land which is necessary to produce a certain food item, expressed in m^2/kg (see appendix, table 17, 18 and 20). For plant-based foods and foods originating from chickens and pigs it was assumed that the required agricultural land was 100 % arable. This assumption was made due to the fact that in Germany pigs and chickens are commonly fed solely from crops and crop-based products (Woitowitz 2007). Cattle however are commonly fed with products derived from both arable and pasture land (Woitowitz 2007). Table 14 shows how different cattle systems (i.e. conventional and organic dairy cows or feeder cattle respectively) are fed with fodder originating from either pasture or arable land. This distinction is necessary in order to apply the right equivalence and yield factors for food items based on cattle.

Table 14: Percentage of pasture or arable land area required for different cattle systems, basic data from Woitowitz (2007), own further calculations

Cattle System		**Pasture land area** [%]	**Arable land area** [%]
Dairy Cow	Conventional	53.12	46.88
	Organic	67.89	32.11
Feeder Cattle	Conventional	10.22	89.78
	Organic	62.67	37.33

By adding up the values for the *Carbon Footprint Fraction* and the *Land-use Footprint Fraction* the total Ecological Footprint value for a certain food item was obtained.

9. Results

Table 15 shows the main results of the conducted Ecological Footprint calculations for various food items at the retail level. It gives the estimated values for the total Ecological Footprint, the *Carbon Footprint Fraction* and the *Land-use Footprint Fraction* respectively. Gerbens-Leenes et al. (2002), Nielsen et al. (2003) and the database FAOSTAT (2010) provided the basic data for the direct land requirements for the considered food items.

Table 14: Calculated Ecological Footprints (total, carbon fraction and land-use fraction) of various food items

Food		Carbon Footprint Fraction [gm²/kg/a]	Land-use Footprint Fraction[1] [gm²/kg/a]	Total Ecological Footprint[1] [gm²/kg/a]
Fruits and Vegetables	Fruits, fresh	1.18	2.51	3.69
	Fruits, frozen	1.21	2.51	3.72
	Vegetables, fresh	0.35	1.51	1.86
	Vegetables, frozen	1.02	1.51	2.53
	Tomatoes, fresh	0.53	0.25	0.78
	Potatoes, fresh	0.40	1.25 (1.00 – 1.51)	1.65 (1.40 – 1.91)
Cereal products	Wheat flour	0.87	7.53 (7.03 – 8.03)	8.40 (7.90 – 8.90)
	White bread, rolls	1.28	4.92	6.20
	Brown bread	1.54	5.72	7.26
Other plant-based foods	Sugar	3.46	4.14 (2.26 – 6.02)	7.60 (5.72 – 9.48)
	Margarine	1.36	107.91	109.27
	Vegetable oil	1.59	22.59	24.18
	Beer	1.11	2.51	3.62
Meat and Meat products	Poultry	8.05	25.10	33.15
	Poultry, frozen	10.79	25.10	35.89
	Pork	5.35	44.17 (43.67 – 44.67)	49,52 (49,02 – 50,02)
	Pork, frozen	8.08	44.17 (43.67 – 44.67)	52.25 (51.75 – 52.75)
	Beef	9.75	142.12 (96.92 – 187.35)	151.89 (106,67 – 197.10)
	Beef, frozen	12.48	142.12 (96.92 – 187.35)	154.62 (109.40 – 199.83)
	Ham	8.33	40.15	48.48
	Sausages	7.27	60.73	68.00
Other animal-based products	Milk	0.78	3.59	4.37
	Cheese	5.79	30.51	36.30
	Eggs	2.62	17.57	20.19

[1]: In the case of several data sources the mean value and the range in brackets is given

It can easily be observed that animal-based products have a much higher Ecological Footprint than plant-based foods – not only regarding the total Footprint value but also the two different fractions. Especially meat and highly concentrated foods like cheese have a high Ecological Footprint. Plant-based products in general have a very low Ecological Footprint, especially foods like fruits, vegetables or potatoes. Exceptions are highly concentrated plant-based foods like for example vegetable oil. The surprisingly high difference between margarine and vegetable oil is due to the varying underlying data sources concerning the direct land requirements for these food items (see appendix, table 17). In general in this calculation the *Carbon Footprint Fraction* contributes only to a relatively small degree to the total Ecological Footprint values – direct land use is the far more important category. However, it has to be kept in mind that food preparation activities (like cooking or frying) or waste disposal issues are not considered in this analysis. These activities can require high amounts of energy and therefore be responsible for a lot of CO_2 emissions – which are not included in these calculations.

For meat it was possible to distinguish between organically and conventionally produced food items at the level of slaughtering (figure 11). The underlying land-use data was provided by GEMIS (Ökoinstitut e.V. 2008), Woitowitz (2007) and Seemüller (2000; see appendix table 18 and 19).

