The global impact of insects

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Farewell address upon retiring as Professor of Tropical Entomology at Wageningen University on 20 November 2014

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

Insects have fascinated me throughout my career. Not just the insects themselves but especially their interaction with humans. It is on this interaction that I would like to focus. I will explain why insects are so successful, how they relate to climate change, and which ecological services they provide. Then I will move to insects as pests and give some examples, which leads me to the development and implementation of integrated pest management programmes and the role of institutions in them. As you probably expected, I will also dwell on the benefits of insects as food and feed, and end with some acknowledgements.

1. Introduction: Insects, the most successful animal group on earth

Insects are the most abundant (10^{19}) and most diverse group of animal organisms on earth. The number of insect species has been estimated to be between 2.5 and 3.7 million (Hamilton et al., 2010). The first recorded insect, *Rhyniognatha hirsti*, lived 400 million years ago (Engel & Grimaldi, 2004). Fossil "roachoids" from 320 MYA to 150 MYA were primitive relatives of cockroaches. Angiosperms started to evolve 130 MYA, as did holometabolan plant feeding insects such as the Lepidoptera (100,000 species) and the phytophagan beetles (150,000 species). An innovation in their evolution was the development of holometabolism and four orders, the Coleoptera, Diptera, Hymenoptera and Lepidoptera, involving 80% of all insect species, underwent a complete metamorphosis (Grimaldi & Engel, 2005). Insects have evolved well-adapted structures and materials over geological time. For example, no group of animals matches the camouflage and mimicry seen in insects. Insect survived four major cataclysms that resulted in planet-wide extinctions. Despite man's effort to eradicate insects, they continue to thrive. I would like to cite from Grimaldi and Engel (2005) who wrote a book about the evolution of insects:

"*People gladly imagine a life without insects. But if ants, bees and termites alone were removed from the earth, terrestrial life would probably collapse. Most angiosperms would* *die, the ensuing plan wreckage would moulder and ferment for lack of termites, soil depleted of nutrients would barely be able to sustain the remaining plants; erosion would choke waterways with silt. Vast tropical forests of the Amazon, Orinoco, Congo and other river basins would die off, and the earth's atmosphere and oceans would become toxic*".

I will mention a number of the designs and processes that make insects so successful (NCSU, 2014). These are often used to solve human problems: "*innovation inspired by nature*." This discipline is called bio-mimicry.

Exoskeleton. The skeleton of insects, the exoskeleton, is located outside the body. Much of it consists of chitin, a polysaccharide that binds with various protein molecules to form a body wall that is elastic as rubber, and hard and rigid as some metals. It can also resist physical and chemical attack. It is covered by a layer of wax that prevents desiccation. This skeleton allows ants to lift up to 50 times their body weight.

Small Size. Most species are between 2 and 20 mm, but there are extremes. Some egg parasitoids, laying eggs in eggs, can be smaller than single-celled protozoans, viz. 0.14 mm, while the largest can be 30 cm in length. The exoskeleton sets an upper limit: doubling the length would increase the volume eight times. Small size means that minimal resources are required for survival and reproduction and provides advantages in avoiding predation (hiding, burrowing, squeezing and blending with the environment).

Flight. Insects are the only invertebrates that can fly and they have done it for 300 million years, 100 million years before the flying reptiles. Flight is a huge advantage for foraging, escape and for colonizing new areas and exploiting new resources. Natural selection has made flight very effective. Compared to birds and bats, the insect muscles of flight produce twice as much power per unit of muscle mass. More than 200 species, including moths, dragonflies, locusts, flies and beetles, migrate over long distances (Johnson, 1969). The Desert locust, *Schistocerca gregaria* (Forskål) (Orthoptera: Acrididae) can fly for up to nine hours without stopping and these locusts have covered distances of up to 4,500 km (Africa to the Caribbean). The Monarch butterfly *Danaus plexippus* L. (Lepidoptera: Nymphalidae) covers more than 4,000 km during its annual migration from Northern America to Mexico (Brower, 1995). Dragonflies have remarkable success rates in capturing prey made possible by outstanding aerobatics (Olberg et al., 2000), and honey bees frequently airlift pollen loads up to 80% of their own bodyweight (Winston, 1987). The Polish researcher (Sotavalta, 1947; Sotavalta, 1953) found that a member of the genus *Forcipomyia* (Diptera: Ceratoponidae) achieved a wing beat frequency of 1046 cycles/sec.

