Circularity in agricultural production

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Background

"No one who had seen widespread hunger during the Second World War could take the risk of allowing food shortages to appear again," stated EU agriculture commissioner Mariann Fischer Boel during a speech on the Common Agricultural Policy in 2008 (Boel, 2008). She was referring to the historical context in which Sicco Leendert Mansholt and his colleagues created a post-war plan to modernise agriculture in Europe, with an emphasis on increasing productivity, farmers' incomes and food supply, and ensuring stable and affordable prices for producers and consumers. The Mansholt Plan to produce "enough food for all" stimulated EU farmers to increase their production efficiency, that is, to produce more food with less labour, land and capital.

We now know that the agricultural policy initiated by Mansholt and his colleagues has been very successful in meeting its initial objective of making Europe more self-sufficient in terms of food products. At the same time, however, it also fundamentally altered the agricultural landscape. Farmers became production-oriented and were encouraged to maximise productivity through increased use of farm inputs such as fossil fuels, pesticides, mineral fertilisers, imported feed, improved plant and animal genetics, advanced machinery and new technology. Over time, the unintended harmful side-effects on the landscape and the environment gradually became unacceptable to European populations and societies.

The current food system has an enormous environmental impact. It is responsible for about a quarter of all greenhouse gases released by human activity, drives deforestation and loss of biodiversity, pollutes fresh and marine waters, and takes up 40% of the world's ice and desert-free land (Poore and Nemecek, 2018). As a result the way we produce food has become a point of contention in high-income countries, and increasingly across the world. There are mounting concerns about a range of issues such as farm size, farm profitability, animal welfare and the risk to human health of zoonotic diseases and processed foods.

It is widely affirmed that the physical limits of the Earth set the ultimate boundaries for all human economic activity (Fischer et al., 2007; Steffen et al., 2015). We all know and agree that the key challenge in the coming decades will be to produce enough safe and nutritious food for future populations without running out of resources or destroying Earth's ecosystems – in other words, without exhausting the biological and physical resources of the planet. This key challenge is therefore the starting point for our argument.

While most scientific studies that explore this challenge search for solutions that would allow more food to be produced with less impact on the environment, very few address the potential of moderating population growth. The majority of the 'more food with less impact' studies are based on so-called product footprints. A product footprint quantifies the resource use or emissions along the entire life cycle of a food product; examples include the water or carbon footprint of a food product (Guinee et al. 2002).

The footprint concept is used in two ways. Production studies explore ways to produce a given food product with less impact on the environment, and promote solutions to improve the technical and environmental efficiency along the food chain, such as increasing crop yields per unit of land or water, increasing feed efficiency or lifetime productivity of animals, and reducing losses along the production chain. Consumption studies, on the other hand, focus on altering human consumption patterns to eating less and healthier foods, wasting less food or substituting high-impact foods with low-impact ones. These studies address the importance of avoiding food waste and overconsumption, and promote either veganism or, for those who require food from animal sources, eating of chicken or fish instead of pork and meat from ruminants.

The footprints of individual food products, however, fall short in addressing the complexity and circularity of food systems. For example, they do not acknowledge interlinkages in the food system. Producing wheat flour for bread or rapeseed oil for cooking also yields straw and rapeseed meal, which can be fed to animals. Moreover, footprints of foods from animal sources do not address feed-food competition (i.e. competition for biomass or natural resources between production of feed for livestock and food for humans) – hence the advice of footprint studies to eat meat or eggs from poultry fed with grain rather than milk and meat from ruminants grazing on marginal lands or fed with straw (Tilman and Clark, 2014; Hallström et al., 2015).

To move towards a sustainable food future which makes optimal use of the earth's natural resources, therefore, we need to move away from the current product footprint approach and start using a food-systems lens. Food systems analysis clearly shows that natural resource use and emissions associated with modern food systems can be substantially reduced by shifting towards a circular food system (Van Zanten et al., 2018a). We – farmers, citizens, policy makers, industry – may once again be on the eve of a radical shift in our European food system, in this case towards a modern circular food system, as already proposed by Mansholt in his famous letter of 1972 (Mansholt, 1972).

The concept of a circular food system

The concept of circularity originates from industrial ecology (Jurgilevich et al., 2016), which aims to reduce resource consumption and emissions to the environment by closing the loop of materials and substances. Under this paradigm, losses of materials and substances should be prevented, and otherwise be recovered for reuse, remanufacturing and recycling. In line with these principles, moving towards a circular food system implies searching for practices and technology that minimise the input of finite resources, encourage the use of regenerative ones, prevent the leakage of natural resources (e.g. carbon (C), nitrogen (N), phosphorus (P), water) from the food system, and stimulate the reuse and recycling of inevitable resource losses in a way that adds the highest possible value to the food system (Jurgilevich et al., 2016).

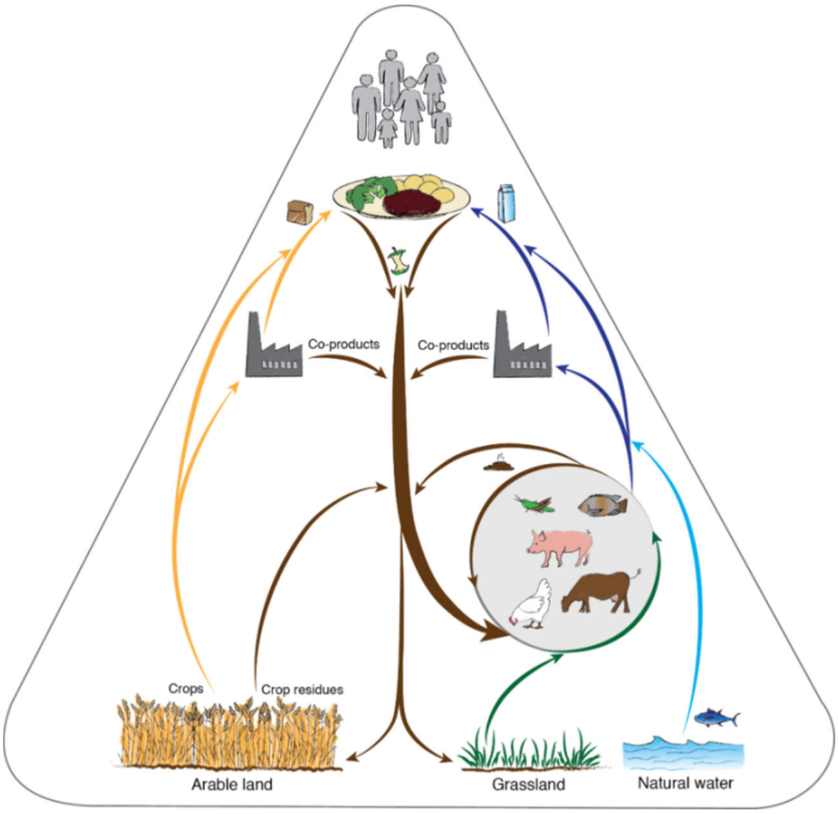

Figure 1. Visualisation of a circular food system (from: Van Zanten et al., 2018b).

Aiming for circularity, therefore, implies that arable land should be used primarily to produce plant biomass for human consumption (Figure 1). The production and consumption of foods from plant sources, however, result in a number of what we will label in this publication by-products, such as crop residues, co-products from industrial food processing, food losses and waste and human excreta. If we consume bread, for example, we also produce straw and husk (i.e. crop residues from cereal production), wheat middlings (a co-product of flour production), food waste and human excreta.

As our first priority, we should prevent human edible by-products, i.e. food losses (e.g. bakery rest streams) and food waste. Unavoidable human edible by-products should be reused as human food wherever possible. Only once such options have been exhausted should they be recycled into the food system - together with by-products inedible for humans - in order to enrich the soil and fertilise crops, or to feed animals.

Our main aim in recycling by-products should be to ensure the quality of our soils, as they are the basis of agriculture. Subsequently, pigs, poultry, farmed fish or insects can utilise by-products and convert them into valuable food and manure. Ruminants, furthermore, can create nutritional value from grasslands by converting grass products into milk, meat and manure. Hence, the role of farm animals in the food system should be centred on converting by-products that humans cannot or do not want to eat into valuable products, such as nutrient-dense food (meat, milk, and eggs), manure and various ecosystem services. By converting these biomass streams, farm animals recycle nutrients within the food system that otherwise would have been lost in the process of food production (Garnett et al., 2015). Furthermore, to enhance soil fertility we should not have recourse only to animal manure, but also reuse nutrients such as phosphorus in, for example, human excreta.

In addition to land, humans can also get food from fresh and saltwater bodies. Like on land, humans could move to harvesting resources from water at a lower trophic level. We could shift our focus from consuming fish species such as salmon and cod to seaweeds, mussels and clams. Similarly, we should no longer feed farmed animals with fish and fish meal harvested from the sea, but with waste-fed insects or plants that are inedible for humans.

We acknowledge that biomass harvested from land or natural bodies of water can be used for many functions other than the growing of human food, such as the production of pharmaceuticals, functional biochemicals, fibre or bioenergy. In this publication, however, we adopt the premise that food production will, in the short and medium term, have priority over other uses of biomass, such as the production of biochemicals or bioenergy. In contrast to food, energy can be produced directly from the sun, wind or running water, for example, whereas biomass is required for humans to fulfil their nutritional requirements. We acknowledge that a circular economy, rather than circular food systems, offers an even broader perspective and may open new opportunities for efficiency gains or regenerative capacity, but consider this beyond the scope of this publication.

Our aim

The aim of this vision paper is to discuss the main principles of a circular food system, with a special emphasis on plant and animal production. Circularity in plant and animal production assumes that plant biomass is the basis of our food system, and should be used primarily to produce human food; that by-products from food production, processing and consumption are reused or recycled into the food system; and that we make the most efficient use of animals by using them to unlock biomass inedible for humans into valuable food, manure and ecosystem services. We start with a description of three main principles relevant for plant and animal production, and subsequently discuss the scale at which circular systems can be developed. Finally, we address the most important barriers to the transition to a circular food system, identify incentives which can stimulate this transition, and formulate relevant research questions.

Principle 1: Plant biomass is the basic building block of food and should be used by humans first

Photosynthesis by plants, and thereby production of plant biomass, is the basis of our food system and the engine of the carbon cycle. For many years, production-ecological principles have been employed to find ways to increase crop production. Factors which define, limit and reduce growth determine the production of crops, and can be influenced by management interventions by farmers. Yield-defining factors include the climate (radiation, carbon dioxide levels, temperature) and crop genetics; yield-limiting factors include water and nutrient availability, while yield-reducing factors include the presence of weeds, pests and diseases (Van Ittersum and Rabbinge, 1997). The term 'potential yield' refers to how much a well-adapted cultivar can produce when grown without limitations in water or nutrients, and without any incidence of yield-reducing factors. For rain-fed conditions, we use water-limited potential yield – defined by the availability of water in the soil and through precipitation – as a benchmark. The difference for a given location between potential yield (under either irrigated or rain-fed conditions) and actual farmers' yield is called the yield gap. The production-ecological principles make it easy to understand that there are basically two ways to increase crop yields in a given area: by raising potential yield through improved genetics or by closing the yield gap through improved crop management. Production-ecological concepts equally apply to grassland and grass production, and to the production of biomass on or in water.

While these concepts have been well developed for yields of single crops (see, for example, Van Ittersum et al., 2013 and Van Ittersum and Rabbinge, 1997), their use in circular plant production requires a broader lens, including several additional perspectives. First, we need to move away from a focus on the highest yields of kernels or tubers of single crops and towards the highest total quantity and quality of whole crops (and other vegetation). This means having an equal focus on the quantity and quality of kernels (or tubers) as on the quantity and quality of straw, leaves or stalks. It requires measuring crop production in more than just kilograms and calories, thinking of them instead as sources of nutrition and functional qualities – this includes considering concentrations of dry matter, amino acids, carbohydrates, fatty acids, minerals and vitamins, as well as qualities like digestibility. Producing better-quality crops means, by definition, generating less by-products that will not be directly used as human food and a greater emphasis on the functionality of non-food by-products. Second, circularity implies that we must move away from a focus on homogenous, single crops to entire cropping systems and crop rotations, which may include mixtures of crops within one field.

Here, we plead for a broader implementation of the production-ecological concepts and for developing them from a circular food system perspective. This implies the production of sufficient quantities and qualities of crop and plant biomass (including from grassland and water), primarily for food, and of by-products and grass that serve the requirements of soils, animals and the bioeconomy. Below, we discuss the possibilities and implications of circularity in relation to managing each of the three groups of growth factors – defining, limiting and reducing factors – in order to increase the quantity and quality of whole crops and cropping systems from a circular perspective by increasing potential yield and reducing yield gaps.

How can potential yields and the functional quality of crops be increased?

Potential yield can be understood as a function of three components: radiation capture by green leaves, conversion of radiation into biomass (radiation use efficiency or RUE) and the share of above-ground biomass harvested for human consumption (harvest index or HI) (Fischer et al., 2014; Monteith, 1977). Most of the historical progress in the breeding of our main cereals – wheat, rice and maize – can be attributed to a substantial increase in HI. But, as crops that bear above-ground grain depend on a stable stem, there appears to be little scope for further increase in HI (Berry et al., 2007).