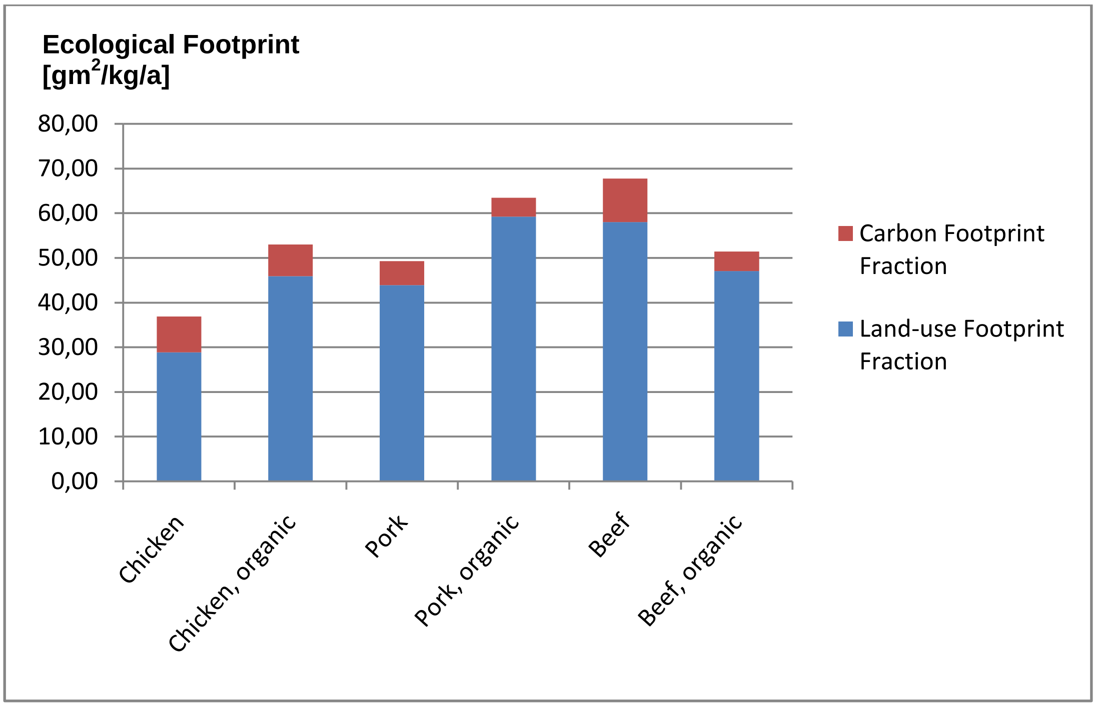

Figure 11: Ecological Footprints of different meat products per kilogram of the slaughtering weight

Organically produced chicken has an approx. 30 % higher Footprint than conventionally produced chicken, with pork this difference lies at approx. 22 %. Organically produced beef has an approx. 24 % lower Ecological Footprint than conventionally produced beef. This is due to the high percentage of pasture land used for feeding the cattle and the low equivalence factor for pasture land (0.51 gha/ha compared to 2.39 gha/ha for arable land). The higher total Ecological Footprint values for organic chicken and pork are solely due to the higher amount of direct land which is necessary in these production systems. This in turn is caused by the lower yields in the considered organic agricultural systems.

The *Carbon Footprint Fraction* is always lower in the organic production system: In the case of chicken it is approx. 12 % lower, for pork approx. 24 % and for beef approx. 55 %. This observation can be explained by the lower use of fossil fuels in organic agriculture (e.g. due to the saving of mineral fertilizers).

Figure 12 shows the difference in the Ecological Footprint values of chicken and pork at different life cycle stages (level of slaughtering and retail level respectively, the underlying data as well as the actual Footprint values are shown in the appendix, table 20 and 21). As the life-cycle moves on, the Ecological Footprint increases. The differences between the level of slaughtering and the retail level lie at 24 % (chicken) or 21 % (pork).