Morphological adaptations. Insect have mouthparts that can attack almost everything: e.g., chewing for foliage, piercing-sucking for blood or plant juices, coiled-sucking for reaching in flowers, sponging-sucking for absorbing liquids. Their legs have numerous functions: spines for uneven surfaces, enlarged femurs for jumping, paddles for swimming, shovels for digging, and pincers for capturing prey.

Reproductive Potential. Females produce large numbers of eggs (100-500 in a lifetime), survival is high and the life cycle is short (often 2-4 weeks). Together, these three characteristics enable insects to produce remarkably large numbers of offspring. Antonie van Leeuwenhoek, the Dutch scientist, in 1687 reared blow flies on a diet of owl meat and found that females produced an average of 144 progeny: half male, half female. Using these data (and assuming no mortality), he calculated that the fly population would grow to more than 1×10^{17} individuals in one year (10 generations). For *Drosophila melanogaster* Meigen (Diptera: Drosophilidae) the same calculations have been made: at the 25^{th} generation the mass of insects would be larger than earth itself (Grimaldi & Engel, 2005). Insects have many adaptations to reach such a high reproductive potential.

Metamorphosis. Nine of the 28 insect orders undergo a complete metamorphosis, and these orders represent about 86% of all insect species alive today. The change from eggs to larvae to pupae and adults involves physical, biochemical, and/or behavioural alterations. The larvae and adults use different types of food, exploit different environmental resources, and even occupy different habitats, promoting survival, dispersal, and reproduction.

Adaptability. A combination of large and diverse populations, high reproductive potential, and relatively short life cycles, has equipped most insects with the genetic resources to adapt quickly in the face of a changing environment. Later I will give examples of insects developing resistance to insecticides.

2. Insects and climate change

More than 55 million years ago, atmospheric CO_2 and global temperature rose (Currano et al., 2008) and associated with these changes the amount and diversity of insect damage increased. If the past indeed is a window on the future, their findings suggest that increased insect herbivory will be one of the unpleasant surprises arising from anthropogenic climate change (Bale et al., 2002; DeLucia et al., 2008).

Tropical insects are relatively sensitive to temperature change and are currently living very close to their optimal temperature. Therefore, warming in the tropics, even when relatively small in magnitude, is likely to have deleterious consequences (Deutsch et al., 2008). In contrast, species at higher latitudes have broader thermal tolerance and are living in climates that are currently cooler than their physiological optima, so that warming may even enhance their fitness. Available thermal tolerance data for several vertebrate taxa exhibit similar patterns, suggesting that these results are general for terrestrial ectotherms. The analyses imply that, in the absence of ameliorating factors such as migration and adaptation, the greatest extinction risks from global warming may be in the tropics, where biological diversity is also greatest.

Methane is an important greenhouse gas, and its atmospheric concentration has nearly tripled since pre-industrial times (Bousquet et al., 2006). The global budget of atmospheric CH_4 is between 500 and 600 Tg (10^9) a year, and more than half of it is anthropogenic. It is mainly the result of environmental microbial processes in wetlands, rice fields, digestive systems of termites and ruminants and microbial oxidation under anoxic and oxic conditions (Conrad, 2009). Termites produce methane (CH_4) through fermentation by methanogenic bacteria in their hindgut [they also produce carbon dioxide and molecular hydrogen (Zimmerman et al., 1982)]. Termites' contribution to global methane emissions is 3%, although others have estimated it to be much higher: 5-27% (Hackstein & Stumm, 1994) and even 12-43% (Zimmerman et al., 1982). There are a number of other arthropod insects species that produce methane such as millipedes (Diplopoda), cockroaches (Blattaria), and scarab beetles (Scarabaeidae) (Hackstein & Stumm, 1994). The authors were wondering whether the increase of atmospheric methane during the past 2 centuries might be caused in part by anthropogenic ecological changes that favoured the expansion of methane-producing arthropods. The question has been posed whether deforestation would have an effect on methane emissions by termites. Although termite numbers increase after deforestation, their numbers probably are not sufficient to consume the large amount of wood that becomes available (Fearnside, 1997).

