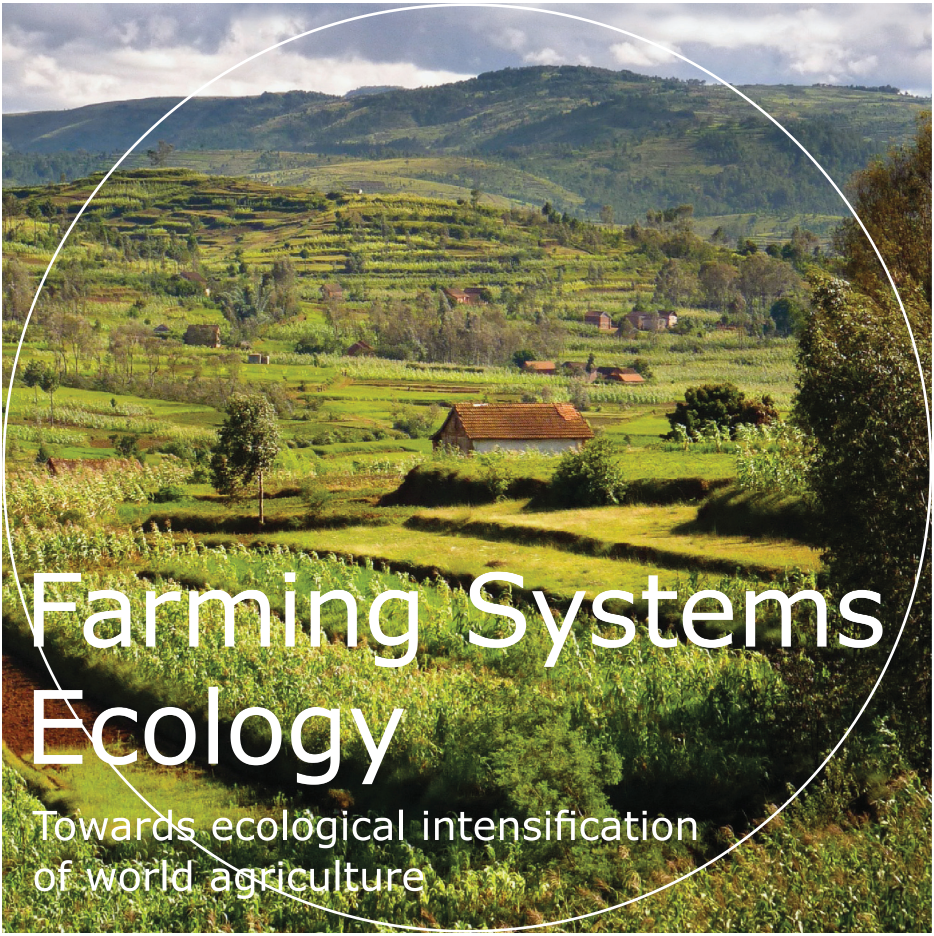

Farming Systems Ecology

Towards ecological intensification of world agriculture

Prof. dr *ir.* Pablo A. Tittonell

Inaugural lecture upon taking up the position of Chair in Farming Systems Ecology at Wageningen University on 16 May 2013

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Rector Magnificus, family, friends, colleagues, ladies and gentlemen,

The on-going international debate on the future of agriculture and its ability to meet expected food demands has recently reached the Dutch media thanks to aired declarations by fervent proponents of agricultural intensification. Their arguments typically stem from a simple question that is posed time and again when it comes to debating alternatives to current agriculture: "*Can organic agriculture feed the world?*" This question is inappropriate, because it leads to a fruitless debate in which parties take to their side very strongly, get emotional and miss the opportunity to learn from each other. The question is also misleading, because by assuming that world food security can be solved through a single set of principles and agricultural practices it prevents any opportunity for out-of-the-box thinking. And, it is fundamentally irrelevant. To demonstrate this, let's just turn it around: *Can conventional agriculture feed the world?*

This is obviously a rhetorical question, because we know that the answer is no. To verify that the current model of conventional agriculture is unable to feed the world it suffices to look at the latest report on food insecurity published jointly by the UN Food and Agriculture Organisation (FAO), the World Food Programme (WFP) and the International Fund for Agricultural Development (IFAD) (State of Food Insecurity in the World 2012). It is estimated that nearly 870 million people, or one in eight, were suffering from chronic undernourishment in 2010-2012. We often hear arguments such as 'Food production worldwide is sufficient, the problem resides in its distribution'. I disagree. I believe that production and access to food cannot be treated separately, because they are strongly interdependent.

The right question to ask ourselves in order to nourish a more fruitful debate is then: *Why does conventional agriculture fail to feed the world?* There are several partial explanations to this, but the more fundamental problems are:

I. Worldwide, food is not produced where it is mostly consumed or needed;
II. Chemical, genetic and energy inputs used in conventional agriculture are not affordable to all farmers;
III. Current trends in diets and food habits are not compatible with the sustainable use of global resources;
IV. Market chains are ineffective in ensuring access to food for everyone and lead to substantial food waste.

If our aim is to design agricultural systems (whether conventional, organic, or something in between) that produce enough to feed the world now and in the future we need to work on these four sets of problems.

I postulate that a more equitable model of food production, able to propend to equity across world regions and generations, can be developed through an *ecological intensification* of current agriculture, both in the North and in the South. But this is not enough. Although food, fibre and energy production are fundamental functions of agroecosystems, current and future life on the planet demand an array of other ecological services from agricultural landscapes. Beyond delivering and benefiting from ecological services of provision, support and regulation, such as nutrient cycling, water capture or biological pest control, multifunctional landscapes are expected to preserve natural habitats for biodiversity, cultural inheritance and diverse rural livelihoods. Ecological intensification may in many cases constitute the way to break through the typical trade-offs between productivity and conservation, or between livelihoods and ecosystem services.

During the first part of this lecture, I will focus on the sets of problems outlined above, presenting a minimum of quantitative evidence to illustrate each point. The second part of the lecture will address the opportunities and challenges associated with the ecological intensification of current agriculture and will present examples that illustrate such opportunities and challenges worldwide. The third and last part of this lecture will introduce Farming Systems Ecology as an integrative, multi-disciplinary approach in research to contribute to the analysis and design of ecologically intensive, sustainable agricultural production systems.

Why does conventional agriculture fail to feed the world?

Unequal access to resources and diverging productivity worldwide

Currently, about half of the food produced in the world comes from smallholder farms, where yields are very low. Of the total world production of cereals, coarse grains, roots and tubers, pulses and oil crops, around 2.8 billon tonnes are produced in developing countries, against 1.8 billon tonnes in developed countries (FAO, 2011; http://faostat.fao.org/). Not all farmers in the developing world are smallholders, but small to medium family farms account for about three quarters of total production in developing countries. Yet, smallholder farmers in most of these countries cannot afford the high levels of external input used in conventional agriculture. Figure 1 illustrates the widening cereal yield gap between example countries in North and in the South since the onset of the 'green revolution'. I deliberately chose not to plot The Netherlands because the range of fertiliser use intensity would have had to be expanded to twice its current value. While world average yields of mayor food crops increased by a factor two in the last 50 years, the total amount of external nitrogen brought in through fertilisers increased seven times in the same period, the amount of phosphorus three times and the amount of water used for irrigation doubled (Foley et al., 2005). The most realistic estimates of food demand by 2050, considering changes in diets and population growth indicate that daily caloric requirements will increase from 19 to 33 PCal per day, worldwide. Or, a 70% increase. Looking at the future, can we envisage replicating the green revolution as it happened in the past? Could we increase nitrogen fertiliser use even further, and for how long?

The intensification trap

The picture is even more deceiving when it comes to energy. Of the total amount of energy contained in one grain of maize produced in high input agriculture about 70% comes from fossil fuels. This somewhat classical figure published by Pimentel and Giampietro in 1994 is only indicative of the high degree of dependency on fossil energy sources of current agriculture. Since the onset of the green revolution, energy inputs in agriculture increased 50 times compared to traditional agriculture. Feeding an average person in the developed world costs about 1500 litres of oil equivalents per year. More than 30% of this energy is used in the manufacture of chemical fertilisers, 19% for the operation of field machinery and 16% for transport. Production of one kilogram of nitrogen contained in fertiliser requires the equivalent energy contained in 1.4 to 1.8 litres of diesel fuel[1]. To feed 9 billon people in 2050 with the current production means of conventional agriculture we will need

[1] Without considering the natural gas feedstock.