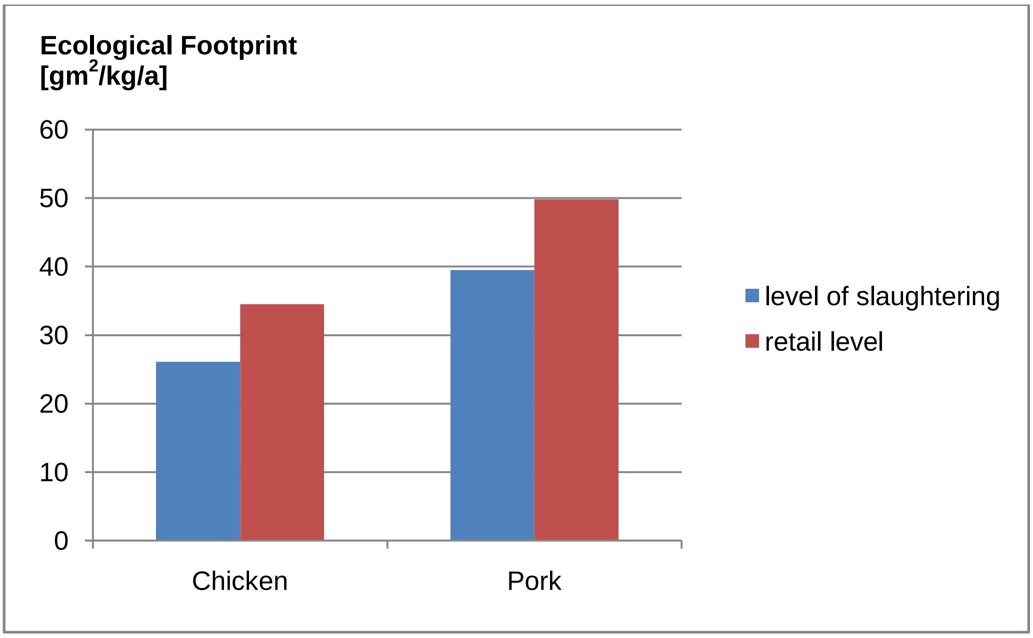

Figure 12: Comparison of the Ecological Footprints of chicken and pork at the slaughtering and at the retail level

Two reasons explain this difference. On the one hand the processing of the freshly slaughtered animal requires a certain amount of energy and therefore causes CO_2 emissions which are included in Footprint calculations. On the other hand not all parts of the slaughtered animal are used for human consumption (Woitowitz 2007). Thus the Ecological Footprint per unit of meat is increased at the retail level.

10. Discussion of the Results

In general the calculated Ecological Footprint values are of the same order of magnitude as values from literature.

When compared to the Ecological Footprint estimates for various food groups (table 10, page 55) from Chambers et al. (2007) it can be observed that the calculated ones are in each case slightly lower. For example fruits have an Ecological Footprint of 5 gm^2/kg to 6 gm^2/kg according to Chambers et al.; the value calculated in this piece of work lies at approx. 4 gm^2/kg. This difference is greater in the case of milk (11 gm^2/kg to 19 gm^2/kg compared to 4 gm^2/kg) or grains (17 gm^2/kg to 28 gm^2/kg compared to 8 gm^2/kg). In the case of meat the calculated values for poultry (approx. 34 gm^2/kg) and pork (approx. 50 gm^2/kg) are not included in the range given by Chambers et al. (69 gm^2/kg – 146 gm^2/kg). Different reasons can explain these differences. On the one hand Chambers et al. used a differing calculation methodology (a top-down approach and not a bottom-up approach). On the other hand Chambers et al. applied global yields and yield factors for their calculations, and not ones which are adapted to the German situation. Last but not least the underlying data Chambers et al. used for the calculations is already over ten years old – while the calculations carried out in this piece of work used the latest available data.

In general the calculated results are more similar to the ones calculated by Collins and Fairchild (2007; table 11, page 56). More or less the same values were obtained for eggs, poultry, beef and sugar. Only slight differences can be observed in the case of potatoes (3 gm^2/kg compared to 2 gm^2/kg), vegetables (4 gm^2/kg compared to 2 gm^2/kg), fruits (5 gm^2/kg compared to 4 gm^2/kg), bread (5 gm^2/kg compared to 7 gm^2/kg), flour (7 gm^2/kg compared to 8 gm^2/kg) and beer (5 gm^2/kg compared to 4 gm^2/kg). The reasons for the higher similarity with the results of Collins and Fairchild than with the ones from Chambers et al. are on the one hand the more exact methodology used by Collins and Fairchild – they calculated their Ecological Footprint values by combining the classical compound approach with environmental IOA – and on the other hand the more recent background data used by Collins and Fairchild. Additionally Collins and Fairchild used the yields and yield factors according to the Welsh situation – which is probably more similar to the German situation than the world's average. However, some Ecological Footprint values for food items greatly differ between Collins and Fairchild und the ones calculated in this piece of work, i.e. the ones for milk (14 gm^2/kg compared to 4 gm^2/kg), cheese (111 gm^2/kg compared to 36 gm^2/kg), pork (19 gm^2/kg compared to 50 gm^2/kg), margarine (66 gm^2/kg compared to 109 gm^2/kg) and vegetable oil (38 gm^2/kg compared to 24 gm^2/kg). Nevertheless, the order of magnitude is still the same and both results indicate the higher Ecological Footprints for animal-based food items or highly concentrated ones.