3. Insects' ecological services

The value of ecological services, such as dung burial, pest control, pollination, and wildlife nutrition, have been quantified for the United States and is estimated to be at least US$ 57 billion annually (Losey & Vaughan, 2006). Surprisingly, 86% of this amount is recreational and commercial fishing. US citizens spend over 60 billion US$ a year on hunting, fishing and observing wildlife (US Census, 1996). Insects are a critical food source for much of this wildlife, including many birds, fish, and small mammals. Americans spend 34 billion US$ on bird watching and most birds (61%) are primarily insectivorous. The value of recreational fishing in the US is about 28 billion US$; it depends entirely on insects.

Another very important ecological service provided by insects is pollination. Using primary data from 200 countries, the level of dependence on animal-mediated pollination for crops that are directly consumed by humans was evaluated (Klein et al., 2007). These authors found that pollinators are essential for 13 crops; production is highly pollinator-dependent for 30, moderately for 27, slightly for 21, unimportant for seven, and of unknown significance for the remaining nine. Native pollinators - almost exclusively bees - of fruits and vegetables produced in the United States are likely to be responsible for benefits of almost 3.07 billion US$ (Losey & Vaughan, 2006). Agricultural intensification may jeopardize wild bee communities and may affect pollination services at the landscape scale. Recommendations for landscape management to conserve and promote insect-mediated pollination include nesting opportunities, floral resources, habitat connectivity and reduction of pesticide use (Klein et al., 2007). Pollinator decline seems to occur all over the world and should be considered in light of the fact that the total economic value of pollination worldwide amounts to 153 billion US$, which represents 9.5% of the value of the world agricultural production used for human food in 2005 (i.e. 1,618 billion US$)(Gallai et al., 2009). Vegetables and fruits derive most added value from insect pollination (about 50 billion US$ each), followed by edible oil crops, stimulants, nuts and spices. The value of the crops that depend on insect pollination is higher than that of crops that do not (761 US$ and 151 US$ per tonne, respectively).

Insects as decomposers. In the tropics, termites (Isoptera) are arguably the most important soil ecosystem engineers. Live biomass densities have been estimated to range from 70 to 110 kg per ha and from 510 to 1,150 g of live weight per nest in the largest nests (Jouquet et al., 2011). Densities between 2,000 and 7,000 individuals per m^2 are quite commonly reported. Population densities suggest termites may represent 40–65% of the overall soil macro-faunal biomass in some biotopes. The ecological services they provide are litter decomposition, bio-turbation and soil formation, nutrient cycling, improvement of hydraulic properties of the soil, prevention of soil erosion, stimulation of vegetal growth and diversity, and increased soil animal and microbial biodiversity (Jouquet et al., 2011).

Cattle were brought to Australia in 1788, but there were no insects that were adapted to feed on cattle dung (Bornemissza, 1976). Twenty-three species of dung beetles, 53 per cent of those released, were known to have become established in 2007 (Ridsdill-Smith et al., 2011). Ecosystem functions provided by dung beetles include nutrient cycling, mixing of dung into the soil, plant growth enhancement, secondary seed dispersal, and parasite and fly control.

The importance of the benefits of insects should be highlighted. We distinguish natural control from biological control. Natural control happens without interference of humans. A myriad of predators and parasitoids that occur naturally keep most pest species under control. It is often not realized that pesticides tend to do more harm to these natural enemies than to the pest insects. Already in 1964, DeBach gave a number of counterintuitive examples of how insecticides can be used to create an insect pest problem (DeBach, 1964). A rapid population increase of the target pest following insecticide applications is called resurgence. This occurs mainly in Homoptera (44%), Lepidoptera (24%) and mites (26%) (Waage, 1989). These are relatively sessile pests, such as scale insects and mealybugs, which are protected from insecticides by a waxy covering, as well as lepidopterous leaf miners or stemborers protected by plant tissue. These pests are less vulnerable to contact insecticides than their natural enemies, which must forage over the plant to find their prey or host. Other reasons for resurgence are differential mortality of insects and natural enemies, enhancement of growth rate of pest populations, phyto-stimulation of pests and removal of competitors, disruption of synchronization between pests and natural enemies, differential resistance development, disruption of food chains and effect of agrochemicals on entomopathogens. In the United States it was calculated that 33% of 68 herbivorous pest species are suppressed by natural control and that the value of this control is 4.5 billion US$ (Losey & Vaughan, 2006).