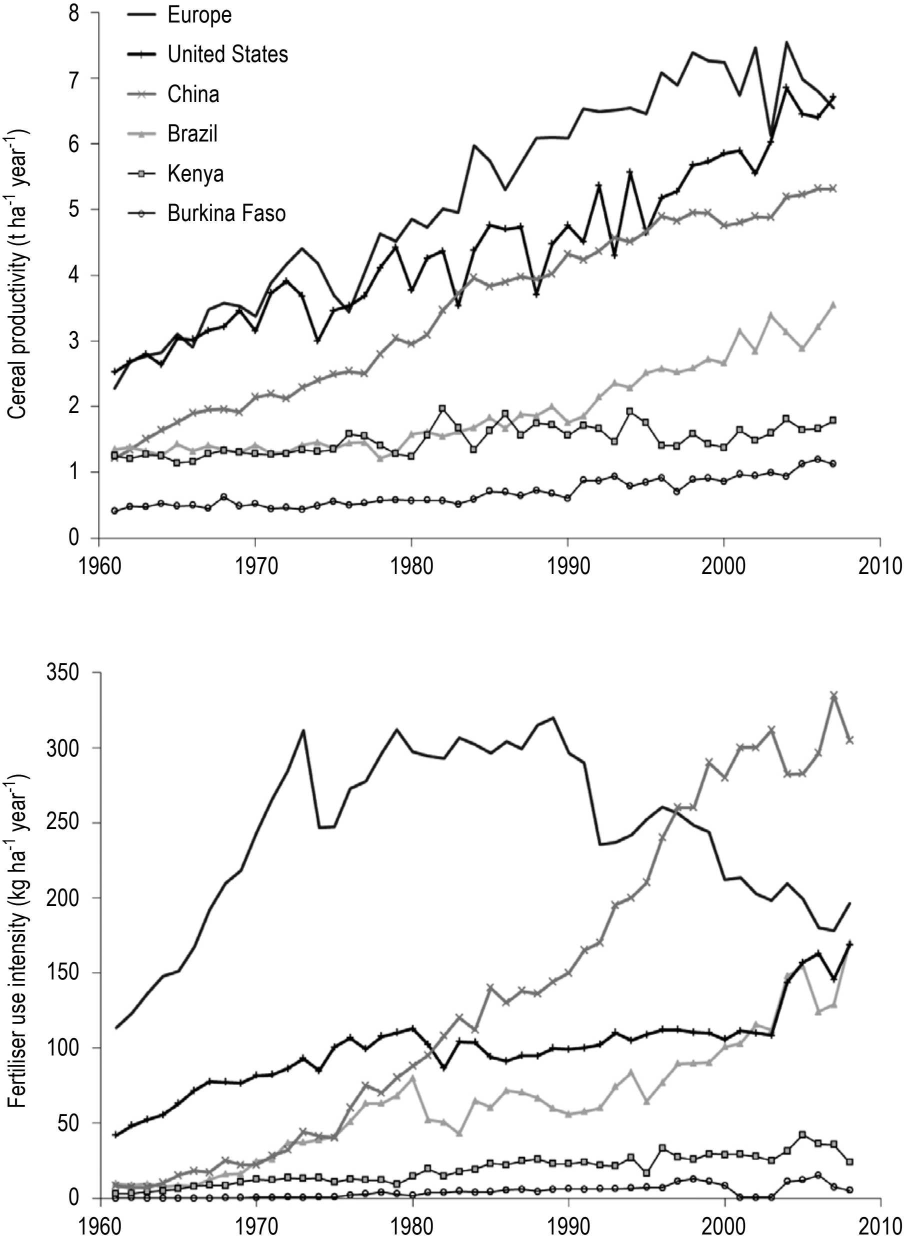

Figure 1 Average cereal productivity and fertiliser use intensity (total fertiliser use over area cropped) at national level for selected countries between 1961 and 2008. Source: FAOstat

ca. 113,000 Million barrels[2] of oil per year, close to 8% of the total world reserve estimated at 1,481,526 Million barrels. In other words, producing food for 9 billion people with conventional agriculture will exhaust our global oil reserves in about 12 years. Globally, we are running towards an intensification trap that we seem to be unable (or unwilling) to perceive. Blind faith in societal resilience, assuming that alternatives will be found and new technologies developed when resources become really scarce, overlooks the environmental cost that such a strategy may have (i.e., are we gong to turn all the fossil carbon stored in oil reserves into atmospheric CO_2 before we start changing technologies?).

Hidden costs

In developed countries, society subsidises conventional agriculture so that farmers are able to purchase the large amounts of fertilisers and pesticides they use or to fuel their tractors. Then, society pays again for the cost of cleaning the ground water from excess nitrates associated with fertiliser use. The costs in public health caused by the use of pesticides were calculated in a UN report to be around 10 billion euro per year – without considering the costs incurred through biodiversity loss when pesticides are applied (e.g., the value of services provided by arthropods worldwide is estimated at 400 billion us$ $year^{-1}$ through biological pest control and at 117 billon us$ $year^{-1}$ through pollination). Zoonosis and resistance to antibiotics associated with intensive livestock also lead to high societal costs. Every day, three to four farmers go bankrupt in The Netherlands because they are unable to repay the debts they acquired to be able to intensify their production. Thus the argument that conventional agriculture produces affordable food might be looked upon quite differently by future generations. If we take a systems perspective and we internalise all the above-mentioned costs in the calculation of food prices, the price difference between conventional and organic food will narrow down, disappear or, in some cases, become more favourable for organic food.

Obesity outweighs hunger

Meeting future (and current!) food demands requires a gradual convergence between supply and demand. It will be impossible to feed the world with organic farming – or with conventional farming – without rebalancing the proportion of animal protein in our diets. The State of Food Insecurity report of 2012 mentioned earlier estimates that of the 870 million people suffering from chronic undernourishment in 2010-2012 the vast majority of them (852 million) live in developing countries. Yet, for the first time in human history, obesity outweighs hunger. The current number of overweight

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[2] 1 barrel = 119.2 litres.

people in the world is estimated at 1300 million (WHO Global InfoBase, 2012). About 65% of the world population live in countries where overweight and obesity kill more people that underweight. These trends reveal not just problems in the distribution of resources or inequity in access to food worldwide, but also the effect of current patterns of food consumption worldwide, notably the increasing intake of energy-dense foods that are high in fat, salt and sugars but low in vitamins, minerals and other micronutrients (WHO Global InfoBase, 2012). Over-consumption of meat and milk products not only lead to obesity and other forms of health risks, but they pose a serious threat to global sustainability, as has been extensively documented in the FAO (2006; updated in 2012) Livestock's Long Shadow report.

Waste causes hunger

Due to poor practices in harvesting, storage and transportation, as well as market and consumer wastage, it is estimated that 30 to 50% (or 1.2 – 2 billion tonnes) of all food produced never reaches the human stomach (Gustavsson et al., 2011; IMECHE, 2013). Wastes may occur post harvesting, post processing, and post consumption. In SE Asia, for example, postharvest losses of rice can range from 40 to 80%. In India, 21 million tonnes of wheat are wasted every year due to poor storage and distribution systems. To assess the order of magnitude of such a figure, it suffices to compare it against the total annual production of wheat in The Netherlands, of 1.2 million tonnes per year. Every year, India looses the equivalent of 18 times the total production of all Dutch wheat farmers considered together[3].

Environmental externalities

It is not my intention to make an account here of all environmental impacts associated with conventional agriculture. This has been well documented, particularly in the critical report commissioned by the top secretariat of the Consultative Group on International Agricultural Research (CGIAR) more than a decade ago (Maredia and Pingalli, 2001). This report provided quantitative estimates of the negative externalities of productivity-enhancing crop technologies in terms of loss of genetic diversity, salinity and water logging (45 million ha worldwide), changes in the level of water table, loss of soil fertility/erosion, water pollution, air pollution, food contamination, impacts on human and animal health and effects on

[3] The argument often heard of that cereal productivity in The Netherlands needs to increase further 'in the name of global food security' is certainly untenable. In other words, if all Dutch wheat farmers go organic and their productivity decreases by 20 or 30% the consequences for global food security will be negligible. However, the new agro-ecological knowledge generated throughout such hypothetical transition, supported by public and private research, would be invaluable for the future of global food security.

pest populations. A recent Europe wide study in which Wageningen University played a central role (Geiger et al., 2010) documents the persistent negative effects of pesticides on biodiversity and on the natural potential for biological control. In other words, the study shows how pesticide use and loss of species diversity leads to greater dependence on pesticides on European farmland – a clear positive feedback.

The two best-known example sites to show what the green revolution was able to achieve in terms of increasing agricultural productivity, the Yaqui valley in Mexico (the birthplace of the green revolution) and the Punjab in South Asia, are also the most conspicuous examples of the extent of environmental damage associated with this form of agriculture. And they are also good examples of the impact of conventional agriculture on human health. Globally, 3 million cases of pesticide poisoning are registered each year, resulting in 220,000 deaths. Incidence levels of acute poisoning vary from 18 to 180 cases per 100,000 permanent rural workers per year (WHO, 2012). Figures on incidence of acute pesticide poisoning among rural residents are more elusive. A study in Belize estimated a total of 17 cases per 100,000 residents. Cases of pesticide poisoning associated with airplane applications over large areas cultivated to soya, often adjacent to human settlement, make it to the press every now and then in countries like Argentina or Brazil. Yet, in spite of 500 million kg of pesticide active ingredient applied every year, yield losses due to major pests in most crops fluctuate around 20-30% - a symptom of the environmental crisis affecting agriculture (Altieri, 2002).

Sustainability and the tyranny of CO_2

Since the term sustainability was coined back in the 1970s it has always been associated with the simultaneous and long-term fulfilment of environmental, economic and social aspirations. Later on, multiple criteria sustainability assessment frameworks were proposed that considered a number of relevant system properties simultaneously (e.g., the MESMIS framework – Lopez Ridaura et al., 2002). Yet, meanwhile, more reductionist approaches have also been recurrent. Since the 1990s, for example, there has been a tendency to translate everything into us$. Attempts to value environmental services are often based on concepts such as ‘willingness to pay’ or opportunity costs, or farmer decisions are studied by assuming utility functions and rational optimisation (i.e., *Homo economicus*), etc. Likewise, today it seems that everything needs to be translated into CO_2 equivalents: To decide whether a practice or produce is sustainable or not, it seems to be enough to look at the CO_2 emission equivalents associated with such practice or produce. Without understating the importance of CO_2 emissions and their effect on global warming, I find such reductionism rather worrisome.

After having developed a wealth of sophisticated methodology for integrated assessments (e.g., van Ittersum et al., 2008) or multiple criteria analysis (e.g., Romero and Rehman, 2003), why are we still using single-criterion assessments? The risk of using methods such as the carbon footprint, for example, is not only that their results are extremely sensitive (they are mostly linear relationships, no interactions, no feedbacks) to parameters estimated through coarse assumptions, but that they can be used to prove almost anything you wish disregarding the broader system picture. This can be dangerous. Let us examine the example of the *plofkip* in The Netherlands, which is currently under debate. It is often argued that, 'in the name of the environment', chickens should be kept in cages that are as small as possible. In this way productivity per animal – and per area of housing facility – increases and consequently the CO_2 emission equivalents per kilogram of chicken meat are reduced. More intensive is more sustainable, is the claim, but this is really an irrelevant argument.