In the case of specific food product Footprints (table 12, page 57) which were calculated by means of a component-based approach similar to the methodology used in this piece of work, only the study of Burger et al. (2009a) regarding spinach can be used for a comparison. The reasons for this are on the one hand the differing food items analysed and on the other hand the fact that most studies did not transfer their data into the unit *global hectare*. Nevertheless, the result of Burger et al. for spinach (approx. 1 gm^2/kg) is very similar to the one obtained for vegetables in this piece of work (approx. 2 gm^2/kg). This indicates that the calculation methodology applied in this research really is a fast and relatively easy way in order to get relatively credible Ecological Footprint values for a variety of food items.

Similarities can also be observed when compared with sustainability indicators besides the Ecological Footprint. Basically all the sustainability indicators considered in this piece of work show high differences between plant-based and animal-based foods and between basic and highly concentrated foods respectively.

This is no surprise especially in the case of the indicators Carbon Footprint and specific land requirements for foods. These two indicators form more or less the basis for the Ecological Footprint calculation and therefore correlations between the results were expected. The same observation was also anticipated in the case of the indicator CED – due to the fact that the energy demand necessary to produce a certain food item is strongly associated with its CO_2 emissions. All these three indicators (Carbon Footprint, specific land requirement and CED) show pretty similar variations between the different considered food items. Exceptions are (in the case of the Carbon Footprint and CED) food items which are associated with a high amount of greenhouse gas emissions besides CO_2. Here the variations between plant- and animal-based food items are slightly different from the ones associated with the Ecological Footprint.

Although the Ecological Footprint does not cover the issue of water the results of the indicator Virtual Water and the Ecological Footprint both feature similar variations between different food items. For example, the Virtual Water content of 1 kg of beef is approx. 62 times higher than the one for 1 kg of potatoes – in the case of the Ecological Footprint this factor lies between 52 (Collins & Fairchild 2007) and 109 (data from this piece of work).

The indicator SPI (chapter 6.3.2.) shows that 1 kg of meat (the mean of chicken, pork and beef) has an approx. 81 times higher ecological impact than 1 kg of potatoes – a higher variation than the one associated with the Ecological Footprint (between 23 and 56, depending on the data). The reason for this difference lies probably in the fact, that the SPI covers more impact factors (Krotscheck & Narodoslawsky 1996; Chambers et al. 2007).

The Ecological Rucksack (chapter 6.2.2.) demonstrates that meat has an approx. 8 times higher impact than potatoes per unit of food. With the Ecological Footprint this factor is a lot higher. The reason for this difference is probably mainly the fact that land-use plays no role in the concept of the Ecological Rucksack but plays the major role in the Footprint calculation.

The reason for the higher values of the considered indicators for animal-based products and also highly concentrated products is the fact that a lot more resources of any kind (for example biotic and abiotic resources, water, energy or land) are required and a lot more waste is generated in order to produce the latter mentioned food items. In the case of animal-based food items this is caused by the low conversion rate between fodder and livestock. Only a small amount of the energy contained in the fodder is converted into meat or other animal-based food items, because the animals need a lot of the energy in order to maintain their metabolism (von Koerber et al. 2007). The different indicators measure different parts of the resource consumption and/or waste generation and therefore show the difference between the plant-based and animal-based food items. In the case of highly concentrated foods the explanation is similar: in order to produce one unit of a certain concentrated food item (e.g. sunflower oil) one needs a lot more units of the precursory food items (e.g. the actual sunflower seeds).

E) OVERALL DISCUSSION

The different assessment methods and indicators reviewed in this piece of work vary in their suitability for assessing the ecological sustainability of food items.

The question which assessment method is most appropriate for evaluating foods depends on the focus of the research. If the focus is on a specific food product LCA is probably the most appropriate method. By means of LCA all the environmental impacts of a given product throughout its entire life cycle can be captured (Jungbluth 2000), the methodology is more or less standardized (Roy et al. 2009) and a growing number of databases and LCA software applications are available to simplify the assessment (Jensen et al. 1997). LCAs give exact and very specific results, but are also very labour- and cost-intensive procedures. Therefore other assessment methods are more useful when the focus of analysis is on food groups or estimates concerning the environmental impacts of different foods. For example MFA can be applied to quantify the use of natural resources for product or material groups. However, the methodology is not yet standardized (Taylor 2000; Wiegmann et al. 2005). To date IOA, PCA and hybrid analysis are commonly used only for assessing specific environmental impacts (for example greenhouse gas emissions or embodied energy). The results are most precise in the case of hybrid analysis, while IOA, although it is fastest to conduct, delivers only rough estimates and PCA stands somewhere in between these two assessment methods (Jungbluth 2000). It seems likely that these assessment methods can be extended to cover more environmental impact categories and therefore become more appropriate for assessing the complete ecological sustainability of foods.