It is also possible to deliberately use natural enemies to control pests and this is called 'biological control'. I managed a project in East Africa, which introduced the parasitoid *Cotesia flavipes* Cameron (Hymenoptera: Braconidae) from Pakistan and India to control the exotic cereal stemborer *Chilo partellus* Swinhoe (Lepidoptera: Pyralidae), which invaded the continent from Asia early last century, causing 73% yield loss. Laboratory studies revealed that the parasitoid could successfully parasitize not only the target stemborer, but also two native stemborers that occur sympatrically with *Ch. partellus* in some locations (Overholt et al., 1997). Since its release in 1993 in Kenya and the rest of southern and eastern Africa, the economic benefits of the parasitoid amount to a net value of 183 million US$ (Kipkoech et al., 2006). Other biological control programmes that introduced predators and parasitoids have even more impressive results (Table 1), in particular the biological control of the cassava mealybug *Phenacoccus manihoti* Mat.-Ferr. (Homoptera: Pseudococcidae). This pest was first observed in Zaire and Congo in the early 1970s and spread throughout the entire African cassava belt. The exotic parasitoid *Apoanagyrus lopezi* De Santis (Hymenoptera: Encyrtidae) was released from 1981 onward (Herren et al., 1987) and brought the pest under control (Zeddies et al., 2001). The cost benefit ratio over 40 years is close to 150 and the economic benefits close to one billion US$.

Table 1. Cost-benefit ratios of biological control programmes

Pest	Benefit/ cost ratio	Benefits (million US$)	Reference
Coffee mealybug (Kenya)	566	42.5 (34 years)	Melville (1959) in (Huffaker et al., 1976)
Cassava mealybug (27 countries Africa)	149	9,400 (40 years)	(Zeddies et al., 2001)
Mango mealybug (Benin)	145	531 (20 years)	(Bokonon-Ganta et al., 2002)
Water hyacinth (Benin)	124	260 (20 years)	(De Groote et al., 2003)
Diamondback moth (Kenya)	24	28.3 (25 years)	(Macharia et al., 2005)
Cereal stem borers (East and southern Africa)	19	185 (20 years)	(Kipkoech et al., 2006)

4. Pesticides and the environment

Pesticides have been considered the panacea for a number of pest problems. However, pesticides have a negative impact on health and the environment, lead to resistance in pest populations and are deleterious for the beneficial insect fauna. Concerning resistance for example, currently 553 insect pest species have become resistant to one or more pesticides: 306 agricultural pests, 202 medical pests, 29 parasitoids and 16 other species (Whalon et al., 2008). For the farmer the benefits (prevented yield loss) should be weighed against costs (pesticides, machinery and labour) and this ratio is expressed in the economic damage threshold, below which it is not economical to use pesticides. The threshold implies that the farmer tolerates some pests in his/her crops as well as the associated damage, such as less aesthetically appealing fruits and vegetables. However, individual farmers tend not to take into account the social costs of pesticides, such as pesticide resistance, although eventually it will affect them, especially when they overuse. This is the tragedy of the commons. The same is true for the destruction of natural enemies, which is not taken into account when economic thresholds are established. If integrated pest management is not practised over a large area, one farmer cannot make a difference by refraining from pesticide use and saving his natural enemies, as these will be destroyed by his neighbour. The social costs are also those related to health and environment, the externalised costs of pesticides. In the United States, these externalities in 1992 were calculated to be about 8 billion US$ annually (Pimentel et al., 1992). Therefore, the threshold of a social planner is always higher than that of a farmer, who tries to avoid risk and uses a prophylactic approach; uncertainty about both damage and crop growth leads to overuse of pesticides

(Sexton et al., 2007). The determination of the net benefits of pesticide use is central to optimal use decisions and, therefore, to the regulation of pesticides. The political response to the externalised costs of pesticides often takes the form of bans or use restrictions. The environmental damage inflicted by pesticides can be much broader than previously assumed. An example has been the effect of neonicotinoids on birds: their numbers declined more rapidly in areas most heavily polluted with these pesticides (Goulson, 2014). In regulating pesticides, social planners should strive for policies that induce optimal pesticide use through efficient policies, such as taxation and subsidization.

Pesticide use requires more attention from economists. More knowledge is needed about the economics of the environmental and human impacts of pesticides so as to facilitate balanced and sound policies to frame pesticide use.