Generally speaking, past breeding efforts have achieved relatively little in terms of increasing the production of dry matter at maturity through increased capture of radiation and RUE. The HI is approaching its theoretical limits, however, so any future increases in potential yield must come from increased radiation capture, and in particular higher RUE, and thus photosynthesis. Increased radiation capture can come from rapid early crop establishment and ground cover with green leaves, long crop growth duration from emergence to maturity and extended staygreen during grain-filling. Cold or heat tolerance plays a role here, as is evidenced by the improved cold tolerance of silage maize in north-western Europe, for instance. Only if the crops are more tolerant to cold or heat will the extended growing period actually allow radiation capture by green leaves and conversion into biomass.

Long crop growth duration results in more biomass, but not necessarily in higher yields. For the latter, it is particularly important to have high radiation capture during the grain filling, or the longer growth duration may simply lead to a lower HI. In addition, crop growth duration is obviously limited by the length of the growing season and by the cropping system (in the case of growing two or three crops a year, for example). Hence, there is some consensus that RUE/ photosynthesis will be the most promising route to increasing future yield potential in crops that have already received ample investment in breeding. That is precisely the reason why so much effort is being put into the Photosynthesis 2.0 project, a European initiative to amplify photosynthesis (Box 1.1).

Until today, plant breeding has been focused mainly on improving the yield and quality of the main product; little has been invested in the quality of the by-products or of the entire crop, based on a circularity perspective. The currently available crops are not necessarily optimal for circular use, and circularity demands feedstock (for food and non-food purposes) with novel properties. Indeed, it requires a systemic rethink of breeding for yield and quality of the main and by-products. This is similar to what is argued for breeding for ecologically and societally resilient agricultural systems (Lammerts van Bueren et al., 2018), but it goes beyond agriculture, as processing and the food system require the right design of crops and plant biomass. Important targets for plant breeding for the purpose of achieving circular food systems are improvement in the yield and quality of different plant components, suitability for downstream processing and functional use, and better resource-use efficiency in crops (low input and high output) (Trindade et al., 2010). For example, tomato leaves and stalks are currently treated largely as waste, ignoring the fact that they contain useful proteins, fibres and other components that can be extracted and used for valuable nutritional, pharmaceutical or industrial applications. Similarly, sugar beet leaves can be an important source of protein, and more – the functional and structural characteristics of the entire leaf can be exploited (Tamayo Tenorio et al., 2018).

Raising potential yield and functionality with diverse cropping systems
When increasing potential yields and quality, the focus is normally on individual and homogenous crops. However, the circularity of food systems requires rethinking which quantities and qualities of different crops are optimal in terms of consumption, production and recycling. It is then crucial to consider which crops to grow in order to deliver the right quantity, quality and functionality of biomass and yields for the entire system. This may well have implications for the mix of starch, protein and oil crops for instance. Growing crops in the right sequence and at the right frequency is also vital for resilient crop rotation and managing yield reductions.

Potential yields per unit area may also be increased through the simultaneous cultivation of multiple crops on a field – intercropping. This has already been practiced in many parts of the world for a long time in order to harvest more per hectare per year. A meta-analysis of intercropping studies showed that such systems have 22% higher yields on average than sole crops (Yu et al., 2015). Many intercropping systems combine a legume and a cereal crop, benefitting from the biological nitrogen fixation of the legume. Another beneficial configuration was found to be a combination of C3 and C4 cereals (crops differing in photosynthesis mechanisms). Intercropping systems used to be popular in regions of the world where there is still little mechanisation of agriculture and manual labour is the rule. However, the promises of increased mechanisation ('robotology') mean that new prospects are emerging for intercropping in modern agriculture. This has triggered research into other intercropping designs, including that of strip or fully mixed intercropping.

Narrowing yield gaps

Farmers' yields are nearly always well below potential (water-limited) yields, be it under irrigated or rainfed conditions. In the most productive agricultural systems on earth, farmers produce around 80-85% of the theoretical maximum. This 80-85% is close to the maximum that is feasible in economic and environmental terms, given diminishing returns to more inputs at such small yield gaps (Cassman et al., 2003; van Ittersum et al., 2013). In many places on Earth, yields are as low as 50% or even 20% of their potential (www.yieldgap.org). These persistent yield gaps are due to a combination of yield-defining (varieties, seed quality and growing season), limiting and reducing factors. They reflect very low productivity and may thus be perceived as negative or alarming – but they also hold promise: they mean that production can be significantly increased on existing agricultural areas, in many cases without irrigation. Over the past decades, this increase has largely been achieved with linear food systems focused on production per hectare and per unit of resource, through the use of modern crop varieties, fertilisers and chemical measures to control weeds, pests and diseases. The question is whether small yield gaps can also be achieved with much more circular systems, that is, production with minimum external resource use and reuse of all biomass. We will first deal with nutrients, as a main limiting factor in plant production that also affects water quality, and then look at reducing factors.

What does circularity mean for yield gaps and food production?

Nutrients - In his book *Farming in Peel and Kempen around 1800*, Aarts (2016) quantifies the flows of nutrients and energy on farms in the southern part of the Netherlands around 1800. He clearly shows that crop production at the time depended on nutrient inputs from manure collected from animals that stayed indoors at night and grazed natural vegetation on wildlands during the day. A continuous removal of nutrients from natural vegetation, however, eventually depleted those soils. Soil mining still occurs today in low-input agriculture in many parts of the world, in particular in sub-Saharan Africa: fields close to the homestead are often enriched in nutrients at the expense of outfields through concentration of crop residues or manure (Giller et al., 2006). The question therefore arises as to whether circular systems can be made productive with no or little dependence on external inputs and without mining other fields. Such systems rely on nutrient inputs through the recycling of manure, crop residues and waste streams (organic household waste) or legume species that fix atmospheric nitrogen through symbiosis with rhizobia bacteria in root nodules (Box 1.2). Here we can learn from organic systems that do rely solely on these sources of nutrients, and nitrogen in particular.

It is tempting to compare crop yields of mainstream agriculture with those of organic agriculture and use them as an indication of how productive circular systems can be. Recent meta-analyses showed average yield differences between organic and mainstream agriculture of 20-25% at the crop level (De Ponti et al., 2012; Ponisio et al., 2014; Seufert et al., 2012). But is it fair to refer to this as an indicator of difference in productivity? Is it too optimistic or can we do better? One may argue the latter, as relatively little research has been carried out into organic agriculture (Tittonell, 2013). This may seem overly optimistic because crop yields in organic systems depend partly on nutrient inputs that have been generated or accumulated from other crops or grassland (De Ponti et al., 2012). This includes, for instance, preceding green manure crops or leys that occupy land but do not directly produce human nutrition, or manure that has been produced with grass, crops or crop residues grown elsewhere. If we account for the area needed to produce these nutrient inputs for crops (especially nitrogen), the difference in crop yield per hectare between organic and mainstream systems is substantially higher than 20-25%. Experimental evidence (Box 1.3) and model-based calculations (Schröder and Sorensen, 2011) suggest yield differences between mainstream and organic systems of ca. 40-50%. Nonetheless, mainstream systems can learn and adopt principles from such circular systems, resulting in much lower emissions per unit area.

The focus on nitrogen as a limiting factor in circular systems can be justified, even though other nutrients (such as phosphorus, potassium or micronutrients) may also be regulating production. This is because nitrogen is mobile and reactive, whereas phosphorus, a second main nutrient for plants, is much less mobile. While this mobility of nitrogen is desirable on the one hand because it allows plants to take it up with water, the downside is that nitrogen can be easily lost to the wider environment in the form of ammonia, nitrous oxide, nitrate or elementary nitrogen gas. The use of cover and green manure crops in-between main crops is essential to keep nitrogen (and other nutrients) circulating within the system and, therefore, avoid losses. Yet, the unavoidable tendency of food systems to lose nitrogen implies that farms trying to fully cover their nitrogen requirements by simply recycling by-products are bound to accumulate phosphorus in their soils as they are applying more phosphorus than can be taken up by their crops (Schröder, 2014). Conversely, farms intending to avoid phosphorus accumulation tend to fall short of their intended nitrogen supply. Adding biologically or chemically fixed atmospheric nitrogen (as is done in mineral fertilisers) then becomes necessary to avoid nitrogen limitation. The level of total nitrogen fertilisation should be at rates matching the crops' needs (often the basis of environmental thresholds), which are highly location-specific. It is worth noting that if mineral nitrogen fertiliser is produced with renewable energy, there seems to be no a priori reason to consider mineral nitrogen inferior to organic or biological sources, as long as environmental thresholds of nitrogen emissions are respected. In contrast to nitrogen, which is abundant in the atmosphere, phosphorus is only available in limited amounts in a few mines in the world, making its recycling in by-products, such as animal and human excreta, essential (see Box 1.4).

Organic fertilisers – The use of unprocessed or processed by-products (manure, crop residues, organic waste – Principle 2) as fertiliser is affected by a number of relevant factors. On the positive side, and importantly, organic fertilisers contain organic matter and micronutrients that contribute to the preservation of soil quality. Also, nutrients in organic fertilisers are at least partly organically bound, while plants take up nitrogen and phosphorus predominantly in mineral form (nitrogen as nitrate or ammonium; phosphorus as phosphate). This implies that organically bound nitrogen and phosphorus can only be taken up by roots after the organic material has mineralised, and are therefore more gradually released, potentially reducing nutrient losses. But there are also a number of challenges which require critical attention to facilitate circularity. First, inasmuch as mineralisation is needed to make nutrients available, their release may be poorly synchronised with crop demand, increasing the risk of losses. Second, the inherent composition of organic nitrogen fertilisers can also stimulate other loss processes such as denitrification and the volatilisation of ammonia (Bos et al., 2017). As a result of these two aspects, nitrogen in organic fertilisers is not perfectly equivalent to nitrogen in mineral fertilisers by mass; in fact, the former is worth only about 70-90% of the latter (Schröder et al., 2007; Verloop, 2013). Third, the composition of organic fertilisers, certainly unprocessed ones, is highly variable across farm, seasons, etc., and as such does not always match the requirements of the plants, which also results in risks for losses. Finally, nutrients are highly diluted in organic fertilisers and are available in fixed ratios which may not necessarily match crop requirements. We already noted that organic fertilisers are relatively rich in phosphorus because of nitrogen losses, which makes it very challenging to provide enough nitrogen without exceeding phosphorus requirements using solely organic inputs (Schröder, 2014). The dilution has implications for storage and transport costs, while the mix of nutrients can be more easily tailored to the needs of the crops with mineral fertilisers. These four factors define the challenges that must be overcome in developing precision fertilisation in circular systems. The good news is that there are possibilities to influence the quality and composition of organic fertilisers, either through crop and livestock management or through processing (see also Principle 2).

So, are circularity in nutrient use and small yield gaps compatible? – In view of the finiteness of resources and the need to reduce harmful emissions to the environment, circularity in nutrient use is a condition and not an option for the food system level. As explained, circular systems can be more demanding for crop production, and may also be affected by more yield limitation than linear systems based on conventional mineral fertilisers. But making use of leguminous species and mycorrhizas (Box 1.4) makes perfect sense in terms of nitrogen and phosphorus fertilisation as well as where nutrition (grain legumes!) is concerned. And by-products, including crop residues and human and animal excreta, must be used first, as these products contain finite resources such as phosphorus and various micronutrients (Withers et al., 2015). Not recycling these because higher efficiencies may be achieved at the crop level with mineral fertilisers is myopic and implies passing environmental consequences on to other sectors or regions (Schröder et al., 2003). It is not the efficiency of subsystems (e.g. crops or livestock production) but the efficiency of the entire food system that matters. Also, there are still plenty of opportunities to process by-products and to improve their value as fertiliser and source of organic matter (Principle 2). At the same time, we know that by-products do not bring in new nitrogen (or phosphorus) into the food system, and that zero-emission agriculture is not realistic, implying that new nitrogen inputs from biological and industrial fixation of atmospheric nitrogen gas are needed to sustain the food system. This is precisely the reason why agricultural systems differ from natural ecosystems. Bringing the generally low nutrient status of natural ecosystems to agriculture would jeopardise food production (Denison and McGuire, 2015). The application of nitrogen in agricultural systems should take place at rates matching the needs of the crops – at the right moment, in the right place and in the right form – while not exceeding environmentally sustainable thresholds. If we want to avoid an expansion of our agricultural area, we must continue to use mineral nitrogen fertiliser. This fertiliser must, however, be produced with minimum emissions or, even better, through renewable energy sources.

Circularity and yield-reducing factors – A key principle in managing pests, weeds and diseases in crop production with low levels of pesticide is advancing diversity in crop and variety mixes at different scales. The diversity principle is based on the fact that plants are usually hosts to selected pests and diseases, and alternating crops in time and/or space helps manage the spread or build-up of pests and diseases. This is generally most effective for soil-bound pests and diseases (such as nematodes): airborne pests and diseases (such as *Phytophthora infestans*) are too mobile for spatial or temporal differentiation to have as much effect. Even so, spatial differentiation can also make a significant contribution to controlling or delaying epidemics of airborne pests and diseases, although the reverse may be true for vector-borne diseases such as viruses.