An indicator for the ecological sustainability of food items should primarily cover the most pressing environmental problems (Burger et al. 2009a). Indicators capturing only one impact category (like for example CED, the Carbon Footprint, Virtual Water content, food miles or direct land requirements) are therefore not appropriate, unless they are used in combination with other indicators (as described below). Currently used aggregated indicators for products, i.e. the Ecological Rucksack, the SPI and the Ecological Footprint each have the problem that due to the aggregation scientific soundness and methodological consistencies may be reduced (Giljum et al. 2006). This is particularly important in the case of the SPI, as this indicator requires many assumptions and simplification steps in order to cover all the assessed impact categories (Krotscheck & Narodoslawsky 1996). Of all the considered aggregated indicators the SPI captures most environmental impact categories. However, due to the complex aggregation scheme the communicability and the use as a consumer education tool are highly questionable. The Ecological Rucksack has the main disadvantage of not covering land usage – which in the case of food production is of particular importance. Furthermore it is debatable whether different environmental impacts can be associated to their weight – which is the basis of the Ecological Rucksack concept (Schmidt-Bleek 1998). The main strengths and weaknesses of the Ecological Footprint will be discussed in more detail in the following paragraphs. An examination as to whether this indicator meets the requirements for a suitable sustainability indicator which were described in chapter 5, page 13 and 14, forms the basis of this discussion.

Overall, the Ecological Footprint can be seen as a very appropriate indicator for the assessment of the ecological sustainability of foods.

First of all it is important to note that the Ecological Footprint concept covers some of the main environmental issues associated with food production (land-use and CO_2 emissions). However, there are still some important issues which cannot be addressed. For example the issues of biodiversity, water or waste products besides CO_2 emissions are not included in the current methodology. Non-renewable resources are also not directly incorporated in the Footprint concept, but only indirectly due to their direct land requirements and CO_2 emissions (World Wide Fund For Nature et al. 2008). Therefore results of Footprint analysis should always be taken as an underestimate. This weakness of the Ecological Footprint is also the main point Fiala (2008) criticises in his piece of work. One also has to bear in mind that non-environmental issues are not accounted for. In the case of food items important examples for the latter are issues of food quality, humane working conditions or animal welfare.

A major advantage of the Ecological Footprint concept is the fact that almost every food product and product category can be assessed – at least in theory. The availability of appropriate data, especially LCA data, is the most important constraint in this connection. Most of the currently available LCA data does not cover the whole life cycle of a certain product. However, as the concept and methodology of LCAs is already pretty well developed and standardized it seems very likely that new data will be generated in the future.

A further strength of the Ecological Footprint is the fact that its results can be compared to the earth's biocapacity. The unit *global hectare* can relate the environmental impact of a certain food to a land area with global average bioproductivity. This for example allows not only comparisons between various foods, but is also the basis for further analysis regarding issues such as how much global area would be necessary to feed different individuals or populations with varying diets. Additionally it is helpful for communicating results to the general public.

In general one can say that of all the reviewed indicators the Ecological Footprint is probably the one which is easiest to communicate. The unit of area and the image of an actual Footprint contribute to this outcome. Therefore the Ecological Footprint is an ideal tool for consumer education. Consumers can learn in a clear and illustrative manner how different foods or diets affect our planet. However, the high communicability is partly due to the fact that a lot of information is aggregated into one number. According to van den Bergh and Verbruggen (1999) this might have a negative impact on scientific soundness and methodological consistency – especially when more environmental impact groups will become incorporated into the Footprint concept.

Further strengths of the concept of the Ecological Footprint include the usage of transparent accounting schemes, system boundaries and data sources for the calculations. The NGO *Global Footprint Network* gives all the information which is necessary to fully understand the calculation methodology. This makes the results verifiable and increases objectivity and credibility. Footprint calculations are also feasible within an adequate effort in terms of time and costs – if the underlying background data is available. Further weaknesses of the Ecological Footprint are the methodology alterations which occur almost every year. This is of course necessary to improve the methodology, but it also leads to difficulties when comparing results from different studies and therefore it can be a hindrance when communicating the Footprint concept. Last but not least the practice of converting CO_2 emissions into forest land is until now not fully accepted in the scientific world (van den Bergh & Verbruggen 1999).

In the case of the Ecological Footprint calculation methodology developed in this piece of work further important issues arise.

First of all it should be noted that the developed methodology equals a component-based or bottom-up approach. The underlying data originates mainly from specific food item assessments, mainly LCAs and not solely (as in the case of compound-based approaches) from broad statistical databases like for example the FAOSTAT. This procedure has the advantage that more specific and exact results can be generated.

However, the usage of this kind of background data also raises some difficulties. On the one hand, LCA databases are often not free of charge (e.g. the database *ecoinvent V2.01*; ecoinvent Centre 2007). On the other hand these databases to date only offer a limited amount of data regarding food items and these data often only account for environmental impacts up to the farm level (e.g. the database *ecoinvent V2.01*; ecoinvent Centre 2007) or retail level (e.g. the databases *GEMIS*; Öko-Institut e.V. 2008 and *LCA Food;* Nielsen et al. 2003). Therefore the important stages of food consumption processes (for example cooling or cooking) and end-of-life recovery or disposal processes are not included. The generated results, especially the *Carbon Footprint Fraction*, should thus be seen as conservative estimates.