There are similarities with the discussion about taking action to revert climate change. Daniel Kahneman is notable for his work on the psychology of judgment and decision-making, behavioural economics and hedonic psychology. He called climate change: "*a distant problem that requires sacrifices now to avoid uncertain losses far in the future*" (Kahneman, 2011). In economics, cost-benefit analysis may be self-defeating. Nicholas Stern of the London School of Economics offers a choice: "*spending one per cent of annual income now, or risking losing 20 per cent of it in 50 years' time*" (Stern, 2007). Policy-makers are intuitively drawn towards postponing action and taking a gamble on the future.

5. Integrated pest management

Agricultural inputs are generally considered a necessity and even my own research in Nicaragua showed synergy between applying fertilizer on maize and applying pesticides to control the defoliator, the Fall Armyworm *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) (van Huis, 1981). Yields increased 6% by applying fertilizer without pesticides and 26% by applying pesticides without fertilizer; however, combining the two increased yields by 60%. Already early in my career I also came to understand that agricultural inputs are not always a blessing. From 1982 to 1985, I drove each day to my work location through 20 km of agricultural fields in Niger. Some farmers used fertilizer and initially the effect was visibly tremendous: a very luxurious millet crop. However, if the rains failed, these fields with millet plants with an abundant leaf area were the first to succumb, while unfertilized crops were able to withstand the drought. In Nicaragua, I was wondering whether defoliating pests would really be a problem under drought conditions as plants with diminished leaf area would evaporate less. Since there was a marked dry season and irrigation was available, the question could be experimentally investigated. Under drought conditions, plants with the defoliating pest *S. frugiperda* grew taller and yielded more than plants free of those pests (van Huis, 1981). Again a diminished leaf area under drought condition was favourable. So, the insect pest stimulated yields.

Some pests are however difficult to control. I will give two examples: the Desert Locust (in the international attempts at global control of which I have been involved from 1984 to 2007), and the Mountain Pine Beetle in Canada: the devastation it brings about made a large impression on me.

5.1 Desert Locust

Outbreaks of the Desert Locust, *Schistocerca gregaria*, may occur anywhere in the whole recession area of the insect, estimated at 14.6 million km^2. This is about half the area that is liable to be invaded by swarms (29.3 million km^2). Such swarms can develop when rainfall is abundant over subsequent breeding areas. Under these favourable conditions locusts are not only capable of increasing rapidly in numbers, but also of changing from a solitary to a gregarious phase. Normally there are two generations a year, but under favourable conditions there can be more. For example, prior to the last plague, from 1986 to 1988, there had been 12–13 generations, meaning two generations during winter and spring and two in the summer (van Huis, 2007). An estimated eight generations occurred before the 1992–1994 upsurge, as well as during the 2003–2005 upsurge. Multiplication rates per generation may reach 16 under favourable conditions. We simulated required control efficiency with multiplication rates of just 5 during five generations: the percentage to be controlled in order to keep the population in check has to be 80%, an almost impossible target (van Huis, 1993). During the plague from 1986 to 1989, 26 million ha were sprayed in the Sahel and North Africa costing 315 million US$ (van Huis, 1995). A report by the U.S. Congress called this a waste of resources and unjudicial use of pesticides (Joffe, 1995; OTA, 1990). During the latest upsurge from 2003 to 2005, 13 million ha were sprayed, costing approximately 260 million US$ (Van Huis et al., 2007). In choosing control strategies, political arguments overruled technical ones. Pesticides were wasted and a huge pesticide waste disposal problem was created (van Huis, 2006).

The largest question we tackled during more than 20 years was about control strategies, and in particular whether early intervention (outbreak or upsurge prevention) would be feasible or whether upsurge elimination would be a better strategy. The discussion is about when to intervene during the sequence “outbreaks – upsurges – plagues”. Initially, only a small part of the locust population is aggregated in treatable targets. However, these small groupings occur over large areas and are difficult to find as we proved during field workshops we conducted with FAO in Egypt and Mauritania. Effective treatment would be unacceptable in terms of costs and environmental pollution. With each subsequent season, the population becomes more gregarious and more locusts congregate in a smaller area. Treating early or waiting becomes a trade-off among control effectiveness in terms of population reduction, what can be achieved and afforded in terms of resources, and how environmental side effects can be minimized. However, upsurge elimination, or delaying control until the population is within well-defined targets, is counterintuitive. Conversely, outbreak and upsurge prevention are psychologically appealing, as immediate action normally minimizes problems that develop and grow over time. In Desert Locust plague prevention this has been a large dispute. The positions taken often are entrenched. I have reviewed them in a publication with FAO (Van Huis et al., 2007). The dispute shows that cognitive biases are important in preventing rational choices.