The principle of diversity can be used in the design of intercropping systems with different plant species in one field, but also in mixing different cultivars of the same species in the same field. Crop rotation can also disrupt temporal or spatial cycles of pests or diseases, except for those with a broad host range or the ability to widely disperse or live in the soil for long periods (Ratnadass et al., 2012). Circularity can stimulate a wider application of crop rotation, for instance through a closer interaction of crop and livestock production and inclusion of grass in crop rotation. And, finally, different crops, field margins and natural vegetation can create diversity at the landscape level. So-called complex landscapes with patches of non-crop habitats (as compared to simple large-scale agricultural landscapes) tend to result in higher natural enemy populations and lower pest pressure (Bianchi et al., 2006), although the latter is not always evident (Karp et al., 2018). In general, managing pests, weeds and diseases in open systems through natural principles still requires our understanding and empirical applications to be enhanced through research. In this sense, horticultural plant production in greenhouses and vertical farms with fully controlled environments (Box 1.5) can, despite their essential difference, inspire the development of less pesticide-dependent and more circular production systems. Interactions between soil management, organic matter in the soil and pest & disease control are also increasingly being investigated – so far with ambiguous findings (Box 2.1).

Can aquatic biomass contribute to circularity?
Freshwater aquatic plants and seaweeds have been used by people for centuries as both food and feed. When properly managed, freshwater plants such as Lemna and Azolla species show productivities which are competitive with biomass production on land. Furthermore, species of *Lemna* and *Azolla* may contain protein concentrations of up to 35%, with an amino acid composition that fulfils the requirements of both humans and animals (Brouwer et al., 2018, and reference therein). Besides their use as food, seaweeds might also have specific benefits as animal feed. For instance, when commercial feed for cows was mixed with small amounts of seaweed (up to 5%), methane emissions were reduced substantially without any effect on in vitro digestibility (Kinley et al., 2016). Furthermore, literature shows that seaweeds and their extracts have antibacterial effects in animal farming, reducing the need for antibiotics.

Aquatic plants are well known for their high rates of nutrient uptake and, in combination with their high productivity, may therefore also function as polishers of eutrophic and/or polluted surface waters (Meerburg et al., 2010). In this way, unavoidable nutrient losses from agriculture may be recycled again, while the aquatic plants deliver biomass, primarily for food and otherwise for feed or biobased products. Of course, if aquatic plants must be fertilised, the risks of emissions must be very carefully managed, in particular in open waters.

Even though aquatic farming is still largely in its infancy, the abovementioned examples clearly show potential as essential components of circular food systems that can produce substantial amounts of biomass with specific qualities while contributing to the recycling of nutrients.

Principle 2: By-products from food production, processing and consumption should be recycled back into the food system

As illustrated in Figure 1, our food system leads to various by-products such as crop residues, co-products from food processing, food waste, and animal and human excreta. As our first priority, we should prevent human edible by-products, i.e. food losses (e.g. bakery rest streams) and food waste. The nature of food losses and waste, however, is diverse and complex, and solutions require a mix of behavioural, regulatory and socio-economic measures which go beyond the scope of this report.

By-products which are not of immediate use for human consumption, such as crop residues, co-products from food processing that are not edible for humans (e.g. beet pulp), slaughterhouse waste, animal and human excreta, or unavoidable food waste, should be recycled back into the food system. All these products contain carbon and nutrients (such as nitrogen and phosphorus), albeit in very different ratios. This makes them valuable as a source of energy and protein, micronutrients or structural material. In principle, by-products can be used for different purposes. We propose the following order of priority to enhance circular food production:

1. Application in the field for the improvement or preservation of soil quality, ranging from soil fertility to soil cover and the avoidance of erosion;
2. Feeding to livestock or insects to produce food from animal sources;
3. Production of bioenergy, nutrient fertilisers or renewable biomaterials to mitigate greenhouse gas emissions;
4. Incorporation in the soil to sequester carbon and mitigate greenhouse gases.

When using by-products, it is again crucial to adopt a food-systems perspective, consider the multiple roles that by-products can fill and optimise the functionality and use of by-products in the local context.

Soil quality

Soil is the basis of productive agriculture. To secure its preservation and future productivity, the first priority for the use of by-products should be to maintain (or improve) soil quality. It is often assumed that soils need a certain minimum of soil organic matter (SOM – Box 2.1), below which there is a loss of desirable soil characteristics (e.g. good texture for seedbed preparation, water infiltration, soil biodiversity and erosion control) and productive capacity (Hijbeek et al., 2017; Sparling et al., 2003). Achieving and maintaining this SOM level requires more effort on sandy soils than on clay soils, and more work on steeper slopes than on flat fields. Threshold values and relationships between SOM and crop productivity are, however, hard to determine with precision. While a lack of SOM is likely to play an important role in the non-responsiveness of certain soils in Africa (Vanlauwe et al., 2015), it must also be noted that SOM concentrations have been decreasing for many croplands in the world while production has been increasing, albeit with improved cultivars, cropping practices, irrigation, and fertiliser and pesticide input (Aref et al., 1997). Benefits of the use of organic inputs, when corrected for nutrient supply, are hard to prove for grain crops, in contrast to root crops (Hijbeek et al., 2016).

Different authors have proposed threshold values of SOM for mineral soils, roughly varying between 1.5 and 3.5%; until this value there are beneficial effects of SOM on soil quality. Above these SOM levels it is often difficult to prove benefits to production, certainly if nutrients are provided by other means (Hijbeek et al., 2017; Schjønning et al., 2018). Hence, it is good agronomic practice to build up soil organic matter to at least location-specific threshold levels and to maintain those levels. In the Netherlands, for instance, it seems that preservation is successfully achieved by farmers, as there are no indications that SOM in agricultural soils has been decreasing overall over the past decades (Reijneveld et al., 2009; Van Grinsven and Bleeker, 2017). Elsewhere in Europe there are substantial areas with insufficient SOM content (based on EU LUCAS soil data), and there is also need for attention to SOM on some farms or fields within farms in the Netherlands. Under West European (temperate) conditions, roughly 2-3% of soil organic matter decomposes every year. As a rule of thumb, under such conditions it is recommended that 1.5-2 tonnes per hectare of humified organic matter (the amount of organic matter still present one year after addition) be added every year to maintain SOM content once it is at a desirable level (Schils, 2012). Crop residues tend to be the main source of organic matter. As positive effects on soil fertility are hard to prove beyond a certain threshold, it may be questioned whether adding more organic matter than is required to maintain a minimum SOM level is an efficient use of biomass for soil fertility purposes (Janzen, 2006) and for developing circular food systems.

Soil-organic carbon sequestration

Fresh organic material added to soils decomposes rapidly. Depending on the composition of the material, temperature and drainage, often at least 70% decomposes within one year, and more in the years thereafter. A meta-analysis of many experiments in the tropics revealed that SOM increased on average by some 8% of the annually added organic matter inputs over a period of around 14 years (Fujisaki et al., 2018). Due to saturation, changes (in this case increases) in SOM decrease with time; the conversion of annually added organic inputs into SOM are lower over longer periods.

In general terms, C-sequestration as SOM is very difficult in dryland areas and even more so in warm conditions. However, it is very effective in peatlands or cold environments (Box 2.1). This calls for a rethink, for example, of the practice of draining peatlands and using them for agriculture, and the possible build-up of SOM especially in wet environments. Note that the addition of organic inputs also requires sufficient amounts of nutrients (nitrogen, phosphorus, etc.) to allow for carbon sequestration (Kirkby et al., 2013; Kirkby et al., 2016; van Groenigen et al., 2017). Normally carbon-nitrogen ratios of around 10 are necessary for SOM, while many crop residues (e.g. straw) will have much higher carbon-nitrogen ratios. Excess carbon is respired quickly when required nutrients are not present to support soil biota growth, while the addition of nitrogen also causes increased greenhouse gas emissions (CO_2, N_2O).

Overall, huge amounts of organic material (and nutrients) are needed to sustainably increase and maintain stocks of SOM. This raises the question as to whether it is sensible to aim for a higher SOM than is strictly beneficial for soil quality purposes. Powlson et al. (2008) compared the use of cereal straw for increased soil organic matter (carbon) sequestration or for combustion to generate electricity. They concluded that combustion of straw to generate electricity compensated for far more CO_2 emissions from fossil energy (coal) than SOM accumulation, assuming a time period of 100 years. When it comes to enhancing the circularity of circular food systems, therefore, we can conclude that once soil quality has been improved to the desired level through the addition of organic by-products, the by-products are more effectively used (to produce food and mitigate greenhouse gas emissions) as feed to produce food from animal sources and renewable energy, fertilisers and biomaterials.

Use as feed to produce animal protein

The second priority for the use of by-products is to feed animals or insects. Research has shown that land is used most effectively if we consume a moderate amount of food produced by animals fed with by-products and grass resources only (Van Kernebeek et al., 2015; Van Zanten et al., 2018a). This aspect is discussed at length under Principle 3.

Production of energy, fertilisers and biomaterials

An increasingly popular use of by-products is anaerobic digestion (AD) to produce biogas as a source of energy and digestate, which contains nutrients and can be used as a fertiliser. Since mineral fertilisers (in particular nitrogen fertilisers) are very energy-intensive to produce, digestate also saves energy when substituted for mineral fertiliser production (Miranda et al., 2015; Tufvesson et al., 2013), although this depends on the amount of water that needs to be removed and transport distances involved.

By-products can be a direct source of nutrients (e.g. animal manure in different forms) or they can be processed to produce fertilisers as a main or by-product (digestate). While unprocessed by-products that are used as fertiliser are often rich in organic matter, this is not necessarily the case for fertilisers based on processed by-products. The quality of unprocessed manure can be influenced through management of the livestock (feeding) and manure storage. For instance, feed that is relatively low in protein content leads to manure with lower mineral nitrogen contents, making it less vulnerable to losses (ammonia) (Schröder et al., 2005), while the phosphorus content of manure can also be managed with phosphorus concentration of feed (Ferris et al., 2010). The quality of fertilisers of organic origin and derived after processing (concentration, fractionation, blending, AD, etc.) has often gradually been improved, overcoming several of their limitations (Oenema et al., 2012; Schoumans et al., 2015; Withers et al., 2015). New forms of manure processing separate manure into fractions rich in nitrogen, phosphorus or carbon, and avoid long storage and the associated losses. New processes can also make use of the blending of by-products, making them more attractive as a fertiliser and for transportation and reduction of greenhouse gas emissions. A number of alternative technologies to recover phosphorus from manures and phosphorus-rich sludge (as well as wastewater and incineration ash) in the form of for instance struvite (Schoumans et al., 2015; Withers et al., 2015) have been investigated (see also Box 2.2). Before the use of unprocessed or processed by-products as a fertiliser is legally approved, issues of contamination with heavy metals (cadmium, zinc and copper, for instance), hormones, medicines and pathogens must be resolved.

Under Principle 1, we already discussed the relative advantages and disadvantages of organic versus mineral fertilisers. Important considerations when using organic fertilisers are that they add nutrients and organic matter simultaneously, release their nutrients more gradually (but not necessarily in a timely fashion), have a fertiliser replacement ratio which is often variable and less than 1, often dilute nutrients (making them bulky to transport), and contain nutrients in fixed concentrations which do not necessarily match the needs of the plants. Nitrogen to phosphorus ratios in particular are often too low. At the same time, the presence of other nutrients (e.g. micronutrients) in fertilisers of organic origin can be a bonus. While the advantages of organic fertilisers are not necessarily evident at the crop level, at a systems level they make perfect sense (Principle 1). It is, however, crucial to account for the implications of that systems perspective: what type of nitrogen-phosphorus and carbon-nitrogen ratios are needed given the demands of the crops and the conditions of the soil, and how can this be targeted through the proper combination of livestock feed, manure management and the processing and application of the organic fertiliser? It is also relevant from an energy perspective to consider the proximity of the location when using bulky fertilisers (Oenema et al., 2012).

Principle 3: Use animals for what they are good at

By recycling biomass unsuited for direct human consumption into the food system, animals can play a crucial role in feeding humanity. They convert biomass unsuitable for human consumption into high-quality, nutritious food, and recycle nutrients into the food system that would otherwise be lost to food production (Garnett et al., 2015). Rather than consuming biomass edible by humans, such as grains, such animals convert so-called ‘low-opportunity-cost feeds’ (e.g. crop residues, co-products from the food industry, inevitable food losses & waste, and grass resources) into valuable food, manure and other products.

As arable land is used primarily for the production of food instead of feed crops (see Principle 1), adopting such an approach means that animals contribute to nutrition supply without using additional arable land. In a comparison between eating no food from animal sources (vegan diet) and eating food produced by animals fed solely with ‘low-opportunity-cost feeds’, Van Zanten et al. (2018a) have shown that the latter frees up about one quarter of global arable land. Human diets containing protein from animals fed solely with low-opportunity-cost feeds use less arable land than a vegan diet and much less arable land than current diets in high-income countries (Figure 2).