It is true that CO_2 emissions per kg of caged chicken meat are less than per kg of free range chicken meat; perhaps 20 to 30% by one estimate (Table 1 – note how variable the estimates can be!). But this is just one single indicator of sustainability (cf. Pelletier, 2008). This indicator says nothing about animal welfare, dependence on antibiotics, working conditions of poultry workers, level of indebtedness of poultry farmers, or chicken meat quality. In any case, CO_2 emissions associated with poultry consumption in The Netherlands represent only about 1% of the total emissions of the Dutch economy – using upper range emissions estimations[4]. Energy, industry and transport account for most of the emissions; agriculture as a whole accounts for about 13% (Olivier et al., 2012). Placing chickens in small cages does not contribute much to reducing emissions in The Netherlands. Thus, if the reason to cage chickens is driven by real concerns about global warming then the discussion is headed in the wrong direction. To seriously reduce CO_2 emissions in The Netherlands, we should cycle more, fly less or set our heaters 1°C lower at home. That will have far greater impact on reducing CO_2 emissions than keeping chickens in small cages.

[4] I assumed emissions per kg of bone-free chicken meat of 6.9 CO_2-equivalents. Total consumption of chicken in The Netherlands is 313,400 tonnes per year (19 kg per capita).

Table 1 Emissions of greenhouse gasses per kg bone-free meat at the farm gate from three different published studies (from Sonesson et al., 2009)

Author	**CO_2-equivalents kg^{-1} meat**
Thynelius (2008)	1.5
Cederberg et al. (2009)	2.5
Williams et al. (2006) Conventional	6.1
Williams et al. (2006) Free range	7.3

All the evidence presented above, which is only partial, indicates that the hegemonic model of global agriculture is obsolete. It is unable to feed the world, it is thermodynamically and socially unsustainable, it pollutes the environment, it is directly and indirectly responsible for biodiversity loss, it impacts seriously on human health. Even if we put values and ethics aside, the hard evidence shows that conventional agriculture is simply not able to feed the world today, and even less so in 50 years time. We need alternatives.

Intensify in the South, 'extensify' in the North, detoxify everywhere

Ecological intensification

Can organic agriculture feed the world? Currently, about 50% of the food consumed worldwide is produced by low-input, smallholder subsistence systems that are not far from what are known as the 'organic' standards. Some of such systems rely on local genetic resources, institutions and traditional practices that in some cases may be millennia old. These systems are often termed 'organic by default' because they use very few or no external inputs. But the analysis done on conventional agriculture in the previous section applies also to current smallholder agriculture. For all the genuine attractiveness of traditional practices and natural resource management systems, it is obvious that they are unable to feed a currently increasing urban population in developing countries. Thus, intensification is urgently needed. But, what form of intensification?

Food production can increase and at the same time be sustainable through the ecological intensification of current agriculture, making intensive and smart use of the natural functionalities that ecosystems offer. Current levels of investment in terms of assets, labour and external inputs and current levels of attainable productivity differ widely worldwide (Figure 1). Contextual demographic and socio-political pressures in the South condemn smallholder systems to very resilient poverty traps (e.g., Tittonell, 2011), while economic pressures push farmers to unsustainable overinvestment and indebtedness in the North (Van der Ploeg, 2009). Agriculture alone cannot solve poverty in places like sub-Saharan Africa, but it can contribute to alleviate the crude reality of thousands of rural families. I hypothesise that serious investment in research on ecological intensification in the South and on ecological 'extensification' in the North will allow moving from trajectory 1 to trajectory 2 in Figure 2. A couple of years ago, and in response to a request from the European Society for Agronomy of which I am a member, we sat together with a group of agricultural scientists from different fields to delineate the areas where public investment in research and education should be targeted to make this happen (Doré et al., 2010). I will not go through all that in detail, but present a few pieces of evidence to sustain my hypotheses.

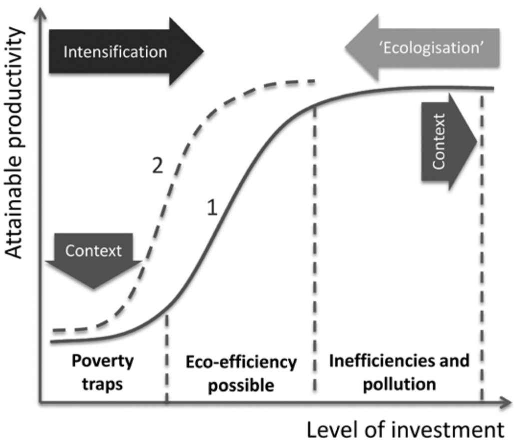

Figure 2 Attainable agricultural productivity per unit land or person as a function of the level of resource investment (capital, labour) possible. See text for explanation

Yield gaps vs. research investment gaps

Two independent studies published recently by two different science groups –not necessarily proponents of organic farming – from North America and Europe revealed that the current average yield gap between organic and conventional yields is merely 20%. This figure varies for different crop types and crop species, and is not constant across all levels of productivity. Both studies used worldwide data. One of these studies was done at Wageningen by De Ponti et al. (2012) and published in Agricultural Systems, while the other one was done by Seufert et al. (2012) and published in Nature. A 20% yield gap means that on the same area of land in which you can harvest 6 t ha^{-1} of conventional wheat, with pesticides, fungicides and mineral fertilisers you could still harvest about almost 5 t ha^{-1} of wheat grown organically. Prof. Martin van Ittersum from the Plant Production Systems group kindly provided me with the database used in the analysis by De Ponti et al. (2012). Figure 3A shows the distribution of organic versus conventional cereal yields around a 1:1 line, indicating that yield gaps were wider in higher productivity environments. For the first quartile, which corresponds to conventional yields lower than 3.3 t ha^{-1} the average yield gap was 16%, or 0.4 t grain ha^{-1} in absolute terms (Fig. 3 B). Only a few observations in the database corresponded to developing countries. The average gap between organic and conventional cereal yields in these cases was 10%.

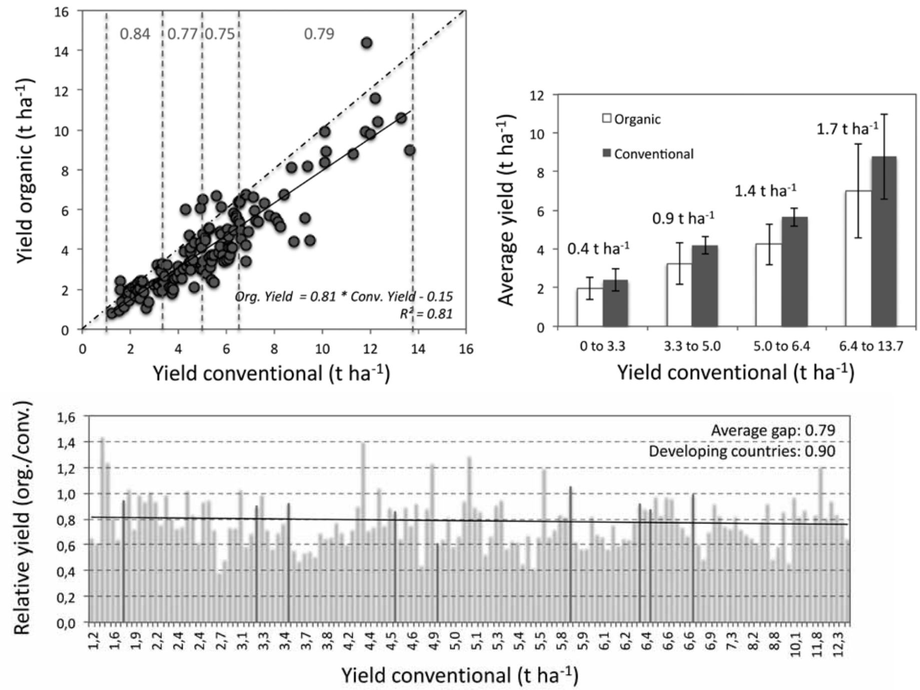

Figure 3 The gap between organic and conventional cereal yields (data source: De Ponti et al., 2012)

Most strikingly, the gap in terms of investments on research, technology and knowledge generation between organic and conventional farming is far greater than 20%. I do not have yet a solid estimate; this is one of our current themes of research at Farming Systems Ecology. My guess, is that the research investment gap between organic and conventional agriculture since the onset of the green revolution, considering both public and private sector investments should be around 90 to 95%. Such figures are difficult to estimate because knowledge generated by research cannot always be exclusively associated with just one form of agriculture. Knowledge on symbiotic nitrogen fixation or on ecological interactions between populations of pests and their natural enemies, coming from biology, is useful to both forms of agriculture but mostly used in organic farming. Over the last ten years or so, the Dutch government stipulated that 10% of the public research budget for agriculture should be spent on organic farming research. This policy has now been discontinued due to the new focus on investing in top-sectors, of which organic food and farming is not considered to be one. Yet, the government committed to invest € 20 million over the next 4 years. Although this sets a very good example worldwide, the investment in public research is meagre when compared with the annual investment in research that a company like Monsanto makes, e.g. of us$ 980 million, or 10% of their sales in 2012 (www.monsanto.com/investors).

Most of the investment in organic farming innovation is actually private: individuals or groups of organic farmers themselves generate most of the knowledge they use, sometimes through trial and error, and facing high production and financial risks. Multinational companies will not invest in organic farming, unless there is something to be manufactured and sold in it, something to make money with. This is not a value-judgement; it is simply natural to private companies to aim for profit. Most of the technologies used in organic farming are knowledge-intensive technologies based on processes, and much less on inputs. Most of these processes are public knowledge, they are public goods, they cannot be commercialised. This is what creates the investment gap between both forms of agriculture. I believe that the role of public funding, for the interest of society as a whole, should be to compensate for such gap.