5.2 The North American Mountain Pine Beetle

During a summer holiday in Canada in 2005, I was shocked by the state of the pine forests. Whole mountain ranges were brown with decaying trees. How did this happen? The beetle outbreak started just 25 years ago, and brought the country one of the worst ecological disasters in its history. Before that time, the beetles had existed in a natural balance with their environment, killing off older trees and making room for new growth (Spross, 2013).

The Mountain Pine Beetle *Dendroctonus ponderosae* Hopkins (Coleoptera: Curculionidae) is a native insect and historically contained to the pine forests west of the Canadian Rockies, which had adapted to the insects' presence. The Mountain Pine Beetle now is the most significant source of insect-caused mortality in mature forests in western North America. The area it affects now extends from the Yukon Territory, Canada, to southern California and New Mexico. The area affected in 2012 was 181,300 km^2, about 4 times the area of the Netherlands and is increasing. Climate warming is mainly responsible (Mitton & Ferrenberg, 2012). The insects colonised larger geographic areas and higher elevations as higher temperatures rendered those areas more hospitable. The flight season begins two months earlier than before and its duration is twice as long. The beetles even began reproducing twice a year rather than once. Because the pine beetles have no diapause, their development is controlled by temperature. They respond to climate change by developing faster. At minus 40 ^{0}C the beetles are killed off (Embrey et al., 2012), but because of milder winters since 1994 the die-off rate of the beetles has been reduced from 80 to 10 percent.

The dominant cause of tree mortality lies in the mutuality between the beetle and virulent blue stain fungi, including several from the genera *Grossmannia*, *Ophiostoma*, and *Leptographium* (Embrey et al., 2012). The beetles disperse the fungal spores with their mouthparts, inoculating host tree phloem while burrowing. The resulting fungal infection blocks the trees' vasculature, resulting in circulatory failure and death.

Making matters worse, the beetles are also producing a positive feedback loop that worsens climate change. As forests are killed off, fewer trees are left to draw carbon dioxide out of the atmosphere. At the same time, the dead trees themselves release the carbon they had previously stored — 990 million tons of CO_2 from the forests of British Columbia alone, as of the middle of last 2012. This amount is equal to five times the annual emissions from all forms of transportation in Canada (Kurz et al., 2008). As for the boreal forests the beetles are moving into, estimates put the amount of carbon stored there at 703 billion tons — twice the storage capacity per unit of area of tropical forests (Spross, 2013).

The disturbances described are projected to increase in frequency and severity of climate change because they threaten the resilience of such forests to withstand disturbance of the carbon pools stored by them (Kurz et al., 2008).

6. IPM and institutions

During my career I have been involved in a number of Integrated Pest Management (IPM) projects in Africa, Asia and Latin America. In the 1950s and 1960s, the research, development and extension model was a top-down, linear transfer of technology (TOT) approach. It was followed in the 1970s and 1980s by farming systems research (FSR), which tried systemically to understand the complexity of total farming systems, looking at the biological, economic and social dimensions. However, the information about farming systems was extracted from farmers and their farms and analysed by scientists, in a manner which enabled the scientists to diagnose and prescribe solutions for farmers (Chambers & Jiggins, 1987). In both TOT and FSR, scientists were considered to be the innovators. The failure of TOT and FSR was followed by participatory approaches including participatory technology development (PTD). The core aim was to put farmers in the centre of the innovation process to, in collaboration with scientists, provide experiential information and design new technologies that suited farmers' needs and adapt existing ones to local circumstances (Thompson & Scoones, 2009). The farmer field school (FFS) approach is a good example.