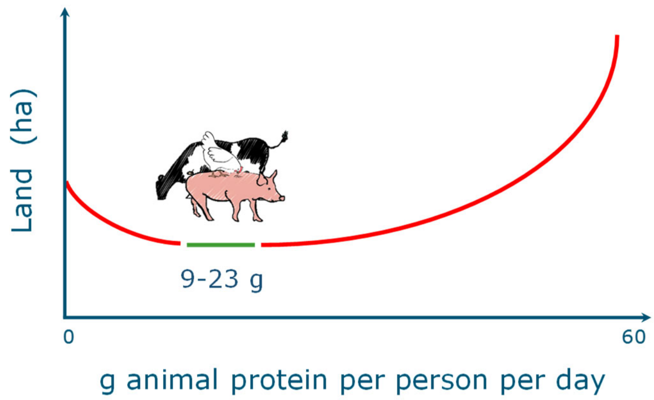

Figure 2. The theoretical relationship between arable land use and daily supply of animal protein (in grams), derived from available global studies (Van Zanten et al., 2018a). People need an average of around 50-60 g of protein a day; the average animal protein supply (excluding fish) is 51 g per person per day in Europe.

In a vegan diet scenario (see Figure 2, zero grams of food from animal sources as x value), crop residues remain on the field to feed the soil or are used as a source of bioenergy, co-products from food processing are wasted or become a source of bioenergy, and grasslands are not used for food production. As these biomass streams are not recycled into the food system by animals, additional crops have to be cultivated to meet the shortfall in nutrition for the human population.

The effective use of arable land for the production of human food is crucial to protect biodiversity, avoid carbon emissions caused by land use change, and effectively use rainwater or fossil phosphorus (Van Kernebeek et al., 2018). However, the amount of food that can be provided by farm animals fed solely with low-opportunity-cost feeds is limited by the quantity and quality of these feeds and the efficiency with which animals utilise them. Initial estimates show that this route can provide up to a third (9-23 g) of the daily protein needs of the average person (50-60 g; see Figure 2; Van Zanten et al., 2018a). Any consumption of food from animal sources above this level would require feeding animals crops edible to humans or converting current grasslands or uncultivated land (such as forests) for crop use. Both scenarios have environmental consequences. We do not yet know exactly how much food could be derived from farm animals fed solely with low-opportunity-cost feed: this will depend on factors such as the quantity and quality of by-products and grass resources available for animals, the type of animals, and how efficiently specific farm animals utilise the feed. These questions are discussed below.

Which leftovers from the production of plant-based food are available for animals?
How much low-opportunity-cost feed is available for farm animals depends on the type of crops for human consumption cultivated on arable land, the amount of food wasted and the use of crop residues, co-products, food waste and grass resources for functions such as soil fertility, bioplastics production and pet food.

To use arable land effectively, the choice of a given food crop should be based not only on its food value for humans, but also on the value of its by-products for animals, the soil and other food system functions. Dual-purpose food-feed crops can therefore play a key role in future nutrition security. Let us use the example of oil for cooking, with a choice between rapeseed and soybean oil, say. Producing one litre of either rapeseed or soybean oil requires around 11 m^2 of land (Poore and Nemecek, 2018). However, soybean meal has a much higher nutritional value for farm animals than rapeseed meal, making it a dual-purpose crop (note that soybean meal has become a main driver of land use change – this violates Principle 1, which states that arable land should be used to produce human food). Another example is maize, which yields both grain for human consumption and thinnings or green stover which can be valuable to feed animals or the soil. The importance of adopting a food-system lens when choosing crop rotation is obvious.

The availability of food waste for farm animals has a significant impact on animal production as the nutritional value of food waste for livestock is often high. This is especially the case when compared with crop residues or co-products from food processing (Van Zanten et al., 2018a). Nonetheless, the reduction of food losses and waste should remain our first priority as this has a direct benefit on the environment and resource use.

Unavoidable food waste can have value as animal feed. Many countries, and the EU as a whole, currently ban the use of food waste as animal feed due to the potential risks to human health like foot-and-mouth disease, classical swine fever and bovine spongiform encephalopathy. There is evidence, however, that feeding food waste to animals (especially to monogastric animals) can be safe when heat-treated. This practice is commonly applied in Japan, where about 35% of food waste is recycled and fed to pigs (Zu Ermgassen et al., 2016). Using food waste as animal feed should therefore be given a priority for future research into sustainable livestock nutrition.

Lastly, the availability of crop residues, co-products from food processing and grazing land also influence the amount of food from animal sources which can be produced with low-opportunity-cost feeds. Crop residues often have a lower nutritional value than food waste and co-products. They also have considerable value for enhancing soil fertility and organic matter as well as producing bioenergy. The use of crop residues to produce food from animal sources can therefore result in trade-offs with soil fertility or climate change. The question as to whether crop residues or co-products from food processing should be used to a) enhance soil fertility, b) produce bioenergy or c) feed animals requires optimisation of the entire food system. This applies not only in terms of land use but also from the perspective of nutrient use efficiency and greenhouse gas emissions. Similarly, we must recognise that grasslands are not a cost-free resource in environmental terms. The grassland currently used by ruminants could potentially be deployed for nature conservation, forests, bioenergy production or, in some cases, crop production. This leads us to the following question.

Which grasslands can be considered available for animals?
While substantial areas of grassland could in principle be used for crop production (Mottet et al., 2017), such land use change could also lead to a loss of soil carbon and biodiversity. The use of grassland by ruminants precludes alternative uses such as natural rewilding or agroforestry (yielding wood as a source of bioenergy), which may be preferable in terms of biodiversity and the climate. While ruminants can create nutritional value from grasslands, they also emit significant amounts of greenhouse gases, including methane. While methane emissions from animals may potentially be offset by soil carbon sequestration in grass-based ruminant systems, a comprehensive recent study found that – although

there is potential for temporary sequestration in certain localised situations – the short-term potential benefits from sequestration at an aggregate global level are considerably lower than the methane and other emissions produced by the animals (Garnett et al., 2017). As long as grass-based ruminant systems release methane and nitrous oxide, there will be an inevitable trade-off between grassland use and greenhouse gas emissions from ruminants. There may also be a trade-off between grassland use and biodiversity loss. This discussion clearly demonstrates the opportunity cost implied when rearing animals on grasslands, and shows that not all grass biomass can be considered a free resource. What is lacking is a systems view on alternative uses of the world's grasslands with respect to food and bioenergy production, and the possibilities of rewilding (i.e. biodiversity).

Which animals are best suited for which types of leftovers or grass resources?
Different animals have different capacity to convert low-cost feeds or grassland into valuable food for human consumption. It is received wisdom that pigs are ideally suited to make the most of food waste as they eat most foods which are also consumed by humans and can consume food with a high moisture content. But might feeding food waste to farmed fish or insects result in relatively more animal product, pound for pound? The ability of various animals to efficiently convert leftovers and grass resources into food for humans is affected, among others, by the species, the breed and the production system. There are animals which are bred to be highly productive on high-quality feeds that may be less suited to utilise leftovers streams (Zijlstra and Beltranena, 2013). This means we need to rethink the concept of resource-use efficiency in the feeding and breeding of animals, and consider a focus on conversion efficiency of biomass that is not edible for humans. We also need to explore the question of allocation: which low-opportunity feeds are available in a given setting, and which animals should receive them to maximise production of food from animal sources while minimising emissions that affect water, soil and air.

Cultural and technological impact
Technological development and cultural changes can have a substantial effect on the availability or quality of low-cost feed for animals. This means they can have a major influence on the amount of food that can be produced by animals in a circular food system. The biological treatment of rice or wheat straw with fungi, can, for instance, significantly improve nutritional value for ruminants, and generally improve the quality of low-cost feeds (Khan et al., 2015). Biological treatment of low-cost feeds such as orange peels and cucumber with yeast, however, instead generates a high-protein substance which is also suitable for direct human consumption, potentially lowering the availability of low-cost feed for farm animals (Mondal et al., 2012). Similarly, biorefining can be used to segregate grass into protein and fibre. The resulting proteins can still be consumed by cattle, but are also highly suitable for pigs or poultry, or can even be processed directly into food suitable for humans. This leads to the question of whether we should feed this grass protein to poultry, pigs, insects, dairy cattle or fish, or whether it would be better to invest in initiatives for making it directly edible for humans. It is important to note that mechanical harvesting of grass for biorefining is currently associated with substantial energy inputs. In other words, harvesting grass for biorefining is only environmentally beneficial if it is driven by renewable energy sources. And harvesting grass from marginal land might be costly even if we had access to infinite renewable energy.

Cultural changes may also affect the availability of low-cost feeds. A widespread dietary shift from white to brown bread, for example, would change the quantity of wheat middlings available. Similarly, if people avoid creating food waste altogether, less of it will be available as livestock feed.

Finally, there are new technological developments that will enable the production of future foods from crops, algae, fungi or animals. This includes the production of meat substitutes that taste like meat from plant-based foods (e.g. soy and wheat protein). Such products may contribute to increasing the consumption of plant-based food at the expense of food from animal sources – a development which is particularly likely in high-income countries. Meat substitutes from plants, however, do not provide the complete array of essential micronutrients, such as vitamin B_{12}, zinc, calcium or omega-3 fatty acids, and therefore often need to be fortified. Future foods from sources such as mycoprotein, insects, seaweed and cultured meat, however, have been shown to provide major environmental benefits while providing the complete array of essential nutrients. Research on the nutrient bioavailability, food safety, production costs and consumer acceptance related to such foods will determine their role in future human diets (Parodi et al., 2018).

Should Europeans eat less food from animal sources?

Feeding primarily low-cost feeds to farm animals will also affect the availability of animal-source food for human consumption, because the amount of such food is limited by the availability and quality of low-cost feeds. There have only been a few studies so far that have estimated the amount of food produced by farm animals fed mostly low-opportunity-cost feed, they all focused on efficiency of land use. These studies show that animals fed mostly low-opportunity-cost feed can produce about 9-23 g of protein, which is about 15-46% of our daily needs (50-60 g per capita). The daily supply of animal protein (excluding fish) per average European is about twice that today (around 51 g). This implies that moving towards a circular food system would require a substantial reduction in the consumption – and hence production – of food from animal sources in EU countries. Consuming less food from animal sources, and feeding animals primarily low-cost feeds, would not only improve the efficiency of natural resource use but also result in lower overall emissions from food production, ease the local recycling of nutrients, and open doors to producing food from animal sources while improving animal welfare as well as landscape and biodiversity. The exact reduction in the consumption of animal products required for this transition in Europe is not, however, known at this time. What we do know is that it will depend on a combination of factors described above (e.g. greenhouse gases ceiling, biodiversity goals, and new technological developments).

At what scale should we develop circularity?

One of the key questions when developing circular food systems is related to the spatial scale to adopt. Nutrients are recycled from soil, water and the atmosphere into living organisms and back, and cross farms, regions and national boundaries. Moreover, due to specialisation and globalisation, nutrients accumulate in areas with high animal (due to manure) and human (food waste or human excreta) density, while they are depleted in other areas.

The scale at which developing circularity is usually discussed ranges from the local to the regional level. Farms are not circular by definition: they are designed to produce and sell human foods, and hence export nutrients via the products they sell. To safeguard soil fertility in the long term, therefore, every farm needs inputs of nutrients, either via biological or industrial nitrogen fixation or through the import of by-products. We have to remember, however, that by-products such as animal or human excreta, do *not* bring new nutrients into the food system, but merely recycle existing ones. As long as we keep losing nutrients from our food system, which will continue to be the case until zero-emission food systems are achieved, we will continue to have to bring in new ones. This especially holds for nitrogen, which is a mobile and reactive nutrient that easily escapes the food system. Since nitrogen gas (N_2) is the most abundant element in the atmosphere, however, we can bring new nitrogen into our food system via biological or industrial N_2 fixation (this will of course be circular only if it is produced with renewable energy). For phosphorus or other micronutrients, however, we fully depend on finite resources, making efficient recycling of by-products in the food system, such as animal and human excreta or wastewater, a necessity.

The scale at which we should aim to close nutrient loops is determined by the interaction between various factors. Differences in agroecological and socioeconomic circumstances, for example, make some areas more suitable to producing certain types of food than others. These advantages may outweigh the emission impact of transport, implying that locally produced food may not always be the best choice from an environmental perspective. The transport potential of nutrients across scales depends to a large extent on the volume of the products transported.

Innovative technology, such as source separation of urine and faeces in innovative animal housing or new sanitation systems, in combination with smart processing of separated sources, can make a significant contribution to reducing the transport costs of animal and human excreta. Moreover, mixing and coupling crop and animal production, be it at a farm or regional level, clearly has advantages in terms of recycling by-products and nutrients from animal manure. Closing nutrient loops also requires that new interactions are built between components of the food system, for example between cities and locations where food is produced. Cities are inevitably sources of large amounts of food waste and human excreta, which could be used as valuable nutrients for food production in urban farming systems that combine plant, insect and fish production.