Crop rotation and productivity gaps

An average yield gap of 20% between organic and conventional agriculture does not imply that world food production will decrease by just 20% if the whole planet turns towards organic farming from one year to the next. Nor is it true that we would need six times more land to produce the same amount of food we produce today under organic farming. Both affirmations are based on narrow visions and uninformed, quick assumptions. Organic farming relies on crop rotations to manage nutrient cycling and to break the reproductive cycle of pests, weeds and diseases. On a farm, crop rotation ensures diversity in space, in time, in resource and labour allocation and in market opportunities, thereby reducing risks. Crops species and crop types are rotated more often in a single field under organic than under conventional management – where they may be often grown as monocultures. The average productivity (t ha^{-1} $year^{-1}$) of any particular crop results from dividing its average yield by its return time in the rotation. This means that the gap in the average productivity of a certain crop in a conventional vs. an organic rotation may be wider than the crop yield gap, because a single crop returns less often in an organic rotation.

Crop rotation does not necessarily mean that the field will be empty or cropped to non-food species when the main crop is not there. For example, most organic farmers in Europe manage mixed farms, integrating crops and livestock, and often also horticulture. Typical rotations and associations of cereals and legumes on these farms are able to yield protein-rich grain that is used in the formulation of feeds for their own animals or for the market. Manure collected from animals fed in this way contains nutrients in forms that are less prone to losses to the environment, thereby increasing recycling and nutrient retention efficiencies in the system. Rotations of crops and grass-legume pasture produce biomass to feed animals, contribute to restoring soil organic matter and soil nitrogen, and to break the cycle of pest, diseases and parasites of both animals and crops. Cultivar mixtures of cereal or root crops contribute to stabilising yields over time and make more efficient use of resources. On such farms, individual crop yields, milk yields and meat production are adequate or sometimes above average[5], they generate respectable jobs in rural areas, environmental services of local and global relevance, and the farm as a whole is less vulnerable to climatic or market volatility.

Thus, organic farming as a means for the ecological intensification of agriculture in Europe requires a systems approach to farming that considers processes at the field, farm, landscape and regional scales. It is much more than just conventional agriculture without inputs. Implementation at large scale will require integration of activities within individual farms and also between different farmers. It will require collective design of pest-suppressive and disease-resistant landscapes. And the need for generalised crop rotations should evolve hand in hand with changes in food habits. There is little chance for crop rotation if the average world diet relies increasingly on cheeseburgers sold at one us$ apiece. The form of 'extensification' of European agriculture in which I believe is not one that sacrifices productivity; it is one that makes agriculture more complex, diverse, knowledge-intensive, and less dependent on fossil fuels. Through increased eco-efficiency, ecological intensification can contribute to detoxify our food and the environment, and to provide an array of ecological services on self-sustaining landscapes. But of course, if we would stop using inputs of fertiliser and pesticides on conventional monocultures as from next year without appropriate re-configuration of the farming system as a whole, without crop rotations, crop associations or other measures for integrated pest and nutrient management, then yes we would probably need not six but three to four times more land to produce the same amount of food we produce today.

[5] Farmers Conny and Kees Steendijk in Zeeland, for example, are able to produce up to 9 t ha^{-1} of wheat per year.

Lessons from the South

A substantial part of the world's agriculture relies on traditional, often local practices that make use of indigenous knowledge and few external inputs. Although they fail to produce enough surpluses to feed increasingly urban populations, low input systems are still key in sustaining rural livelihoods in the South. Such is the case of sub-Saharan Africa, where 70% of the population and most national economies rely heavily on smallholder rainfed agriculture. But such is also the case of ancient agricultural systems that proved sustainable in parts of Asia, Latin America or the Pacific, from where knowledge and lessons can be drawn to inform agroecological practices. Unravelling traditional knowledge systems requires understanding of the socio-cultural dimensions of indigenous agroecosystems, of their history and context, and of local values and perceptions on natural resources. Strategies for the sustainable intensification of smallholder agriculture in the South can be built on such knowledge base, taking into account the particularities of these farming systems: they are dynamic, diverse and highly heterogeneous (Tittonell, 2007).

A substantial part of their heterogeneity in space is caused by the heterogeneous distribution of human-induced soil degradation, which by preventing farmers from achieving the genetic potential of new crop varieties or of technologies for soil fertility management keeps African rural households locked in pervasive poverty traps (Tittonell and Giller, 2012). The extent of soil degradation in sub-Saharan Africa is estimated at 70% of the farmland (Vlek et al., 2008). Rehabilitating degraded soil is a major research challenge for those working in research for development in this continent. On degraded soils, crops do not respond to fertilisers, N-fixing legumes are unable to grow or to fix N, and labour productivity is extremely low (Giller et al., 2011). Research on sandy soils in Zimbabwe indicates that application of 20 tonnes of manure dry matter per ha per year are necessary, over more than five years, to restore productivity to its original levels (Ruzinamhodzi et al., 2012). In smallholder crop livestock systems in Africa, to collect 20 t year^{-1} of manure dry matter a farmer needs to own, in the best of cases, at least 20 cows (Tittonell et al, 2009; 2012). In most smallholder systems I know in Africa, the few farmers who own livestock have no more than one or two cows per household, and farm one to three hectares of land on average. Soil rehabilitation or soil fertility maintenance cannot rely only on manure inputs. In fact, no single technology will work but a combination of different things, including both local and scientific knowledge.

In the Sahel, soil management practices based on indigenous practices and resources from the natural vegetation proved effective for the gradual rehabilitation of degraded soils (Lahmar et al., 2012). Local shrubs of the genera *Piliostigma* and *Guiera* are used as crop shelters or 'fertility islands', and as a source of biomass for mulching (these shrubs, which are unpalatable to livestock, are the only green biomass present in the landscape throughout the dry season), thereby bringing inputs of organic matter to the soil, increasing water infiltration and reducing soil temperature. At the same time, planting basins are dug to create an irregular surface and concentrate water infiltration in one fourth of the surface area of a field. Through the combination of these measures plus appropriate crop varieties and use of small, localised amounts of mineral P fertiliser, it is possible to harvest a crop from a degraded soil in the first year of rehabilitation. In a Pan-African project funded by the European Union and led by the Africa Conservation Tillage network, of which I am a board member, we are studying and at the same time promoting these systems among farmers in the Sahel through innovation platforms (http://abaco.act-africa.org). This is a case of ecological intensification based on indigenous knowledge and local resources, which requires key inputs from scientists.

The potential of old good agronomy
In other cases, ecological intensification in Africa requires mostly researchers' knowledge. Figure 4A shows the results of an on-farm research program conducted on 60 households in the densely populated highlands of western Kenya (Tittonell et al., 2008). The fields of all farms were classified according to their distance from the homestead. The grey bars represent average yields obtained by farmers in those fields, with or without inputs of nutrients. They show a gradient of decreasing productivity at increasing distances from the homestead. Earlier work in the region provided evidence to ascribe such gradients to decreasing levels of soil fertility across farms of different resource endowment (Tittonell et al., 2005a,b) but also to deliberate 'management intensity gradients', as farmers invested less effort and inputs in fields perceived to be poor (Tittonell et al., 2007). What Figure 4A also shows is the yields obtained in researcher-managed plots that were established on the very same fields. Some of these plots received N, P and K fertilisers, while others did not. Most strikingly, researcher-managed control plots without fertilisers but planted at the right time, weeded often, with the right plant spacing and using certified local cultivars yielded more than farmer managed fields with or without fertilisers.

The example above illustrates the potential of proper agronomic management per se to increase yields. In the mid-distance and remote fields of these 60 farms proper agronomy without fertiliser inputs more than double maize yields. Increasing yields in Africa is not only a matter of bringing in nutrient inputs, but to understand under which circumstances they are likely to be effective. Yet, if all these smallholder farmers were to use mineral fertilisers then severe logistic problems in their distribution would emerge. A model-aided study in the highly populated district of Vihiga, in western Kenya calculated that substantial productivity increases could be brought about through the annual replenishment of 2 to 3% of total farm soil P stocks with mineral P fertilisers (Tittonell et al., 2009). Considering the average farm sizes in the area, and assuming optimistically that 60% of the households would eventually use fertilisers, to provide enough fertilisers for the resulting 105,000 households in Vihiga district will require 12,000 t of fertiliser per year. This is equivalent to 400 lorry full loads per year. The extent and status of the current road network in the region would not support more than 10% of that traffic. In terms of sustainability, fertilisers are often more of a palliative measure rather than a long-term solution to poor farm productivity or to poverty alleviation.