A further weakness in the developed Footprint methodology is the fact that the underlying data comes from a variety of sources. This was necessary because a single database or literature source did not offer the required information. Nevertheless this procedure decreases scientific soundness and methodological consistency.

One solution of overcoming the above mentioned constraints of the sole use of the indicator Ecological Footprint could be the combination with other sustainability indicators.

This has already been suggested for example by Burger et al. (2009a) or Giljum et al. (2009). In order to capture the main environmental impact categories Burger et al. suggests combining the Ecological Footprint with the Ecological Rucksack concept (figure 13). The environmental categories abiotic material input, biotic material input and water input are covered by the Ecological Rucksack (MIPS), land area and the output category CO_2 emissions is measured by the Ecological Footprint.

By this means all the major environmental problems except the generation of waste products besides CO_2 emissions and the impact on biodiversity are covered. However, this combination scheme also contains some weaknesses. First of all, greenhouse gases besides CO_2 are of great importance in the case of food production and therefore should not be neglected if possible. Secondly, there is a certain overlap between the two used indicators, as the Ecological Footprint covers the categories biotic materials and partly the abiotic materials as well. Therefore this combination scheme is debatable.

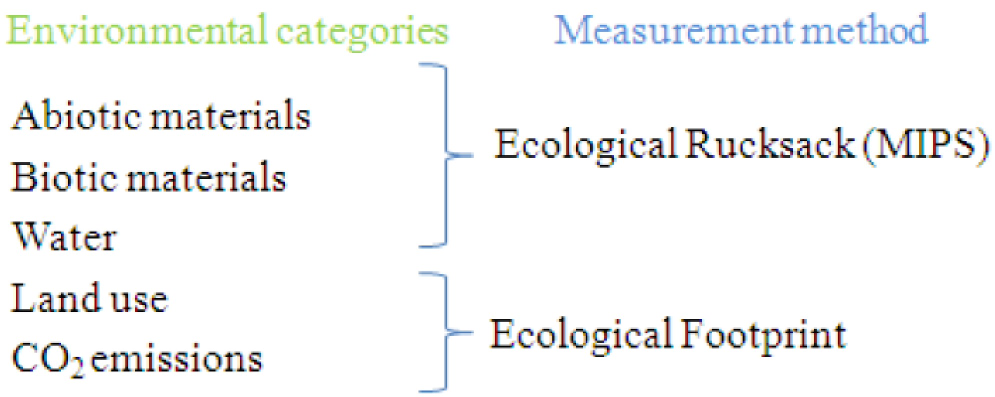

Figure 13: Combination of the Ecological Rucksack and the Ecological Footprint in order to capture the major environmental impact categories, according to (Burger et al. 2009a)

Giljum et al. (2009) developed a different combination of resource use indicators (figure 14). Four different indicators (i.e. Ecological Rucksack, Water Footprint, actual land use and the Carbon Footprint) are used to capture the environmental impact categories biotic and abiotic materials, water, land area and greenhouse gas emissions. This means that all the major environmental issues are covered. Only the issues of pollution (besides greenhouse gas emissions) and of biodiversity are neglected. However, none of the reviewed sustainability indicators covers the latter aspect. Burger et al. (2009a) does not even list it as one of the main input categories which should be covered by comprehensive indicators for products. The reasoning behind this is the fact that the other indicators, especially land-use, already indicate effects on biodiversity (e.g. due to habitat destruction; Giljum et al. 2009). Nevertheless, this practice might need to be reconsidered.

The main weakness of Giljum et al. `s combination scheme is probably the low communicability. The usage of four indicators is although scientifically sound and very comprehensive, perhaps not the most appropriate tool for consumer education purposes. In this case, the fewer indicators applied the better.

Resource use category		Product level	
Materials	biotic	Material Rucksack of products	biotic
	abiotic		abiotic
Water		Water Rucksack / Water Footprint of products	
Land area		Actual land use of products	
GHG emissions		Carbon Footprint of products	

Figure 14: Resource use indicators for products suggested by Giljum et al. (2009)

One suggestion to capture the major environmental impact categories and at the same time ensure high communicability might be the combination of the "Footprint family", i.e. the Water, Carbon and Ecological Footprint. By this means not only the major environmental issues are captured, but the different indicators share some common principles and are clear and illustrative as well. The only major problem in this combination scheme is the overlap between the Carbon Footprint and the Ecological Footprint – both cover the aspect of CO_2 emissions. However, this is for example also the case with the possible future tool for indicating the ecological sustainability of products REAP. REAP combines amount of greenhouse gas emissions and the Ecological Footprint for expressing the key environmental impacts (Barrett et al. 2004). Due to the fact that REAP leaves out the issue of water a combination of the "Footprint family" would be yet more comprehensive.