Besides the transport argument, motives for buying local food include perceived quality and freshness, transparency about how food is grown and made, and support for the local economy. Moreover, countries often aim to sustain a degree of food and resource sovereignty, not only to cope with disruptions in the food supply but also in order to maintain an advanced agricultural knowledge system and remain innovative in agriculture and food production. This geopolitical argument also favours the recycling of nutrients at a relatively small regional scale.

The optimal scale at which nutrients should be recycled in the food systems remains context-specific and requires an integrated analysis of the abovementioned factors. But if Europeans consumed only food from animals that recycle locally produced low-opportunity-cost feeds, they would certainly consume – and hence produce – less food from animal sources in Europe, facilitating the local recycling of most nutrients in animal and human excreta.

Barriers and incentives towards circular food production

Without any claim to exhaustiveness, this section lists important barriers to the transition to a circular food system, and identifies incentives that can stimulate this transition.

Rethinking EU regulations about using food waste or processed animal protein as feed
Although food waste is highly valuable as animal feed, an important concern is that it can transmit diseases if containing animal residues (uncooked meat, bone meal). The recycling of swill (i.e. household, restaurant or catering waste) as animal feed was banned in the EU in 2002 after the foot-and-mouth disease epidemic in the United Kingdom in 2001, which is thought to have been started by the illegal feeding of uncooked swill to pigs. While this law still permits feeding some food waste to animals, such as foods from plant sources that pose no risk of contamination with animal products, only a few percent of all EU food waste is currently recycled as animal feed (Zu Ermgassen et al., 2016). Similarly, the EU banned the use of processed animal protein (except fish meal and blood meal from non-ruminants) in all farm animal feed, such as meat or bone meal, because it was linked to the spread of bovine spongiform encephalopathy (BSE) in cattle, and BSE-infected meat was associated with variant Creutzfeldt-Jakob Disease in humans.

In countries such as Japan, Thailand or South Korea, however, about 35 to 40% of food waste is safely recycled as pig feed. Heat treatment deactivates viruses causing foot-and-mouth disease and classical swine fever (Edwards, 2000; Garcıa et al., 2005; OIE, 2009), and renders food waste safe for animal feed, while BSE is prevented by feeding food waste to pigs or poultry only. Zu Ermgassen et al. (2016) clearly demonstrated that feeding swill to pigs could reduce the land used by EU pork production by a fifth, potentially freeing up 1.8 million hectares of agricultural land. These countries have a useful lesson for the EU when it comes to recycling food waste.

Such examples justify a rethinking of EU legislation about the use of food waste and processed animal protein as animal feed. Of course, changes in legislation should never be made at the expense of feed and food safety and traceability, as public trust in the food system is crucial and one mistake or scandal can do much harm for the future. Feeding food waste and processed animal protein to animals requires not only support from policy makers, the public and the farm animal industry, but also investment in the collection and transport of food waste, and technology to heat-treat waste or processed animal protein.

Rethinking the EU Fertilisers Regulation
The European Commission launched several actions in 2017 to stimulate the transition towards a circular economy. One important action was changing the EU Fertilisers Regulation 2003/2003, which addresses the rules which apply to the trading of fertilising products. The current regulation forbids the free trade of nutrient fertilisers of plant or animal origin across borders, preventing the closing of nutrient loops in the European food system. The new regulation aims to achieve free trade of fertilising products, and defines standards for acceptable nutrient contents as well as levels of contaminants. Biomass streams that meet these new criteria can be reused as fertiliser. To enable the future recycling of plant and animal biomass, we therefore need to invest in assessing and improving the agronomic and environmental value of fertilising products resulting from acceptable processing techniques, such as anaerobic digestion, compositing, reverse osmosis, incineration and filtration. Moreover, for several of these technologies we need to invest in new strategies to minimise contamination with pathogens and the risk of residues in substances such as animal manure. Finally, we must create awareness among farmers about the potential fertilisation value of these new products.

The reviewed Fertilisers Regulation does not, however, yet target all available biomass streams with a fertilisation potential. The nutrient resources which are potentially available but not included include sewage sludge and human excreta. Nutrient sources from sewage sludge, including struvite, lead to concerns of contamination with new emerging contaminants (residues of pharmaceuticals, hormones, etc.). As with animal manure, we must invest in technology to minimise contamination with pathogens or the risk of residues (pharmaceuticals, hormones) in human excreta.

Rethinking the Common Agricultural Policy

The Common Agricultural Policy (CAP) provides several possibilities to support circularity in food production. The recent legislative proposal for the first pillar of the CAP includes a new green architecture for direct payments. This new architecture allows for enhanced conditional criteria for direct payments to farmers and introduces so-called eco-schemes. While the conditionality of criteria is largely pre-specified at the EU level, Member States also have options for tailoring them to national requirements. This includes measures to maintain the land in a good agricultural and environmental condition (all-year land coverage, protection of permanent pastures, soil preservation measures), and support a circular system. Eco-schemes, moreover, offer possibilities to support the reduction of greenhouse gas emissions for specific regions (e.g. peat areas).

The second pillar of the CAP in the green architecture includes the agri-environmental and climate action (AECS) schemes, including measures for biodiversity preservation, landscape protection and climate action. With regards to climate action, Member States have several options to propose new measures, including ones on carbon sequestration and environmentally friendly land management practices. As the EU and its Member States have also committed themselves to meet the Paris agreement on climate change, and agriculture is part of the sectors expected to contribute to achieving these commitments, there is a need for action and smart use of the possibilities the CAP offers in this regard.

Aside from the AECS, the second pillar of the CAP offers several possibilities to support investments that could contribute to a development of agriculture which would take into account sustainability criteria and utilise the possibilities to make the agriculture and food system more circular. Two types of measures can contribute to this: (i) classical investment subsidies with a green rather than productive main focus (e.g. subsidies for so-called green label stables); and (ii) funding of European Innovation Partnerships (EIP-Agri). Especially EIPs offer potential to stimulate circularity, as they aim to bring actors from the entire research and innovation value chain together with the purpose of streamlining efforts and accelerating market take-up of innovations that address key challenges for Europe. Because circular food systems require innovations and stakeholder collaboration, this instrument is particularly well suited to supporting desired transitions towards sustainability and inclusive growth. As an example, an EIP could work on solutions that reduce food waste by transforming it in a safe way into valuable animal feed or expand the functionality of organic manure as a fertiliser for the arable sector.

Rethinking the metrics used for circularity

At present, product footprints are increasingly used by industry and society to reduce the environmental impact of food production. As discussed in the introduction, however, product footprints do not encompass the full complexity and circularity of food systems as they do not address interlinkages within the food system or the issue of feed-food-fuel competition. The current product footprint approach, therefore, does not direct us towards a circular food system, especially not in the field of animal sciences. Feeding more concentrates instead of roughage to cattle, for example, would reduce the footprint of beef (De Vries et al., 2015), but at the same time increase feed-food competition and thus increase the land use of the entire food system (Van Zanten et al., 2018a). Similarly, dietary footprint studies advise that people should eat meat or eggs from grain-fed poultry rather than milk and meat from ruminants grazing on land unsuitable for crop production.

The move towards using animals for the purpose which best suits them, namely converting biomass inedible for humans into valuable food, requires multiple metrics. We need to measure the efficiency with which biomass inedible for humans is converted into human food (Ertl et al., 2015). But we also need measures that assess the resource-use efficiency of the entire food system, such as the land-use ratio (Van Zanten et al., 2017), which determines whether a net gain in protein output might accrue from the use of land by either animals or cropping. Besides these product-based measures, however, we also need to look at the application of animal and human excreta per hectare of land (i.e. maximum nutrient fertilisation application rules) or emissions in a specific region (carbon dioxide emission ceilings). A transition towards a circular food system, therefore, requires a smart combination of metrics at different scales (farm, product, region).

Rethinking economic growth
An increasing number of people today question whether economic growth as measured by gross domestic product (GDP) should remain the basic measure of our economy. There are several suggestions on how to broaden the GDP concept. The idea of green growth, suggested by the OECD, for example, focuses on achieving economic growth and development while ensuring that natural assets continue to provide the ecosystem services on which our wellbeing relies. Others suggest similar concepts like sustainable growth or inclusive growth. These concepts are often based on the idea of decoupling, that is, the need to separate economic growth from its resource use and environmental impact. The feasibility of this decoupling, however, has been questioned by others (Fletcher and Rammelt, 2017). Some say we should no longer focus on growth at all, but rather aim to achieve sufficiency and equity to maintain our quality of life (O'Neill et al., 2018). In terms of food consumption, aiming for sufficiency and equity would imply eating according to dietary guidelines, consuming a moderate amount of food from animal sources, and addressing levels of global inequality.

Two main arguments are given for moving away from a focus on economic growth. The first one points out that we live on a planet with finite resources. This implies that we cannot increase our economic growth and associated material consumption indefinitely as this will eventually cause catastrophic changes to the Earth's ecosystem. The concept is clear enough – however, it requires a significant reduction in consumption in places like Europe or the US to make room for growth in places like Africa, making it unpalatable. The second argument has a more social basis. Research has shown that once people's basic needs are met (e.g. they have sufficient food, drink, housing, clothing, etc.), additional financial resources do not appear to generate additional happiness. Instead, people value things like personal relationships, a healthy life, a safe community or a secure job.

Is there an alternative to economic growth? How do we achieve a high quality of life without economic growth? This rethinking of economic growth is referred to as the new economics, economic de-growth, sustainable prosperity or a steady-state economy. In this new economy, resource use is stabilised in order to respect planetary boundaries (implying reductions in the use of resources in high-income countries in order to allow growth in Africa or developing Asia), and the aim of increasing GDP is replaced by the goal of improving quality of life. Potential directions or pathways are currently being discussed by different economists (see, for instance, the conference on post-growth or de-growth held in Brussels on 18-19 September 2018). Although nobody knows exactly how to move towards a circular economy, suggestions like true pricing, subsidising of sustainable initiatives, increasing taxes on the use of new resources while lowering tax on labour, and adapting production volumes are among the most often proposed solutions. They must go hand in hand with education and transparent information to increase awareness of the unsustainability of our present food production and consumption patterns and to change social norms and values in favour of more sustainable consumption patterns.

Rethinking economic growth will clearly have implications for the prices paid to farmers for their products, and hence food prices and the share of income we spend on food. For the sake of people as well as the planet, however, such sacrifices may need to be made.

Future research areas

This publication discussed the main principles of circularity in plant and animal production in particular. It does not aim to present a single design or blueprint for circularity in food production, let alone a plan for how to realise it. The food system is inherently associated with material and nutrient losses, which are partly impossible to recover and will remain so in the foreseeable future. A completely circular food system, therefore, may be a utopia. Moreover, the manner and speed at which we will move towards circular food systems will depend on social and political choices with many shades of green and grey, and are highly context-specific.

Scientific advances related to circularity in food production currently seem to be in their infancy. We therefore propose the following key research areas:

1. Redesign of crops, cropping systems and crop rotations, focused on diversity, to optimise the total circular production and use of biomass, and the use of regenerative resources.
2. Rethinking of the recycling of materials (organic matter and nutrients) in by-products back into the food system in a way that adds the most value to the entire food system. This includes addressing the question of which by-products are available where and have most value for what purpose: feeding the soil or the animals, or production of renewables? But it also considers the development of new practices or technology to enhance the precision fertilisation of cropping systems (including intercrops), to overcome the food safety risks of recycling food waste or human excreta, or to increase the fertilisation potential of animal manure.
3. Improving our understanding of the role of farm animals in a circular system. This poses questions such as: Which farm animals use which by-products and grass resources most efficiently (including insects and fish) in terms of both land use and greenhouse gas emissions?
4. Understanding at which scales the circularity of food systems must be pursued in different biophysical and socioeconomic contexts. This requires things like the development of new ways to reinforce interactions between plant and animal production, building new interactions among components within the entire food system (e.g. between cities and urban farming), and overcoming the nitrogen limitation in circular production systems by balancing new nitrogen inputs via legumes and mineral fertiliser produced with renewables.
5. Developing initiatives to reduce the consumption of food from animal sources in high-income countries.

Box 1.1 – Boosting photosynthesis

Theoretically, there are many options to improve the productivity of crop photosynthesis. A computer simulation study (Yin and Struik, 2017) showed that multiple integrated options often result in a boost that exceeds the sum of the gains from individual improvement options. Using the current understanding of individual steps along the chain from leaf biochemistry to crop production, Yin and Struik (2015) calculated that if all attainable options (for improving radiation-use efficiency (RUE) and light interception efficiency) are combined, crop productivity may be improved by some 36-64% on the basis of the highest current yield level under favourable conditions and depending on the photosynthesis mechanism (so-called C3 or C4).