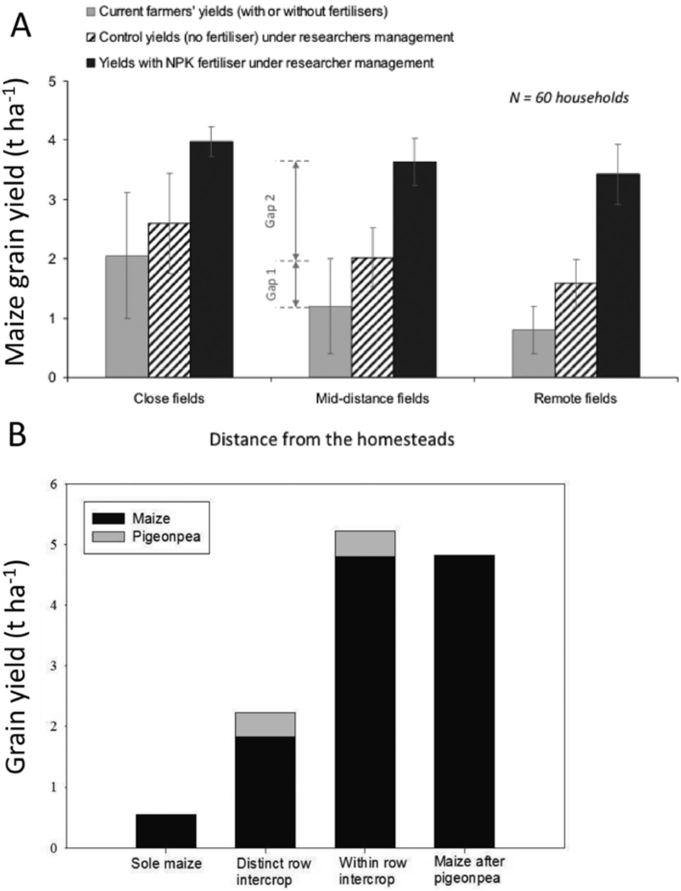

Figure 4 (A) Average maize grain yields in farmers fields located at increasing distance from the homesteads under farmer and researcher management in Kenya (Tittonell et al., 2008); (B) Yield of sole maize, maize and pigeon pea intercrops and maize in rotation with pigeon pea under conservation agriculture in Mozambique (Ruzinamhodzi et al., 2012)

Due to limited access to animal manure, a strong hypothesis developed that claims that soil organic matter can be built through use of mineral fertiliser to increase biomass productivity and incorporation of crop residues into the soil (e.g., www.agra-alliance.org). Without going into the debate on whether crop residues should be used to feed livestock or to feed the soil, data from 40-year experiments in West Africa that started from recently cleared savannah soils show that while crop productivity could be maintained in the long term through annual applications of fertilisers, soil organic matter levels could not (Kintché et al., 2010). The annual rate of carbon loss from the soil due to tillage (accelerated oxidation) and erosion was greater than the rate of carbon inputs through residue incorporation. And here is where conservation agriculture (CA), which is based on minimal soil disturbance, mulching and crop diversification (rotation, intercrops) can play a role as a means of soil rehabilitation (Tittonell et al., 2012). Finally, there is not enough 'space' here to discuss the potential of biological N fixation, a most important and - in my view - underutilised process in agriculture. Just as illustration, recent research on alternative CA systems in Mozambique by Rusinamhodzi et al. (2012) reports maize grain yields of nearly 5 t ha^{-1} after 3 years of maize-pigeon pea intercrops without fertilisers, as compared with yields lower or equal than 1 t ha^{-1} for sole maize without or with N and P fertiliser (Figure 4B).

Farming systems are moving targets

Resource degradation and the concomitant degradation of rural livelihoods in Africa are often assumed to follow a continuous, reversible trajectory in time. This assumption justifies categorising households according to their level of resource endowment (e.g., poor, mid-class and wealthy). This assumption has also led to the idea that a certain threshold of resource endowment should be crossed for households to reach higher welfare equilibriums (i.e., a tipping point in terms of asset holdings) (cf. Tittonell et al., 2010). Households that undergo a contraction of their natural resource, financial and human capitals become increasingly vulnerable and susceptible to poverty traps. Impoverishment often involves liquidation of capital assets, including land or livestock to cover immediate expenses, loss of social credit, and frequently a thorough reconfiguration of livelihood strategies. The labour force of impoverished households is sold cheaply to wealthier ones, thereby reinforcing the gap between both. Children from impoverished households may be removed from school, reducing even further their opportunities to step out of the poverty trap. On the other extreme, well-to-do households exhibit different livelihood strategies that may not necessarily rely on agricultural assets. Their way out of agriculture may be contemporaneous, or through investments in higher education for the next generation.

The diversity of possible livelihood strategies and development pathways in a densely populated region of western Kenya has been categorised through a typology that distinguished five rural household types. This typology, which was later corroborated across a wider range of agroecosystems of East Africa (Tittonell et al., 2010), differentiates households pursuing basically three main livelihood strategies, which may be described as Dorward (2009) did: hanging-in, stepping-up or stepping-out. Figure 5 shows the five household types placed in a two-dimensional plain defined by levels of resource endowment and 'performance' in terms of indicators of well-being; i.e., income, food security, investment capacity, etc. Households of type 3, 4 and 5 may be distributed along a curve that represents low welfare equilibrium (System state I): increasing resource endowment allows increasing performance up to a certain level P' (moving from T5 to T3), and vice versa (from T3 down to T5). The poorly endowed households of type 5 are 'hanging-in' at meagre levels of well being, with several feedback mechanisms confining them to very resilient poverty traps. The point [P'; R'] corresponds to a threshold of accumulated asset holdings that may allow investments to be able, in the short or the long term, to 'step up' to a higher welfare regime (System state II: T2 households) (cf. Figure 5). Resource contraction along the high welfare regime may reduce performance down to a certain level P''. The point [P''; R''] corresponds to a degree of impoverishment that often forces wealthier households to 'step out' of farming through engagement in off-farm activities, totally or partially, in order to preserve their level of well being (T1 households).

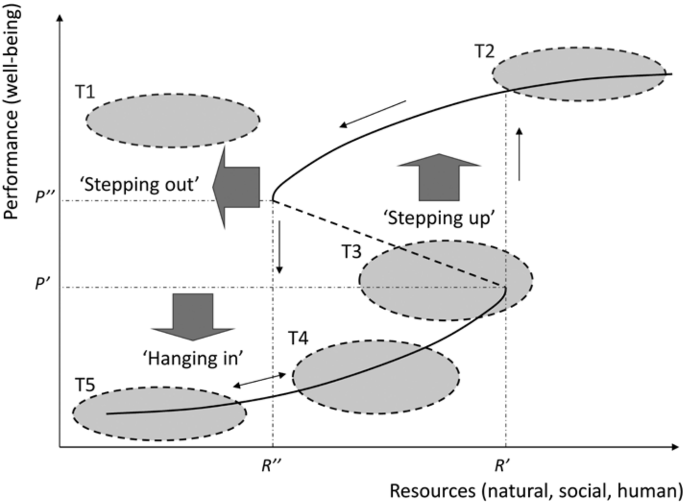

Figure 5 Theoretical representation of the position of five household types (T1-T5) that are common in East Africa in a two-dimensional plain defined by resource endowment and performance (in this case, 'well-being'). Full lines indicate two alternate system regimes

Resource contraction may take place through liquidation of asset holdings after a drought or to face the costs of funerals, through asset subdivision due to inheritance, or when household members face long lasting health problems that compromise their labour force, or their social and financial capitals, etc. Success in preserving levels of well being when stepping out of agriculture depends on educational levels, financial capital and opportunities (e.g., to find wage jobs in urban areas, to start a business, etc.). Often the step out of agriculture may be temporary, or partial, when part of the income obtained off-farm is reinvested in agricultural assets (notably in acquiring livestock). Obviously households of type 3, 4 or 5 may attempt to step out of agriculture from different situations defined by P and R levels, but a distinction is made between families that pursue an off-farm strategy (T1) from those that are 'expelled' from agriculture when unable to sustain a living in rural areas[6]. For all these reasons, such categorisations of rural livelihoods that link household diversity and long-term dynamics, through concepts from the realm of resilience thinking, are essential when targeting strategies for the sustainable intensification of smallholder agriculture, or to inform policy development for impact. Also in the developed North farming systems are moving targets, and the system transition towards Agroecology can also be seen as a discontinuous, hysteretic regime shift that can be favoured/supported through appropriate policy.

Agriculture and ecosystems services: trade-offs and synergies

Ecologically intensive farming makes use of ecological functions to sustain agroecosystem productivity. Biological diversity, but also cultural and management diversity play a major role through their impact on dynamic system properties such as stability, resilience and adaptation. This challenges the widespread notion that builds on the idea that to increase primary productivity it is necessary to 'simplify' the natural system (cf. Odum, 1985). For diversity to be effective, however, it must be organised in a very precise way. Network analysis of smallholder crop-livestock farms in Africa reveals large differences in terms of organisation and configuration of their nutrient flows – and in their recycling and nutrient use efficiency – across systems that are comparable in terms of diversity (Rufino et al., 2009). Reliance on biological diversity in agroecosystems leads to possible synergies between agricultural production, livelihoods and ecosystem services of local and global relevance. An assessment of carbon stocks in aboveground perennial plant biomass in smallholder agricultural landscapes of Kenya revealed a positive association between carbon sequestration (capture and storage) and plant biodiversity (Henry et al., 2009). Across farms (n = 368 fields), from 40 to 80% of the carbon was stored in individual

[6] I circumscribe the concept of stepping out (T1) to cases in which off-farm strategies are a choice, and off-farm activities become the major component of total income

trees growing scattered in agricultural fields and homegardens (with densities of around 20 t C ha^{-1} on average), from 5 to 15% in windrows (ca. 25 t C ha^{-1}) around farms or fields and the rest in pure stand woodlots (50 to 110 t C ha^{-1}). Hedgerows stored between 5 and 25 t C ha^{-1} according to their density and species composition.

Unfortunately the Kyoto protocol does not take into account biodiversity, so that a diverse tree community on-farm has the same value than a mono-specific tree plantation. Trees on-farm represent not only a sink of carbon but they also provided shelter, fuel and construction wood, fodder and fruits for self-consumption and the market, and contributed to reduce soil erosion. Trees participated in the capture and recycling of nutrients through exploration of deep soil layers. Likewise, examples of crop water and nitrogen facilitation by *Faidherbia albida* have been documented throughout Africa (e.g., Rhoades, 1995). *Senna siamea* trees can recycle Ca^{+2} from deep soil layers and thereby contribute to raise topsoil pH and nutrient availability in savannah soils of West Africa (Vanlauwe et al., 2005). These and many other examples indicate that trees have an important role to play in the design of ecologically intensive agroecosystems to overcome the generally perceived trade-offs between productivity (livelihoods) and ecosystem services. But the management (and abundance) of trees in agricultural landscapes can be challenging when they are owned collectively in a rural community, which calls for complex approaches to natural resource management.