As the Ecological Footprint methodology is constantly being improved it also seems possible that someday greenhouse gas emissions besides CO_2 will become included. In that case a combination of the Ecological Footprint and the Water Footprint would be sufficient.

F) CONCLUSION AND OUTLOOK

It can be concluded that in general the Ecological Footprint concept qualifies for evaluating the ecological sustainability of food items.

The compound-based or top-down approach is more appropriate if the focus is solely on the impact of food groups. This type of analysis is sufficient to generate core messages (like the high impact of animal-based foods) and information which can be useful, for example, for broad consumer education efforts. The component-based or bottom-up approach, however, is more appropriate if the focus is on very specific food items. Food items of the same food group or even the same kind of food but from varying companies can be analysed and compared with each other (depending on the available data). This type of approach would also be the one to choose in the event of using the Ecological Footprint as the basis for a labelling system in order to indicate the ecological sustainability of different foods for consumers.

The component-based Ecological Footprint methodology developed and applied in this piece of work is especially useful for generating fast and relatively accurate Footprint results for a variety of foods, as collection of underlying data is not necessary. However, up until now appropriate data is only available for a limited number of food items. Therefore, if the focus of research is on a specific food item this approach is perhaps not possible. In that case the underlying data needs to be gathered first, for example by conducting an LCA for this food product.

Unfortunately, the Ecological Footprint concept is currently not free from constraints (as described in the previous chapter). In order to overcome these constraints various ideas for improvement have to be discussed and (in case of a beneficial outcome) implemented.

First of all the different Footprint methodologies need to become more harmonized and standardized. A first step towards this has recently been made – the *Global Footprint Network* has published Ecological Footprint standards in order to ensure that Footprint assessments are produced consistently and according to the current best practice. These standards cover all kinds of Footprint analysis, among them products, and will help to improve the comparability between different studies (Global Footprint Network 2009). Incidentally, the Footprint calculations carried out in this piece of work are in compliance with these newly published Footprint standards.

Generally speaking however, these standards are to date not very comprehensive and give space for improvement. Furthermore, the LCA methodology is not yet completely standardized either (Jungbluth 2000; Chambers et al. 2007). Therefore it can be strongly recommended to enforce the standardisation processes not only for the Ecological Footprint but also for LCA.

Secondly, the Footprint calculation methodologies need to be improved. Especially the issues of greenhouse gas emissions beside CO_2 need to be incorporated into the Ecological Footprint concept. In the field of food production the aspects of e.g. methane and laughing gas are of particular importance. The question how to incorporate these emissions is currently one of the research priority areas set by the NGO *Global Footprint Network* (Ewing et al. 2009). For the time being however, one could think about combining the indicator Ecological Footprint with other ones, as described at the end of the previous chapter.

Last but not least, in order to be able to conduct Ecological Footprint assessments which are feasible within an adequate effort in terms of time and costs the data availability needs to improve. This not only includes the generation of data, but also the free distribution of the existing and the newly collected data. It seems likely, however, that this is a future trend, as more and more projects with these goals are being set up (for example the project *Netzwerk Produktepass*). An increase in underlying data will accelerate the amount of possible Footprint calculations which means that there is a large potential for future research applications. For example the Ecological Footprint of certain diets of individuals or even populations could be assessed more accurately.

Finally, one can say that the Ecological Footprint has the potential to become an even more successful, communicative and renowned indicator of the ecological sustainability. However, the methodology still needs to be developed further and the high level of transparency has to be retained in order to maintain the currently prevailing objectivity and credibility.

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H) APPENDIX

Table 16: Associated CO_2 emissions of food items considered in the Footprint analysis, stated per kg of food, GEMIS data (Ökoinstitut e.V 2008)

Food		Associated CO_2 Emissions (GEMIS data) [kg/kg]
Fruits and Vegetables	Fruits, fresh	0.42
	Fruits, frozen	0.43
	Vegetables, fresh	0.12
	Vegetables, frozen	0.36
	Tomatoes, fresh	0.19
	Potatoes, fresh	0.14
Cereal products	Wheat flour	0.31
	White bread, rolls	0.46
	Brown bread	0.55
Other plant-based foods	Sugar	1.24
	Margarine	0.49
	Vegetable oil	0.57
	Beer	0.40
Meat and Meat products	Poultry	2.88
	Poultry, frozen	3.85
	Pork	1.91
	Pork, frozen	2.89
	Beef	3.48
	Beef, frozen	4.46
	Ham	2.98
	Sausages	2.60
Other animal-based products	Milk	0.28
	Cheese	2.07
	Eggs	0.94

Table 17: Direct land requirement of food items considered in Footprint analysis, stated per kg of food