The key trait linked to RUE is Pmax (light-saturated maximum photosynthesis rate per unit leaf area) and there is some evidence that RUE has been higher in recent winter wheat and maize varieties thanks to a greater Pmax. Long et al. (2006) reviewed the literature on optimising RUE and Pmax and concluded that RUE could theoretically be roughly twice as high as it is in high-yield crops today. There is an important difference in Pmax between so-called C3 (e.g. wheat, rice, potato) and C4 (mostly crops found in tropical environments, such as maize, sorghum and sugarcane) plant species (the figure reflects the number of carbon atoms in the initial photosynthetic product). C3 plants have a lower Pmax and thus exhibit much earlier radiation saturation, largely because more than 30% of the assimilates that are formed first under the current atmospheric conditions are lost through a process called ‘photorespiration’. C4 plants rely on a coordinated functioning of photosynthetic biochemistry and special leaf structure that effectively supresses photorespiration, thereby enabling a higher Pmax than C3 plants. There are several ongoing genetic engineering programmes that aim to introduce the full C4 mechanism into C3 crops, such as rice, in order to supercharge the productivity of C3 crops. While phasic progress has been made (Wang et al., 2017), introducing the full C4 mechanism in C3 leaves is extremely challenging and will require many more years to achieve (Sage, 2016).

Another key photosynthetic trait for increasing RUE is the initial light-use efficiency of the photosynthetic light response curve. This trait is particularly relevant in the context of crop stands or canopy, where lower leaves are often shaded by upper leaves, limiting their photosynthesis. Initial light-use efficiency is generally conservative among C3 plants, so there is little scope to improve it through breeding. There is also little chance to improve it by introducing the C4 mechanism because the initial light-use efficiency is similar in C3 and C4 plants under the same atmospheric conditions. A more feasible approach to improve the photosynthesis of lower leaves in a canopy is to modify the canopy structure with more erect upper leaves, allowing more incoming radiation to penetrate to the bottom of the canopy. This strategy is especially useful for a full canopy under high light conditions as erect upper leaves would intercept less light, thereby also avoiding so-called ‘photodamage’ to top leaves caused by high light intensity.

It is crucial to note that the full benefit of extra photosynthesis (source) also requires extra grain (sink). Since crop plants have finely balanced source-sink relationships (Denison, 2007) reaping the benefits of any change in photosynthesis (source) may take decades of breeding (Hall and Richards, 2013).

Box 1.2 – Biological fixation of atmospheric nitrogen

Biological fixation of nitrogen gas in plants, especially leguminous plants, can play an important role in circular food production. Legume crops may fix up to 100-300 kg of N/ha per year (Giller, 2001; Herridge et al., 2008); this effect is most prominent under conditions of low nitrogen availability in soils when other nutrients (in particular phosphorus) are not limiting. If the crop is harvested for human consumption, it immediately substitutes mineral or organic fertilisers, and if the legume crop is used as feed or green manure it can substitute fertiliser nitrogen in subsequent crops through the use of manure or the residual effects of green manure. Legume crops also have beneficial effects on succeeding non-legume crops in crop rotations under nitrogen-limiting conditions. There are major research initiatives to engineer cereal crops to enable them to fix nitrogen with rhizobia (see https://www.ensa.ac.uk). Results to date suggest that many of the genes needed to allow rhizobial infection and to form nodules are present in cereals (Rogers and Oldroyd, 2014), but the engineering of effective symbiosis is at a very early stage.

Box 1.3 - The Planty Organic experiment

Planty Organic is an organic arable farming system in Kollumerwaard in the north of the Netherlands that provides 100% of its own nitrogen through leguminous crops and the use of cut-and-carry fertilisers produced on farm (Van der Burgt et al., 2018). The system was shown to be nitrogen-limited. Some key results of the experiment have been compared to those of a mainstream system from the same area in Table 1. It should be noted that the Planty Organic system has a six-year rotation, with a relatively large share of green ground cover throughout the year thanks to green manure and alfalfa-clover leys. Alfalfa-clover also took up one entire production year of the rotation, which implies that all yields must be corrected downwards by 1/6 or around 17% to arrive at the actual crop yields per hectare per year.

The Planty Organic system has yields similar to those of organic systems elsewhere in the country. The yield difference between organic and mainstream systems is 20-25% (based on average crop yield differences between organic and mainstream found in the literature), to which we need to add 17%; however, one could also argue that the relative yield of the Planty Organic system is 64/120 = 0.53 (ratio of nitrogen in products, see Table 1). The data also reveals that losses per hectare of Planty Organic are less than half of those seen in mainstream systems, while nitrogen use efficiency (N output/N input) is similar (65-69%). The only way to improve productivity of the Planty Organic system in a circular manner is to recirculate processed household waste derived from the nitrogen (and other nutrients) in the product that leaves the farm. This would decrease the yield difference between the organic and mainstream systems. Even so, these waste products have a nitrogen-phosphorus ratio that is lower than that desirable for crops because nitrogen is easily lost in its cycle through animals, industry and humans.

Table 1. Average inputs and performance over five years (2012-2016) of the Planty Organic system and a mainstream arable farming system in Friesland (the Netherlands). Soil-organic matter contents were approximately the same and did not change over time; the soil is a rich clay-loam soil (Van der Burgt et al., 2018).

Variable	Planty Organic	Mainstream
N input (kg N/ha)	96	186
N uptake (kg N/ha)	234	212
N in product (kg N/ha)	64	120
N in product/N uptake (%)	27	57
N in product/N input (%)	69	65
N losses (kg N/ha)	28	66
N losses/N input (%)	31	35
Green ground cover (% of year)	82	69

Box 1.4 – Phosphorus

Phosphorus is an essential macronutrient for plants, and often, next to nitrogen, a limiting resource for yield. It is also a finite resource; it is estimated that known reserves (mostly in the form of phosphate rock) feature in few places on earth and will last in the order of one to several centuries (Sattari, 2014). From the point of view of resource availability, circularity is therefore absolutely essential for this element if life on earth is to also be possible by the year 2500. Compared to nitrogen, phosphorus is far less mobile in the environment, which may be negative for plant uptake as phosphorus is often present in the soil in forms not easily accessible for plants. However, it can also be positive from an environmental and circular perspective as much of the phosphorus not taken up by crops will accumulate in soils and become available to crops in later years. This so-called legacy phosphorus is particularly important in historically over-fertilised soils in north-western Europe and China (Sattari et al., 2012). It allows equilibrium fertilisation in many soils in the Netherlands, that is, inputs and outputs match, and sometimes inputs can be even lower than outputs. Organic fertilisers are often relatively rich in phosphorus, which limits their use – legislation restricts the use of organic inputs based on their phosphorus concentrations – and this implies suboptimal fertilisation in terms of nitrogen.

Biological processes can assist the uptake of phosphorus by plants. Mycorrhizas are a symbiotic association between a fungus and the roots of host plants which has multiple properties, of which its interaction with phosphorus is the most prominent. While the plant supplies the fungus with carbohydrates, the fungus facilitates the uptake of phosphorus by extending soil exploration via higher root length density and better soil contact. Although there are similarities with nitrogen and rhizobia, the essential difference is that there is no new phosphorus involved in the symbiosis between roots and mycorrhizas, while rhizobia mobilise new reactive nitrogen. Most crop plants have associations with mycorrhizas and they are normally present in all agricultural soils. The contributions of the symbiosis to phosphorus uptake increase under phosphorus-limiting soil conditions; when phosphorus is abundantly available, the mycorrhizal contribution decreases. Good quantitative estimates of the contribution of mycorrhizas under farming conditions are scarce; Kuyper and Giller (2011) estimated phosphorus fertiliser savings at around 10%. Measures to enhance the contribution of mycorrhizal fungi under phosphorus-limiting conditions include inoculation with strains targeted at increased crop yield, reduced or zero tillage, avoidance of certain fungicides and avoiding non-host crops (e.g. cabbage and sugar beet), but it is fair to note that all of these require substantial practical interventions (Koele et al., 2014).

Box 1.5 - Horticultural plant production in greenhouses and vertical farms

In a way, advanced horticultural systems in greenhouses and vertical farms can be regarded as circular systems *avant la lettre*. Growing plants in greenhouses or vertical farms can achieve extremely high production rates per unit land area. The plants typically grown in greenhouses are vegetables such as tomato, pepper, cucumber and lettuce, and cut flowers or pot plants. Only 0.5% of arable land in the Netherlands is used for greenhouses, but the agricultural production value is 24% of the total (Verhoog, 2016). In cool climates, greenhouses usually have a glass cover, while a plastic film generally suffices in warm climates. The indoor climate of greenhouses can be fairly well controlled, while the supply of carbon dioxide, water and nutrients can be computer-controlled. There are many ongoing innovations which will further improve yield, quality and sustainability, such as the use of LED lighting, greenhouse covers that diffuse light with improved light transmission and insulation capacity, robots, plant sensors and artificial intelligence. As a result, a tomato grower in the Netherlands, for instance, typically produces 70 kg of fruits per square metre per year (Vermeulen et al., 2017).

Most pests and diseases that affect greenhouse vegetable crops can be controlled by biological agents, so the use of pesticides is limited. Crops are often grown on substrates such as rockwool, perlite or coir. This not only allows crops to be grown on soils not suitable for plant production (due to soil contamination, for instance), but also allows a precise supply of water and nutrients according to the needs of the plants, and makes it possible to collect and reuse drained water and nutrients so that emissions are nearly zero (Beerling et al., 2014).

In cool regions of the world, greenhouse production needs energy for heating and, when lamps are installed, for lighting the greenhouse. Although energy-use efficiency in the Netherlands in 2016 had improved by 59% compared to 1990 (Van der Velden and Smit, 2017), energy consumption remains high, constituting about 15-30% of the total annual costs of a nursery (Vermeulen et al., 2017). The sector is therefore putting lots of effort into reducing the use of fossil fuel, for instance by using novel insulation technologies, more efficient LED lamps, innovative growth strategies and geothermal heat. The greenhouse air is enriched by carbon dioxide, which may come from the flue gases produced by the heating system or by industry; in some cases tanks with carbon dioxide gas are used.

Vertical farming is a new production system which can be considered a next step to full control of the production process. This technique refers to the production of plants in stacked layers where LED lamps provide the light for plant growth. Particularly interesting for the production of fresh vegetables in urban regions, this production system allows for guarantees on quantity and quality of the vegetables any day of the year independent of weather, climate change or location. Annual production levels per layer can be at least as high as in a greenhouse, and depending on the number of layers, the production per unit of land area can be many times that possible in a greenhouse or on an open field. This system is expected to enable plant production without use of pesticides or nutrient emissions, and with only two to four litres of water per kilogram of produce, lower transport mileage, and less food waste (thanks to the better quality of the whole plant, longer shelf-life and shorter distance to consumer). The lamps still require a high input of electricity, however, and the production system is also very capital intensive. The full control of the growth environment allows conditions to be chosen in a way that improves product quality (taste, aroma, appearance, shelf-life, nutritional value, safety). Vertical farming is still a new production system for which many developments are expected over the coming years.

Box 2.1 – Soil organic matter

It is generally agreed that soil organic matter (SOM - which contains ca. 50% soil organic carbon (Pribyl, 2010) - and a range of others elements including nitrogen, phosphorus and sulphur) fulfils a range of purposes, in particular holding and releasing (or buffering) nutrients, holding and releasing (or buffering) some soil water, improving soil structure and workability, and maintaining soil microbiology and soil life. It is also hypothesised that SOM and soil management, through soil life, may suppress pests and diseases or contribute to other ecosystem services, although empirical evidence in farming is still scant (Gagic et al., 2017; Tamburini et al., 2016; Van Gils, 2017). Although soil life is stimulated by organic inputs, there is little evidence that this increases the uptake efficiency of nutrients or natural pest suppression.

The quality of organic inputs for soils depends on the biodegradability of the organic matter and the amounts of nitrogen, phosphorus and sulphur to be released and available for plants. Both readily and slowly degradable components are important. The readily degradable parts are important to feed soil life, improve soil structure and deliver nitrogen, phosphorus and sulphur to plants. The slowly degradable parts (also labelled effective organic matter) contribute to the soil organic matter content.

At constant input levels of organic matter, soils arrive at equilibrium levels of SOM: the higher the input level, the higher the equilibrium level. The equilibrium level also depends on the type of organic matter (Yang and Janssen, 2000; Yang and Janssen, 2002) and on whether we are dealing with a sandy or clay soil (Bimüller et al., 2014; Feller and Beare, 1997; Hassink, 1997). Temperature also has an important effect on the decomposition of organic matter – a nine-degree higher average temperature, for instance, roughly doubles the decomposition rate (Yang and Janssen, 2000; Yang and Janssen, 2002). Finally, mineralisation of the organic matter completely stops under anaerobic conditions (peatland with high water table). The SOM content of a soil in a given climate therefore depends on drainage, soil texture and organic input type and levels, and may vary widely from below 1% for some sandy soils to 10% or more on clay soils (and almost 100% for peat soils) (Loveland and Webb, 2003).