The evidence presented throughout this section indicates that there is ample scope to design alternative agricultural systems to intensify production in the South and to 'extensify' production in the North, using less external inputs and without compromising global food security. Yet this is all partial evidence, and much research is still needed. Strategies for the ecological intensification of global agriculture require systems approaches and the ability to deal with diversity, to integrate disciplines, and to account for biological and human-nature interactions across spatial and temporal scales.

Farming Systems Ecology

What kind of science for ecological intensification?

Agroecology, organic farming, and integrated resource management in low-input systems have one thing in common: they require sophisticated, holistic design. We will not make much progress if we reason at the scale of single crops or animal herds, or by focusing on single technologies. We need to embrace the complexity inherent to agroecosystems. But let us first define some key elementary concepts to avoid misinterpretations. A system is a limited portion of reality, in which we can identify components (or sub-systems) interacting with each other and with the exterior environment through inputs and outputs. A model is a simplified representation of a system that enables us to study its properties and behaviour. The system itself (i.e., the limited portion of reality) is known as the ontological system, while the model (its representation) is a semiotic system. Moving from ontological to semiotic systems implies variable degrees of reductionism, and depending on the objectives for which the model is built explicit choices are made regarding the level of detail in the model or the components and interactions to be represented.

Models can be thus developed with the objective of understanding a system (analysis) or to contribute to systems design, with the latter being a main focus of our research at Farming Systems Ecology (FSE) group. An adaptation of a diagram drawn by a former professor from our group may help clarifying (Figure 6). While in research we analyse systems in order to enhance our understanding of the relationship between structures and functions, and ultimately infer their purpose, in design we move in the opposite direction. The purpose is known, and through a process of knowledge synthesis we try to identify the necessary functions to fulfil such purpose as well as the structures needed to sustain such functions. Although agro-ecosystems can be defined as cybernetic systems that are steered through human agency, a distinction should be made between systems that are purely mechanic from systems that depend on biological components such as microbes, or on stochastic drivers such as the weather. An engineer can easily design a radio on paper and, if the model design he uses is accurate enough then the radio that could be built based on such design should work properly. A typical example of this was the design of the first vehicles for space travel that could not be tested before they were put in orbit – no experimentation could be made and yet in most cases the experience was successful (de Wit, 1982).

In biological systems uncertainties are large and predictions are less reliable. We study structures to understand functions. We come up with ways of describing the causality at play between structure and function and, thanks to experiments, with a probability of certitude associated with our statements. Experimentation is thus an essential step during the analysis and design of systems with important biological dimensions, such as agroecosystems. Alternative and low input farming systems, such as conservation agriculture, organic farming or traditional smallholder agricultural rely largely on organic resources and biodiversity for their functioning. Their biological dimension is thus of greater importance than in conventional systems, as they rely largely on organic matter decomposition or biological N_2 fixation for nutrient supply, on soil-root feedbacks or on rotational carry-over effects for suppression of soil-borne diseases, on crop livestock interactions for nutrient

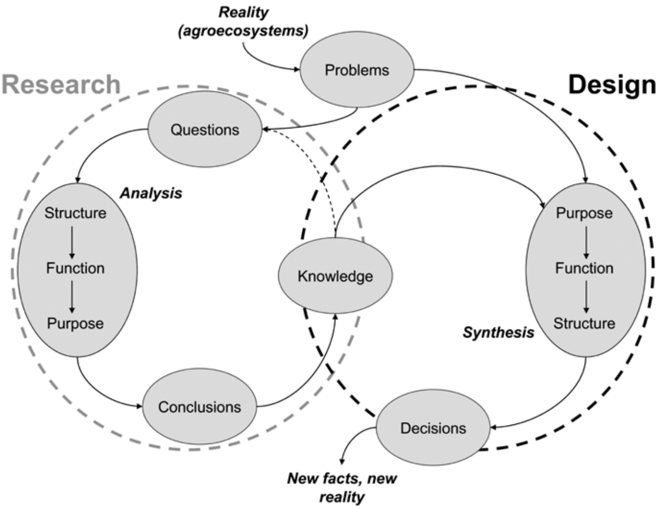

Figure 6 Scheme illustrating the differences between research and design in the realm of agricultural systems (adapted from Goewie, 1997)

cycling or on natural agents for pest control. Some of such biologically mediated interactions may be lost in experiments conducted under controlled conditions, as they are a simplification of the actual agroecosystem (Figure 7).

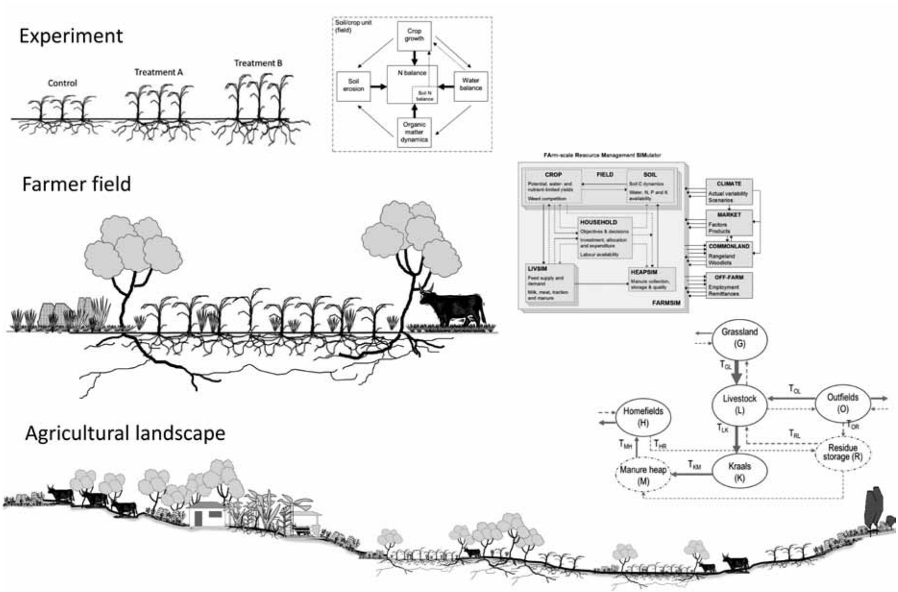

Figure 7 Examples of models dealing with abiotic interactions at field, farm and landscape level. An experiment is in itself a simplified model of the actual agroecosystem (Tittonell et al., 2012b)

In some cases, results from experiments can be scaled up across diverse landscapes through the use of models, but models of biological systems remain highly uncertain and need repeated testing through experimentation.

A Farming Systems Decalogue

To teach farming systems analysis to postgraduate students, bridging systems theory and practice, I came up with ten sets of principles and methods that I consider to be the backbone of quantitative, multi-scale and interdisciplinary analysis of farming systems. Why ten? This is really arbitrary, not normative. For merely didactic purposes I chose to name this list the Farming Systems Decalogue. This just makes it easier for students to remember. The Decalogue is thus built on the idea that comprehensive methodological approaches to quantitative farming systems analysis should include the necessary tools and concepts to allow minimally to:

I. Categorise and describe diversity and dynamics of farming systems;
II. Categorise and describe their heterogeneity and variability in space and time;
III. Capture spatio-temporal patterns of factor allocation at farm scale;
IV. Quantify interactions between systems components (e.g., crop-livestock);
V. Scale up and down from single fields to multifunctional landscapes;
VI. Involve actors and embrace lay knowledge systems;
VII. Capture collective decisions and resource flows in communities/territories;
VIII. Analyse (quantify and map out) trade-offs within rural livelihood systems;
IX. Prospect farming futures and explore scenarios;
X. Inform effective targeting of agricultural innovations.

The order of these ten sets is not rigid, the list may not be exhaustive, and the relative importance of each set of principles and methods depends on the objectives for which a farming systems analysis needs to be done. They combine systems analysis theory, on-farm research and participatory approaches, multivariate statistics, use of geographic information systems and simulation modelling. Disciplines as diverse as agronomy, animal husbandry, ecology, farm economics and rural sociology are integrated through a systems perspective. These principles are being gradually included in the curricula of the various courses – MSc and PhD – our group teaches. These ten principles pertain mostly to the realm of farming systems *analysis*, all of which can certainly inform farming systems *design* (e.g., trade-offs analysis, targeting innovations, etc.). At FSE we count on a diversity of methods for farming systems analysis, and my previous experience in projects such as AfricaNUANCES, CA2Africa or ABACO are clear examples of that. For conciseness, I am not going to present any example here; they can be found throughout my publication list.

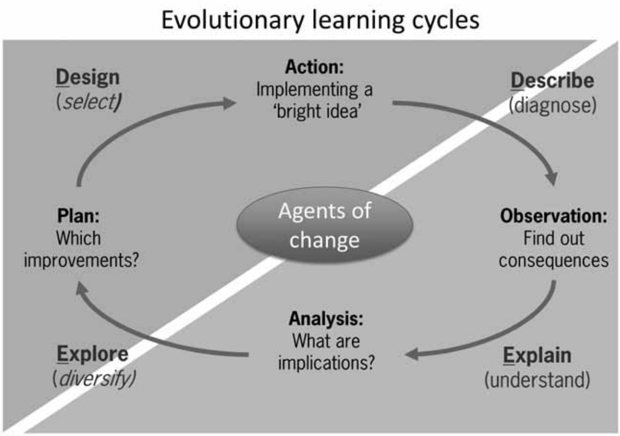

Figure 8 Diagram describing the approach used to support co-innovation and design in agroecosystems, based on Kolb's adult learning cycle. Tools such as models or participatory prototyping are deployed at different stages to diagnose, understand, explore diversity of options and implement actions. Agents of change (farmers, knowledge agents, policy makers) are involved in all steps. Note the parallel with the DEED approach. Source: EULACIAS project (wageningenUR.nl/fse)

Agroecosystem (re-)design: from plot to landscape

The design of farming system requires specific methods (cf. Figure 6) and a clear definition of the design object. That is why I prefer to refer to *agroecosystem* design. The agroecosystem concept can be more easily linked to a physical management unit (farm, territory, watershed, etc.) than the farming system, which is a more abstract concept that is used to mean different things in different contexts. In agroecosystem design, approaches are needed to integrate and synthesise knowledge, select and implement alternatives, and evaluate their performance. Such has been the approach used in the EULACIAS project led by the Farming Systems Ecology group (Figure 8) (e.g., Dogliotti et al., 2010). Prototyping, participatory planning and testing, pilot or model farms and model cropping or livestock systems, or territorial approaches such as enclosures are examples of methodologies used to test innovative designs. These methods may be used to evaluate and fine-tune a pre-selected innovation or to compare alternative innovations and inform choices. System models used in parallel can contribute to integrate, synthesise, evaluate and pre-select alternatives. Agroecosystem design and the development of the necessary methods for that are core activities at FSE. I will present some examples of such activities that span scales from the plot to the landscape or territory.