Food		Direct Land Requirement [m²/kg/a]	Data source
Fruits and Vegetables	Fruits, fresh	0.5	Gerbens-Leenes et al. (2002)
	Fruits, frozen	0.5	Gerbens-Leenes et al. (2002)
	Vegetables, fresh	0.3	Gerbens-Leenes et al. (2002)
	Vegetables, frozen	0.3	Gerbens-Leenes et al. (2002)
	Tomatoes, fresh	0.05	FAOSTAT (2010)
	Potatoes, fresh	0.2 0.3	Gerbens-Leenes et al. (2002) Nielsen et al. (2003)
Cereal products	Wheat flour	1.4 1.6	Nielsen et al. (2003) Gerbens-Leenes et al. (2002)
	White bread, rolls	0.98	Nielsen et al. (2003)
	Brown bread	1.14	Nielsen et al. (2003)
Other plant-based foods	Sugar	0.45 1.2	Nielsen et al. (2003) Gerbens-Leenes et al. (2002)
	Margarine	21.5	Gerbens-Leenes et al. (2002)
	Vegetable oil	4.5	Nielsen et al. (2003)
	Beer	0.5	Gerbens-Leenes et al. (2002)
Meat and Meat products	Poultry	5.0	Nielsen et al. (2003)
	Poultry, frozen	5.0	Nielsen et al. (2003)
	Pork	8.7 8.9	Nielsen et al. (2003) Gerbens-Leenes et al. (2002)
	Pork, frozen	8.7 8.9	Nielsen et al. (2003) Gerbens-Leenes et al. (2002)
	Beef	20.9 40.4	Gerbens-Leenes et al. (2002) Nielsen et al. (2003)
	Beef, frozen	20.9 40.4	Gerbens-Leenes et al. (2002) Nielsen et al. (2003)
	Ham	8.0	Nielsen et al. (2003)
	Sausages	12.1	Gerbens-Leenes et al. (2002)
Other animal-based products	Milk	1.2	Gerbens-Leenes et al. (2002)
	Cheese	10.2	Gerbens-Leenes et al. (2002)
	Eggs	3.5	Gerbens-Leenes et al. (2002)

Table 18: Associated CO_2 emissions (GEMIS data; Ökoinstitut e.V. 2008) and direct land requirements for organic and conventional chicken, pork and beef respectively, data stated per kg of food

Food		Associated CO_2 Emissions (GEMIS data) [kg/kg]	Direct Land Requirement [m^2/kg/a]	Data source (direct land requirement)
Chicken	Conventional	2.87	4.5 7.0	Woitowitz (2007) Seemüller (2000)
	Organic	2.52	8.1 10.2	Woitowitz (2007) Seemüller (2000)
Pork	Conventional	1.91	7.1 10.4	Woitowitz (2007) Seemüller (2000)
	Organic	1.51	10.1 13.5	Woitowitz (2007) Seemüller (2000)
Beef	Conventional	3.48	11.4 13.6	Seemüller (2000) Woitowitz (2007)
	Organic	1.56	15.3 20.7	Seemüller (2000) Woitowitz (2007)

Table 19: Calculated Ecological Footprints (total, carbon fraction and land-use fraction) of organic and conventional chicken, pork and beef respectively, data stated per kg of food

Food		Carbon Footprint Fraction [gm^2/kg]	Land-use Footprint Fraction [gm^2/kg]	Total Ecological Footprint [gm^2/kg]
Chicken	Conventional	8.05	28.86	36.91
	Organic	7.06	45.92	52.98
Pork	Conventional	5.35	43.92	49.26
	Organic	4.22	59.22	63.45
Beef	Conventional	9.75	58.03	67.77
	Organic	4.38	47.04	51.42

Table 20: Associated CO_2 emissions (GEMIS data; Ökoinstitut e.V. 2008) and direct land requirements for chicken and pork at the slaughtering and retail level respectively, data stated per kg of food

Food		Associated CO_2 Emissions (GEMIS data) [kg/kg]	Direct Land Requirement [m^2/kg/a]	Data source (direct land requirement)
Chicken	Slaughtering level	2.87	3.6	Nielsen et al. (2003)
	Retail level	3.36	5.0	Nielsen et al. (2003)
Pork	Slaughtering level	1.91	6.8	Nielsen et al. (2003)
	Retail level	2.26	8.7	Nielsen et al. (2003)

Table 21: Calculated Ecological Footprints (total, carbon fraction and land-use fraction) for chicken and pork at the slaughtering and retail level respectively, data stated per kg of food

Food		Carbon Footprint Fraction [gm^2/kg]	Land-use Footprint Fraction [gm^2/kg]	Total Ecological Footprint [gm^2/kg]
Chicken	Slaughtering level	8.05	18.07	26.12
	Retail level	9.42	25.10	34.52
Pork	Slaughtering level	5.35	34.13	39.48
	Retail level	6.34	43.50	49.84