Box 2.2 – Circulating phosphorus

The case of reusing nutrients from by-products is well illustrated with phosphorus (Oenema et al., 2012; Schoumans et al., 2015; Withers et al., 2015). Globally and annually, animal manure contain more phosphorus than mineral fertilisers, and a large share of that manure (in some countries, including China, around half) is discharged to surface water or wasted. Other by-products that contain phosphorus include sewage sludge, compost and animal bones from slaughterhouses. The separation and extraction of phosphorus from by-products can occur at various stages of the phosphorus lifecycle. Many of the current efforts recover it from end-stream wastes rather than preventing high concentrations in manure, for instance through lowering the phosphorus content of animal feed or separating the collection of human and animal urine and faeces at source (Cordell et al., 2011).

There is evidence that many agricultural soils already rich in legacy soil phosphorus (such as in Europe and China) can be largely maintained with recirculating phosphorus (from all by-products and losses), while agricultural soils which have not been fertilised as much historically (in particular in sub-Saharan Africa) need investments of mineral fertiliser to build up legacy phosphorus (Sattari et al., 2012). A 5R stewardship system has been proposed to help identify and deliver a range of integrated, cost-effective and feasible technological innovations to improve the efficiency and circularity of the use of phosphorus: realign inputs, reduce losses, recycle phosphorus in bioresources, recover phosphorus in waste, and redefine phosphorus in food systems (Withers et al., 2015).

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References
Aarts, F., 2016. Boeren in Peel en Kempen omstreeks 1800. Boekengilde, Enschede, the Netherlands.

Aref, S., Wander, M.M. and Sparks, D.L., 1997. Long-term trends of corn yield and soil organic matter in different crop sequences and soil fertility treatments on the morrow plots. Advances in Agronomy, Academic Press, 62: 153-197.

Beerling, E.A.M., Blok, C., Van der Maas, A.A. and Van Os, E.A., 2014. Closing the water and nutrient cycles in soilless cultivation systems. Acta Horticulturae, 1034: 49-55.

Berry, P.M., Sylvester-Bradley, R. and Berry, S., 2007. Ideotype design for lodging-proof wheat. Euphytica, 154: 165-179.

Bianchi, F., Booij, C.J.H. and Tscharntke, T., 2006. Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. Proc. R. Soc. B, 273: 1715-1727.

Bimüller, C., Mueller, C.W., von Lützow, M., Kreyling, O., Kölbl, A., Haug, S., Schloter, M., Kögel-Knabner, I., 2014. Decoupled carbon and nitrogen mineralization in soil particle size fractions of a forest topsoil. Soil Biology and Biochemistry, 78: 263-273.

Boel, M.F., 2008. Standing the test of time: the past, present and future of the CAP. Opening ceremony at the Accademia dei Georgofili, Florence, Italy.

Bos, J.F.F.P., Ten Berge, H.F.M., Verhagen, J. and Van Ittersum, M.K., 2017. Trade-offs in soil fertility management on arable farms. Agricultural Systems, 157: 292-302.

Brouwer, P., Schluepmann, H., Nierop, K.G.J., Elderson, J., Bijl, P.K., Van der Meer, I., De Visser, W., Reichart, G.-J., Smeekens, S., Van der Werf, A., 2018. Growing Azolla to produce sustainable protein feed: the effect of differing species and CO2 concentrations on biomass productivity and chemical composition Journal of the Science of Food and Agriculture.

Brouwer, P., Van der Werf, A., Schluepmann, H., Reichart, G.-J. and Nierop, K.G.J., 2016. Lipid yield and composition of Azolla filiculoides and the implications for biodiesel production. Bioenery Research, 9: 369-377.

Cassman, K.G., Dobermann, A., Walters, D.T. and Yang, H., 2003. Meeting cereal demand while protecting natural resources and improving environmental quality. Annu Rev Environ Resour, 28: 315–58.

Cordell, D., Rosemarin, A., Schröder, J.J. and Smit, A.L., 2011. Towards global phosphorus security: A systems framework for phosphorus recovery and reuse options. Chemosphere, 84: 747-758.

De Ponti, T., Rijk, B. and Van Ittersum, M.K., 2012. The crop yield gap between organic and conventional agriculture. Agricultural Systems, 108: 1-9.

Denison, R.F., 2007. When can intelligent design of crops by humans outperform natrual selection? In: Spiertz, J.H.J., Struik, P.C. and Van Laar, H.H. (Editors), Scale and complexity in plant systems research: gene-plant-crop relations. Springer-Verlag, Heidelberg, pp. 287-302.

Denison, R.F. and McGuire, A.M., 2015. What should agriculture copy from natural ecosystems? Global Food Security, 4: 30-36.

De Vries, M., Van Middelaar, C. E., and De Boer, I.J.M., 2015. Comparing environmental impacts of beef production systems: A review of life cycle assessments. Livestock Science, 178, 279–288.

Feller, C. and Beare, M.H., 1997. Physical control of soil organic matter dynamics in the tropics. Geoderma, 79: 69-116.

Ferris, C.P., McCoy, M.A., Patterson, D.C. and Kilpatrick, D.J., 2010. Effect of offering dairy cows diets differing in phosphorus concentration over four successive lactations: 2. Health, fertility, bone phosphorus reserves and nutrient utilisation. Animal, 4: 560-571.

Fischer, J., Manning, A.D., Steffen, W., Rose, D.B., Daniell, K., Felton, A., Garnett, S., Gilna, B., Heinsohn, R., Lindenmayer, D.B., MacDonald, B., Mills, F., Newell, B., Reid, J., Robin, L., Sherren, K. and Wade, A., 2007. Mind the sustainability gap. Trends Ecology and Evolution 22, 621-624.

Fischer, T., Byerlee, D. and Edmeades, G., 2014. Crop yields and global food security : will yield increase continue to feed the world? ACIAR monograph; no. 158. Australian Centre for International Agricultural Research, Canberra, XXI, 634 pp.

Fletcher, R. and Rammelt, C., 2017. Decoupling: a key fantasy of the post-2015 sustainable development agenda. Globalizations 14: 450-467.

Fujisaki, K., Chevallier, T., Chapuis-Lardy, L., Albrecht, A., Razafimbelo, T., Masse, D., Ndour, Y.B. and Chotte, J.-L., 2018. Soil carbon stock changes in tropical croplands are mainly driven by carbon inputs: A synthesis. Agriculture, Ecosystems & Environment, 259: 147-158.

Gagic, V., Kleijn, D., Baldi, A., Boros, G., Jorgensen, H.B., Elek, Z., Garratt, M.P.D., De Groot, G.A., Hedlund, K., Kovacs-Hostyanszki, A., Marini, L., Martin, E., Pevere, I., Potts, S.G., Redlich, S., Senapathi, D., Steffan-Dewenter, I., Switek, S., Smith, H.G., Takacs, V., Tryjanowski, P., Van der Putten, W.H., Van Gils, S. and Bommarco, R., 2017. Combined effects of agrochemicals and ecosystem services on crop yield across Europe. Ecol Lett, 20(11): 1427-1436.

Garnett T., Röös E. and Little D.C., 2015. Lean, green, mean, obscene…? What is efficiency? And is it sustainable? Animal production and consumption reconsidered, Food Climate Research Network (FCRN).

Garnett, T., Godde, C., Muller, A., Roos, E., Smith, P., De Boer, I.J.M., Ermgassen, E., Herrero, M., Van Middelaar, C.E., Schader, C. and Van Zanten, H.H.E., 2017. Grazed and confused? Ruminating on cattle, grazing systems, methane, nitrous oxide, the soil carbon sequestration question – And what it all means for greenhouse gas emissions. Oxford, UK: Food Climate Research Network (FCRN).

Giller, K.E., 2001. Nitrogen fixation in tropical cropping systems. CABI publishing, Wallingford, UK.

Giller, K.E., Rowe, E.C., de Ridder, N. and Van Keulen, H., 2006. Resource use dynamics and interactions in the tropics: Scaling up in space and time. Agricultural Systems, 88(1): 8-27.

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., De Bruijn, H., van Duin, R., Huijbregts, M.A.J., Lindeijer, E., Roorda, A.A.H., Van der Ven, B.L. and Weidema, B.P., 2002. Life Cycle Assessment: An operational guide to the ISO standards. Centrum voor Milieukunde – Leiden University. Kluwer Academic Publishers, Leiden, the Netherlands.

Hall, A.J. and Richards, R.A., 2013. Prognosis for genetic improvement of yield potential and water-limited yield of major grain crops. Field Crops Research, 143: 18-33.

Hallström E., Carlsson-Kanyama, A. and Börjesson, P., 2015. Environmental impact of dietary change: a systematic review. Journal of Cleaner Production 91:1–11.

Hassink, J., 1997. The capacity of soils to preserve organic C and N by their association with clay and silt particles. Plant and Soil, 191(1): 77-87.

Herridge, D., Peoples, M. and Boddey, R., 2008. Global inputs of biological nitrogen fixation in agricultural systems. Plant and Soil, 311(1): 1-18.

Hijazi, O., Munro, S., Zerhusen, B. and Effenberger, M., 2016. Review of life cycle assessment for biogas production in Europe. Renewable and Sustainable Energy Reviews, 54: 1291-1300.

Hijbeek, R., Cormont, A., Hazeu, G., Bechini, L., Zavattaro, L., Janssen, B., Werner, M., Schlatter, N., Guzmán, G., Bijttebier, J., Pronk, A.A., van Eupen, M. and Van Ittersum, M.K., 2017. Do farmers perceive a deficiency of soil organic matter? A European and farm level analysis. Ecological Indicators, 83: 390-403.

Hijbeek, R., Van Ittersum, M.K., Ten Berge, H.F.M., Gort, G., Spiegel, H. and Whitmore, A.P., 2016. Do organic inputs matter – a meta-analysis of additional yield effects for arable crops in Europe. Plant and Soil, 411(1-2): 293-303.

Janzen, H.H., 2006. The soil carbon dilemma: Shall we hoard it or use it? Soil Biology and Biochemistry, 38: 419-424.

Jurgilevich, A., Birge, T., Kentala-Lehtonen, J., Korhonen-Kurki, K., Pietikäinen, J., Saikku, L. and Schösler, H., 2016. Transition towards Circular Economy in the Food System. Sustainability 8(1): 69.

Karp, D.S. et al., 2018. Crop pests and predators exhibit inconsistent responses to surrounding landscape composition. Proceedings of the National Academy of Sciences of the United States of America, 115(33): E7863-E7870.

Khan N.A., Hussain, S., Ahmad, N., Alam, S., Bezabhi, M., Hendriks, W.H., Yu, P. and Cone J.W., 2015. Improving the feeding value of straws with *Pleurotus ostreatus*. Animal Production Science 55: 241-245.

Kinley, R.D., De Nys, R., Vucko, M.J., Machado, L. and Tomkins, N.W., 2016. The red macroalgae Asparagopsis taxiformis is a potent natural antimethanogenic that reduces methane production during in vitro fermentation with rumen fluid. Animal Production Science, 56(3).

Kirkby, C.A., Richardson, A.E., Wade, L.J., Batten, G.D., Blanchard, C. and Kirkegaard, J.A., 2013. Carbon-nutrient stoichiometry to increase soil carbon sequestration. Soil Biology and Biochemistry, 60: 77-86.

Kirkby, C.A., Richardson, A.E., Wade, L.J., Conyers, M. and Kirkegaard, J.A., 2016. Inorganic Nutrients Increase Humification Efficiency and C-Sequestration in an Annually Cropped. Plos One, 11(5): e0153698.

Koele, N., Kuyper, T.W. and Bindraban, P., 2014. Beneficial organisms for nutrient uptake. VFRC report, Virtual Fertilizer Research Center, Washington, D.C., 63 p.

Kuyper, T.W. and Giller, K.E., 2011. Biodiversity and ecosystem functioning below-ground. In: J.M. Lenne and D. Wood (Editors), Agribiodiversity management for food security. CABI, Wallingford, pp. 134-149.

Lammerts van Bueren, E.T., Struik, P.C., Van Eekeren, N. and Nuijten, E., 2018. Towards resilience through systems-based plant breeding. A review. Agronomy for Sustainable Development, 38(42), 1-21.

Long, S.P., Zhu, X.-G., Naidu, S.L. and Ort, D.R., 2006. Can improvement in photosynthesis increase crop yields? Plant, Cell and Environment, 29(3): 315-330.

Loveland, P. and Webb, J., 2003. Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. Soil and Tillage Research, 70: 1-18.

Magnani, C., Isaac, V.L.B., Correa, M.A. and Salgado, H.R.N., 2014. Caffeic acid: a review of its potential use in medications and cosmetics. Anal. Methods, 6(10): 3203-3210.

Mansholt, S., 1972. The Mansholt letter to Malfatti, February 1972, Brussel.

Meerburg, B.G., Vereijken, P.H., De Visser, W., Verhagen, J., Korevaar, H., Querner, E.P., De Blaeij, A.T. and Van der Werf, A., 2010. Surface water sanitation and biomass production in a large constructed wetland in the Netherlands. Wetlands Ecology and Management, 18(4): 463-470.