The first example concerns a case of agroecosystem re-design. Intensive rice cultivation on terraced landscapes, flood plains or valley bottoms is a common feature of agricultural landscapes in vast areas of Asia or Madagascar. The association of rice with ducks, sometimes also fish and N-fixing bacteria (Anabaena azollae) associated with ferns of the genre *Azolla* is an ancient system that proved sustainable in many parts of South East Asia. Research done in cooperation with the University of Brawijaya in Indonesia aims at optimising such systems (Khumairoh et al., 2012). Preliminary results show that an increasing complexity in the system, moving from sole rice to rice + ducks + fish + *Azolla* resulted in more than doubling rice yields, while providing at the same time substantial amounts of animal protein (Figure 9A). Further research aims at understanding the mechanisms and interactions that explain the substantial 'jumps' in system performance as complexity increases, as well as the environmental impacts that may be associated with these practices. Other examples of research for the design of complex adaptive systems at FSE is the development of disease-tolerant potato cropping systems through cultivar mixtures, which we do in collaboration with Organic Plant Breeding, or the design of integrated crops and free-range chicken production systems using the type of mobile chicken housing that can be seen on the Droevendaal farm. Yet, trade-offs may emerge around the implementation of such complex management systems at the scales of the farm or the landscape, especially in situations of resource scarcity (cf. Figure 9B and C).

Societies value agricultural landscapes in different ways, in accordance with their culture, needs and perceptions. Rural communities in the South and/or land use planners, mostly in the North, shape their landscapes responding to resource utilisation priorities, but also as a result of demographic changes throughout their history. The resulting landscape patterns and organisation have a strong influence on the functioning of the agroecosystem, particularly on the capacity of the remaining diversity of plants, animals and microorganisms to contribute to systems regulation. This calls for innovative approaches that regard the agricultural landscape as a support of functional biodiversity for (i) agricultural production; (ii) sustainable management of natural resources and wildlife; and (iii) provision of ecological services (e.g., regulation of water dynamic, of pest populations). Trade-offs between these three sets of objectives are not uncommon. FSE has a number of modelling tools that allow exploring alternative farm and landscape configurations and their properties through spatially explicit, multi-objective evolutionary algorithms (Groot and Rossing, 2011). These tools lend themselves very effectively to the analysis of trade-offs and synergies between agriculture production and ecosystem services (Figure 9B) in interaction with stakeholders through co-innovation processes (Rossing et al., 2012). The spatial patterns generated in this way can be linked to mechanistic processes relevant to the ecological functionality of the landscape.

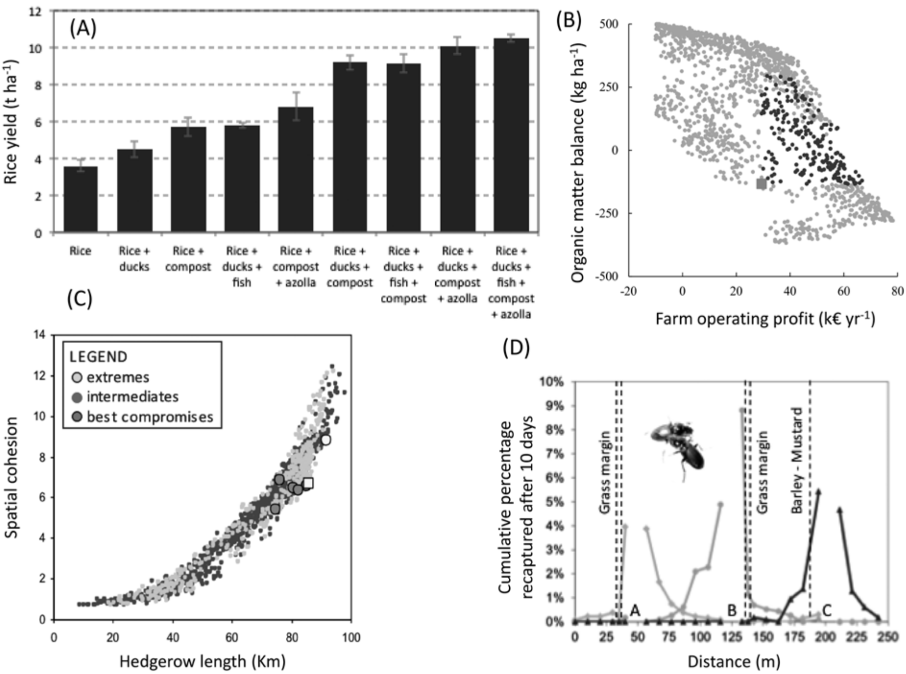

Figure 9 Examples of on-going research at the Farming Systems Ecology group aiming at supporting agro-ecosystems design. (A) Rice yield at increasing levels of agroecosystem complexity in Indonesia (Khumairoh et al., 2012). Illustration of trade-offs at farm (B) and at landscape (C) level when implementing new management practices or technologies at field scale analysed with evolutionary models (Groot et al., 2012). (D) Effect of field margins and grass strips on the dispersal of the beneficial ground beetle Pterostichus melanarius in an agricultural landscape (Allema et al., 2013)

A good example of this is the design of pest suppressive landscapes. Research done in collaboration with the Crop and Weed Ecology group in The Netherlands aims to inform pest-suppressive landscape design by generating maps of arthropod-mediated ecological services at national level based on vegetation maps, to engage with stakeholders that are effective 'landscape managers' (the *Biodiversiteit werkt!* Project), or to understand the dynamics of biological control agents on heterogeneous landscapes (Allema et al., 2013 – Figure 9D). Landscape design for biological control requires fine-tuned ecological engineering, in order to provide alternative sources of food and shelter for natural enemies distributed strategically in space and time (e.g., sources of nectar throughout the season), matching demand and supply (e.g., flower morphology to match the morphology of insect proboscis) and offering hibernation sites (e.g., Bianchi et al., 2013). A project tackling similar questions around the design of effective biological control for maize stem borers is being implemented in Ethiopia in collaboration with CIMMYT (PhD Thesis of Yodit Kabede) through the project Attic (Agro-ecosystem diversity, trajectories and trade-offs for intensification of cereal-based systems). In this project, we examine the changes in agroecosystem structure and functioning resulting from the effect of contextual drivers to understand relevant current and future trade-offs around ecological intensification across scales (Figure 10).

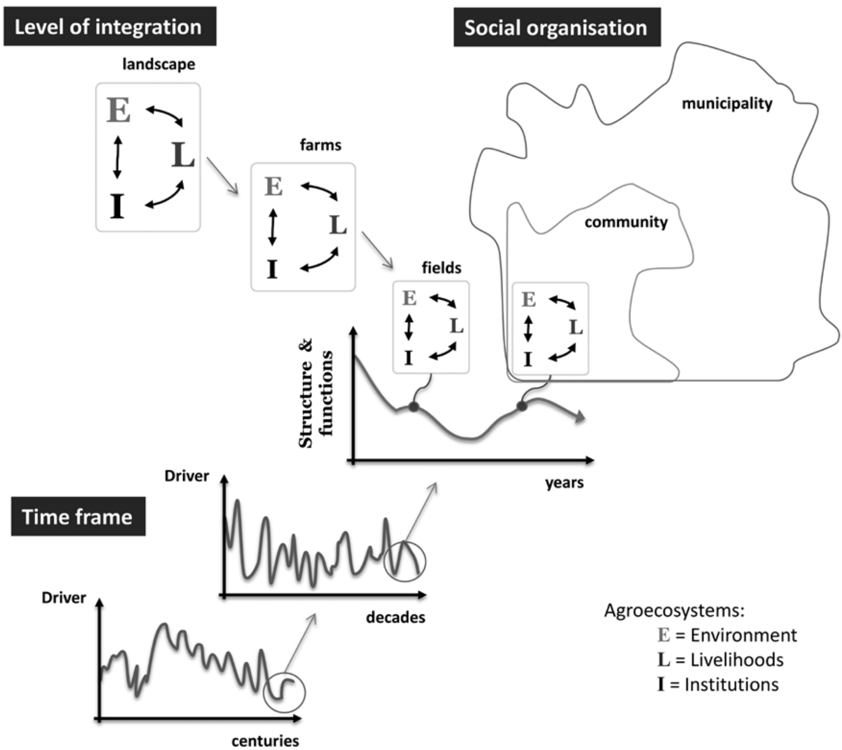

Figure 10 Trajectories of change in the structure and functioning of agroecosystems (encompassing their environmental, livelihood and institutional dimensions) as determined by the dynamics of contextual drivers and cross-scale interactions. The example is illustrated for a field-to-landscape interaction, but is equally valid for higher scales (from Valbuena et al., 2013)

Another example of this kind of research at FSE is the design of ecologically intensive livestock systems based on natural grasslands in the South American Campos biome, also known as the 'Pampas' of southern Brazil, Argentina and Uruguay. On these vast landscapes, our research in collaboration with local institutions such as the University of la Republica in Uruguay aims at designing management systems based on regulating grassland species composition (e.g. C3 and C4 species) in space and time in order to match biomass quantity and quality to livestock requirements throughout the year, with no or few external inputs, preserving species diversity, and reducing risks associated with climatic fluctuations (PhD Theses of Andrea Ruggia and Pablo Modernel). In such extensive systems, individual farmers can be landscape managers. In regions where farm sizes are smaller, landscape management requires collective action. Such is the case of a region in Chiapas, southern Mexico, where the creation of a biosphere reserve coupled with the signature of trade agreements with the United States generated changes in land use systems and competing claims on natural resources (Speelman et al., 2013). Our research there makes use of social learning games and agent based systems to contribute to negotiated design of sustainable land use systems by supporting dialogue (PhD Thesis of Erika Speelman).