Miranda, N.D., Tuomisto, H.L. and McCulloch, M.D., 2015. Meta-analysis of greenhouse gas emissions from anaerobic digestion processes in dairy farms. Environmental Science & Technology, 49(8): 5211-5219.

Mondal, A.K., Sengupta, S., Bhowal, J. and Bhattacharya, D.K., 2012. Utilization of fruit wastes in producing single cell protein. International Journal of Science, Environment and Technology 1: 430-438.

Monteith, J.L., 1977. Climate and the efficiency of crop production in Britain. Philosophical transactions of the Royal Society of London. Series B, Biological sciences, 281: 277-294.

Mottet, A., De Haan, C., Falcucci, A., Tempio, G., Opio, C., and Gerber, P., 2017. Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. Global Food Security, 14, 1–8.

Oenema, O., Chardon, W., Ehlert, P., Van Dijk, K., Schoumans, O. and Rulkens, W., 2012. Phosphorus fertilisers from byproducts and wastes. Proceedings nr. 717, International Fertiliser Society, Leek, UK, 55 p.

O'Neill, D.W., Fanning, A.L., Lamb, W.F. and Steinberger, J.K., 2018. A good life for all within planetary boundaries. Nature Sustainability 1: 88-95.

Parodi, A., Leip, A., De Boer, I.J.M., Slegers, P.M., Ziegler, F., Temme, E.H.M., Herrero, M., Tumisto, H., Valin, H., Van Middelaar, C.E., Van Loon, J.J.A. and Van Zanten, H.H.E. Future foods: towards a sustainable and healthy diet for a growing population. Nature sustainability (in press).

Ponisio, L.C., M'Gonigle, L.K., Mace, K.C., Palomino, J., De Valpine, P. and Kremen, C., 2014. Diversification practices reduce organic to conventional yield gap. Proceedings of the Royal Society B: Biological Sciences, 282(1799): 20141396-20141396.

Poore, J. and Nemecek,T., 2018. Reducing food’s environmental impacts through producers and consumers. Science 360: 987-992.

Powlson, D.S., Riche, A.B., Coleman, K., Glendining, M.J. and Whitmore, A.P., 2008. Carbon sequestration in European soils through straw incorporation: limitations and alternatives. Waste Management, 28(4): 741-746.

Pribyl, D.W., 2010. "A critical review of the conventional SOC to SOM conversion factor. Geoderma, 156(3-4): 75-83.

Ratnadass, A., Fernandes, P., Avelino, J. and Habib, R., 2012. Plant species diversty for sustainable management of crop pests and diseases in agroecosystems: a review. Agronomy for Sustainable Development, 32: 273-303.

Reijneveld, A., Van Wensem, J. and Oenema, O., 2009. Soil organic carbon contents of agricultural land in the Netherlands between 1984 and 2004. Geoderma, 152(3-4): 231-238.

Rogers, C. and Oldroyd, G.E., 2014. Synthetic biology approaches to engineering the nitrogen symbiosis in cereals. Journal of Experimental Botany, 65(8): 1939-46.

Sage, R.F., 2016. A portrait of the C4 photosynthetic family on the 50th anniversary of its discovery: species number, evolutionary lineages, and Hall of Fame. Journal of Experimental Botany, 67: 4039-4056.

Sattari, S.Z., 2014. The legacy of phosphorus: agriculture and future food security. PhD thesis, Wageningen University, Wageningen, the Netherlands, 210 pp.

Sattari, S.Z., Bouwman, A.F., Giller, K.E. and Van Ittersum, M.K., 2012. Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle. Proceedings of the National Academy of Sciences of the United States of America, 109(16): 6348-6353.

Schils, R., 2012. 30 vragen en antwoorden over bodemvruchtbaarheid. Alterra, Wageningen UR, Wageningen, the Netherlands, pp. 143.

Schjønning, P., Jensen, J.L., Bruun, S., Jensen, L.S., Christensen, B.T., Munkholm, L.J., Oelofse, M., Baby, S., Knudsen, L., 2018. The Role of Soil Organic Matter for Maintaining Crop Yields: Evidence for a Renewed Conceptual Basis. Advances in Agronomy, 150: 35-79.

Schoumans, O.F., Bouraoui, F., Kabbe, C., Oenema, O. and Van Dijk, K.C., 2015. Phosphorus management in Europe in a changing world. Ambio, 44 Suppl 2: S180-S192.

Schröder, J.J., 2014. The position of mineral nitrogen fertilizer in efficient use of nitrogen and land: A Review. Natural Resources, 5: 936-948.

Schröder, J.J., Aarts, F., Ten Berge, H.F.M., Van Keulen, H. and Neeteson, J.J., 2003. An evaluation of whole-farm nitrogne balances and related indices for efficient nitrogen use. European Journal of Agronomy, 20: 33-44.

Schröder, J.J., Bannink, A. and Kohn, R., 2005. Improving the efficiency of nutrient use on cattle operations. In: E. Pfeffer and A.N. Hristov (Editors), Nitrogen and phosphorus nutrition of cattle. CABI, Wallingford, UK, pp. 255-279.

Schröder, J.J. and Sorensen, P., 2011. The role of mineral fertilizers in optimising the use efficiency of manure and land. Proceedings 701, International Fertiliser Society, Leek, UK, 20 p.

Schröder, J.J., Uenk, D. and Hilhorst, G.J., 2007. Long-term nitrogen fertilizer replacement value of cattle manures applied to cut grassland. Plant and Soil, 299: 83-99.

Seufert, V., Ramankutty, N. and Foley, J.A., 2012. Comparing the yields of organic and conventional agriculture. Nature, 485(7397): 229-32.

Sparling, G., Parfitt, R., Hewitt, A. and Schipper, L., 2003. Three approaches to define desired soil organic mattter contents. Journal of Environmental Quality, 32: 760-766.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., De Vries, W., De Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B. and Sörlin, S., 2015. Planetary boundaries: Guiding human development on a changing planet. Science 347(6223).

Tamayo Tenorio, A., Kyriakopoulou, K.E., Suarez-Garcia, E., Van den Berg, C. and Van der Goot, A.J., 2018. Understanding differences in protein fractionation from conventional crops, and herbaceous and aquatic biomass - Consequences for industrial use. Trends in Food Science & Technology, 71: 235-245.

Tamburini, G., De Simone, S., Sigura, M., Boscutti, F., Marini, L. and Kleijn, D., 2016. Conservation tillage mitigates the negative effect of landscape simplification on biological control. Journal of Applied Ecology, 53(1): 233-241.

Tillman, D. and Clark, M., 2014. Global diets link environmental sustainability and human health. Nature 515: 518-522.

Tittonell, P., 2013. Farming Systems Ecology -Towards ecological intensification of world agriculture. Inaugural lecture, Wageningen University, the Netherlands, 44p.

Trindade, L.M., Dolstra, O., Van Loo, E.N. and Visser, R.G.F., 2010. Plant Breeding and its role in a Biobased Economy. In: H. Langeveld, J. Sanders and M. Meeusen (Editors), The Biobased Economy: Biofuels, Materials and Chemicals in the Post-oil Era. Earthscan Publications, London, pp. 67-82.

Tufvesson, L.M., Lantz, M. and Börjesson, P., 2013. Environmental performance of biogas produced from industrial residues including competition with animal feed – life-cycle calculations according to different methodologies and standards. Journal of Cleaner Production, 53: 214-223.

Van der Burgt, G.J., Rietema, C. and Bus, M., 2018. Planty Organic 5 year: evaluation of soil fertility, nitrogen dynamics and production. Publication number 2018-004 LbP, Louis Bolk Institute, Bunnik, The Netherlands, 38 p.

Van der Goot, A.J., Pelgrom, P.J.M., Berghout, J.A.M., Geerts, M.E.J., Jankowiak, L., Hardt, N.A., Keijer, J., Schutyser, M.A.I., Nikiforidis, C.V. and Boom, R.M., 2016. Concepts for further sustainable production of foods. Journal of Food Engineering, 168: 42-51.

Van der Velden, N. and Smit, P., 2017. Energiemonitor van de Nederlandse glastuinbouw 2016, Wageningen Economic Research, Wageningen UR, the Netherlands.

Van Gils, S., 2017. It depends: effects of soil organic matter in aboveground-belowground interactions in agro-ecosystems. PhD thesis, Wageningen University, Wageningen, The Netherlands, 176 pp.

Van Grinsven, H. and Bleeker, A., 2017. Evaluatie Meststoffenwet 2016: Syntheserapport. 2258, PBL Planbureau voor de Leefomgeving, Den Haag, the Netherlands.

Van Groenigen, J.W., van Kessel, C., Hungate, B.A., Oenema, O., Powlson, D.S., van Groenigen, K.J., 2017. Sequestering Soil Organic Carbon: A Nitrogen Dilemma. Environmental Science & Technology, 51(9): 4738-4739.

van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance—A review. Field Crops Research, 143: 4-17.

Van Ittersum, M.K. and Rabbinge, R., 1997. Concepts in production ecology for analysis and quantification of agricultural input-output combinations. Field Crops Research, 52: 197-208.

Van Kernebeek, H.R.J., Oosting, S.J., Van Ittersum, M.K., Bikker, P. and De Boer, I.J.M., 2015. Saving land to feed a growing population: consequences for consumption of crop and livestock products. The International Journal of Life Cycle Assessment, 21(5): 677-687.

Van Kernebeek, H.R.J., Oosting, S.J., Van Ittersum, M.K., Ripoll Bosch, R. and De Boer, I.J.M., 2018. Closing the phosphorus cycle in a food system: insights from a modelling exercise. Animal 12: 1755-1765.

Van Zanten, H.H.E., Mollenhorst, H., Klootwijk, C.W., Van Middelaar, C.E. and De Boer, I.J.M., 2016. Global food supply: Land use efficiency of livestock systems. The International Journal of Life Cycle Assessment, 21, 747–758.

Van Zanten, H.H.E., Herrero, M., Van Hal, O., Röös, E., Muller, A., Garnett, T., Gerber, P.J., Schader, C. and De Boer, I.J.M., 2018a. Defining a land boundary for sustainable livestock consumption. Invited review in Global Change Biology, 24: 4185-4194.

Van Zanten, H.H.E., Van Ittersum, M. and De Boer, I.J.M., 2018b. The role of animals in a circular food system. Global food security (in preparation).

Vanlauwe, B., Descheemaeker, K., Giller, K.E., Huising, J., Merckx, R., Nziguheba, G., Wendt, J., Zingore, S., 2015. Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. Soil, 1(1): 491-508.

Verhoog, D., 2016. Het Nederlandse agrocomplex 2015, LEI Wageningen University & Research centre, Wageningen, the Netherlands.

Verloop, K., 2013. Limits of effective nutrient management management in dairy farming: analyses of experimental farm De Marke. PhD thesis, Wageningen University, the Netherlands, 192 p.

Vermeulen, P.C.M., Raaphorst, M.G.M. and Eveleens, B., 2017. Quantitative Information on the Dutch Greenhouse horticulture 2016-2017: key figures on vegetables, cut flowers, pot and bedding plants crops, Wageningen UR Greenhouse Horticulture, the Netherlands.

Wang, P., Khoshravesh, R., Karki, S., Tapia, R., Balahadia, C.P., Bandyopadhyay, A., Quick, W.P., Furbank, R., Sage, T.L., Langdale, J.A., 2017. Re-creation of a key step in the evolutionary switch from C3 to C4 leaf anatomy. Current Biology, 27(21): 3278-3287.

Withers, P.J., Van Dijk, K.C., Neset, T.S., Nesme, T., Oenema, O., Rubaek, G.H., Schoumans, O.F., Smit, B., Pellerin, S., 2015. Stewardship to tackle global phosphorus inefficiency: The case of Europe. Ambio, 44 Suppl 2: S193-S206.

Yang, H.S. and Janssen, B.H., 2000. A mono-component model of carbon mineralization with a dynamic rate constant. European Journal of Soil Science, 51: 517-529.

Yang, H.S. and Janssen, B.H., 2002. Relationship between substrate initial reactivity and residues ageing speed in carbon mineralization. Plant and Soil, 239: 215-224.

Yin, X. and Struik, P.C., 2015. Constraints to the potential efficiency of converting solar radiation into phytoenergy in annual crops: from leaf biochemistry to canopy physiology and crop ecology. Journal of Experimental Botany, 66(21): 6535-6549.

Yin, X. and Struik, P.C., 2017. Can increased leaf photosynthesis be converted into higher crop mass production? A simulation study for rice using the crop model GECROS. Journal of Experimental Botany, 68(9): 2345-2360.

Yu, Y., Stomph, T.-J., Makowski, D. and Van der Werf, W., 2015. Temporal niche differentiation increases the land equivalent ratio of annual intercrops: A meta-analysis. Field Crops Research, 184: 133-144.

Zu Ermgassen, E.K.H.J., Phalan, B., Green, R.E. and Balmford A., 2016. Reducing the land use of EU pork production: where there's swill, there's a way. Food Policy 58: 35-48.

Zijlstra, R. and Beltranena, E., 2013. Swine convert co-products from food and biofuel industries into animal protein for food. Animal Frontiers, 3, 48–53.