The demand for research to support re-design of agroecosystems is permanent. Let's take the example of the new manure regulations in organic farming. Livestock played a central role in agroecosystems throughout the history of farming. Crop livestock integration is key in organic farming. Studies being conducted in France indicate that about 70% of the nutrients that are used for crop production in organic farming comes from conventional farms (Nowak, 2013). After a process of decreasing reliance on manure from conventional farms, new regulations in The Netherlands compel organic farmers to use manure that comes exclusively from organic animal production. Because the sources of certified 'organic' manure are still limited, this regulation is likely to induce a reconfiguration of current farming systems, as organic arable or horticultural farmers will have to integrate livestock production in their activities for effective nutrient cycling. Our research should support such transitions in the most effective way.

Research domains at the Farming Systems Ecology group

FSE combines social-ecological knowledge with systems analysis techniques, and a solid understanding of farming realties in the both temperate and tropical regions of the world, for the design of ecologically intensive agroecosystems. New forms of agriculture are urgently needed to be able to secure access to healthy food for 9 billon people in 40 years, with the resources currently available on the planet, while curtailing current environmental degradation. Agroecology can be a source of both solutions and preventive actions for tomorrow's problems of global agriculture. Thus, far from focusing our attention exclusively on research solutions for the organic farming sector, we aim to develop agroecological knowledge able to contribute *alternative* solutions to the major challenges facing current agriculture, namely:

(i) global food security;
(ii) provision of ecological services;

(iii) food and environmental health;
(iv) adaptation to climate change; and
(v) preservation of the biological and cultural diversity of agricultural landscapes.

In cooperation with other research groups at Wageningen and abroad we conduct multi-scale and inter-disciplinary research organised in four domains defined by the level of integration of the target agroecosystem (field, farm, landscape, territory) and by the nature of the research questions they address: analysis-oriented or design-oriented (Figure 11). Agro-ecosystem properties and functions (1) and Social-ecological interactions (2) are analysis-oriented domains that aim to generate the knowledge and understanding necessary to inform innovative design. Sustainable food baskets (3) and Multifunctional landscapes (4) are design-oriented domains that address current societal demands on global agriculture, in line with the need to design agroecosystems able to produce sufficient and safe food and ecological services in self-sustaining landscapes. The 'How?' list in Figure 11 illustrates our methods and disciplines; the 'What?' list illustrates our themes and target systems. Next to the design of alternative integrated crop-livestock systems, our research embraces the spatially explicit design of alternative landscape configurations and their impact on agroecosystem functioning, spatial dynamics of pest and predators, understanding of collective management of communal resources in rural territories, and the analysis of human-nature interactions in biodiversity rich areas.

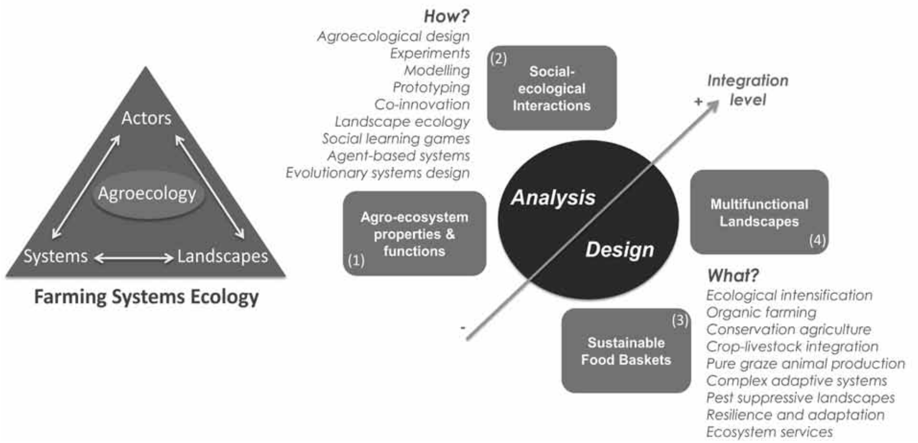

Figure 11 (Left) Farming Systems Ecology portraits Agroecology in the realm of systems analysis, landscape processes and collective action. (Right) Our four research domains are determined by the nature of the research questions addressed (analysis-oriented vs. design-oriented) and by the level of integration of the agroecosystem considered

Concluding remarks

Over time, I acquired first-hand experience working as an agronomist in the private sector, with large commercial farms, for a seed company or farming for the food industry. In the last ten years I have been active in the realm of international research for development, working with smallholder farmers in the tropics. After having seen both sides of the coin, I am convinced that agriculture needs knowledge-intensive management systems to increase yields and access to food and incomes in the South, and knowledge-intensive design to reduce the dependence on external (fossil fuel) inputs in the North. The design of landscapes that support an ecologically intensive agriculture creates opportunities for synergies between food production and ecosystem services. Most importantly, this can contribute to detoxify or food and our environment.

The model of intensification per unit area or per animal, which is deeply rooted in the mind of scientists from the green revolution generation is now obsolete. We need to think outside the box. Increasing the already high cereal yields in Europe by one ton per ha would have enormous environmental and economic costs, and will have little impact on reducing world hunger. Increasing current cereal yields by one ton per ha in Africa, for instance, which could be easily achieved through agro-ecological intensification would represent a doubling of the current cereal production in that continent, with less environmental and economic costs than further intensification of European agriculture. And, most importantly, food will be produced where it is urgently needed, and where the surpluses can generate extra income for poor rural households.

We need new science to contribute to the design of knowledge-intensive systems such as organic farming, which relies more on process- than on input-based technologies. The private sector will never invest in process-based technologies, unless there is a product or a service that could be sold with them. A certain crop rotation or a grazing system cannot be patented or sold on the market. Private companies will always invest in developing new input-based technologies. That is the core of their business, and there is nothing wrong with that. To compensate for such trends the public sector needs to invest in the development of process technologies, in integrated systems research, in holistic approaches.

Wageningen University has a well-established reputation on systems analysis and systems thinking. We have therefore a key role to play in creating awareness on the risk of narrow visions and single-criterion assessments: Inability to think systems wise has led some to conclude that "organic farming is more polluting" based on the fact that CO_2 emission equivalents are greater per kilogram of produce, disregarding the multiple consequences generated through deforestation in the South, with the production of synthetic inputs or with maritime transport associated with current practices of conventional farming in Europe. Such visions, based on the analysis of a single indicator – CO_2 emissions in this case – are too biased and risky. Although this has been said all too often, it seems to be necessary to insist: sustainability assessments require considering multiple criteria simultaneously.

The several examples presented during this lecture illustrate how the same principles that can contribute to reducing environmental impact and energy dependence of agriculture in the developed North are also useful in raising agricultural productivity in the developing South. Investment in research on ecological intensification pays off, as demonstrated by e.g. (i) the ability of organic farming to produce yields that are only 20% lower than in conventional agriculture with far less inputs of energy and meagre public investment in knowledge generation, (ii) the impact that agronomic management or the optimisation of traditional management can have on rising yields and rehabilitating soils in Africa, (iii) the natural potential of biological N fixation that is largely underutilised in agriculture, or the (iv) effectiveness of ecological engineering in agricultural landscapes to render agriculture more resilient and less dependent on agro-toxics.

There is ample room for improvement, but there are still many challenges ahead. The type of research necessary to support ecological intensification should be one that integrates processes across scales and disciplines. To understand many of the natural mechanisms that support agroecological design we need to move from the field plot to the landscape level. Concomitantly, understanding the role of human agency in agroecosystem design requires shifting from individual decision-making to collective action. Farming systems ecology integrates multiple disciplines through systems approaches to the analysis and design of ecologically intensive agriculture. It builds on the tradition of production ecology from the Wageningen school of thought initiated by Professor C.T. de Wit, and relies on principles of systems ecology for the study of biotic interactions, landscape dynamics and social-ecological feedbacks. Farming systems ecology is at the crossroad of different disciplines, scales and integration levels. This makes collaboration with other research groups, both at Wageningen and elsewhere, an essential part of our research strategy.

As our approach is being recognised and valued in the international arena, FSE is brought to participate in a large number of new research initiatives, including the new collaborative research programs of the CGIAR. A total of 12 new PhD students working in different parts of the world joined our group only in the last year. At national level, the re-direction of our research priorities during this new phase creates renewed opportunity to play a complementary role in the Dutch organic farming arena, contributing our systems expertise, our tools and our training capabilities. Our current engagement with the Farming Systems Design community, with the Scientific Society for Agroecology in Latin America, with the African Conservation Tillage network and with the International Federation of Organic Agriculture Movements (IFOAM) opens new opportunities for continuous learning and impact.

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I have spoken.

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‘The model of intensification that is deeply rooted in the mind of scientists from the green revolution generation is obsolete. We need to think outside the box. Agriculture needs knowledge-intensive management systems to improve food security and incomes in the South, and to reduce the dependence on external (fossil fuel) inputs in the North. The design of landscapes that support an ecologically intensive agriculture creates opportunities for synergies between food production and ecosystem services. Most importantly, this can contribute to detoxify or food and the environment.’

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