IPM efforts started in 1966, after the publication in 1962 of Rachel Carson's book Silent Spring, with the establishment of a FAO panel of experts in IPC (Integrated

Pest Control). In 1974, FAO and UNEP formulated the Cooperative Global Program for the Development and Application of IPC in Agriculture (based on "success" of the IPM cotton project in Nicaragua). In 1980, the FAO Inter-Country programme for the Development and Application of Integrated Pest Control in Rice in South and South-East Asia pioneered the Farmer Field School approach. In 1995, the Global IMP Facility was launched, an activity of FAO, UNDP, UNEP and WB.
Let me review some of the projects, which resulted from these IPM initiatives.

The claimed success of a project executed by FAO, UNDP and INTA between 1970 and 1979, entitled "Integrated pest management in cotton and basic food grains in Nicaragua" started off FAO's global IPM programme. This success was described in the landmark publication of Lou Falcon and Ray Smith entitled "Guidelines of IPM in cotton" (Falcon & Smith, 1973). I worked in the Nicaragua project. In 1979, I analysed the so-called "success" and concluded that the number of applications and costs of pesticides had not decreased. In their analysis, Falcon and Smith (1973) related pesticide applications to yield without taking into account crucial confounding factors, such as rainfall and farm size. Also, only 20% of total cotton area in the country was under IPM. My report was never published; I was strongly advised not to, as it could harm my future career. Notwithstanding my findings at the time, I believe that the IPM approach was excellent, but that the institutional framework and political support were lacking to make it a success.

One of the projects within FAO's Global IPM programme was the "Development and Application of Integrated Pest Management in Cotton and Rotational Food Crops in Sudan" executed between 1978 and 1996 by FAO and UNEP for the amount of 8.3 m US$ (Eveleens, 1983). I visited the project in 1997 and was impressed by the power of natural enemies to control the white fly *Bemisia tabaci* (Gennadius) (Homoptera: Aleyrodidae). That pest was not a problem in the area in which the project was able to prevent pesticide application, while the main area - that received 8 pesticide applications - was severely attacked by the white fly. However, the package deal between the Gezira Board and the pesticide industry proved very powerful.

Another large project initiated by FAO's Global IPM programme was "Research and Development of IPM for Basic Food Crops in Sahelian Countries" executed from 1980 to 1987 by CILSS, FAO and USAID for 30m US$. Only the first phase was implemented (Zethner, 1995). From 1982 to 1985, I was responsible for a complementary DGIS-funded IPM project, which trained professionals from Sahelian countries. The CILSS/FAO/USAID project stopped after the first phase because it did not deliver the expected results. In hindsight, the focus on IPM seemed ill advised. IPM often is a response to the negative consequences of chemical pest management in high external-input agriculture (Van Huis & Meerman, 1997). However, for subsistence crops, pest problems are often not a major concern. The project dealt with technology development in which farmers were not involved. A proper initial diagnosis of the problems was absent and institutional issues were ignored, such as the role of Plant Protection Services, which were geared towards chemical control solutions (Van Huis & Meerman, 1996).

Another large project was the "Inter-country National IPM rice programme in South and Southeast Asia " of which the first phase was executed in Indonesia between 1989 and 1992 by FAO (Gallagher et al., 2009). It was in this project that Russ Dilts, Peter Kenmore and Kevin Gallagher developed the IPM farmer field school as an effective tool for training farmers in IPM. Based on this experience, Farmer Field Schools were implemented in 87 countries and more than 10 million farmers were trained (Braun & Duveskog, 2008). In Indonesia one million farmers were trained, and although this sounds impressive, it only represents 2% of all farmers in the country (Oudejans, 1999).

The question here is: what triggered the emphasis on IPM in Indonesia? In November 1986, the then president of Indonesia, Suharto, issued Instruction INPRES/386, which banned 57 brands of broad-spectrum pesticides, while the subsidies for pesticides were withdrawn (a total of 400m US$ starting with 85% of pesticide costs in 1985 and ending with 0% in 1998). The person behind this decision was the Minister of Finance, Prof. Ali Wardana (James Fox; pers. comm.). It was a major trigger for the introduction of IPM, and it was taken notwithstanding involvement of the President's relatives in the pesticide trade. Looking back, it seems that the Indonesian government became convinced that pesticide use was a major *cause* of the devastation of rice fields brought about by the Brown Planthopper's (*Nilaparvata lugens* (Stål) (Homoptera: Delphacidae) increasing resistance and resurgence. Suharto's predecessor Sukarno had been brought down by popular upheaval caused by food (rice) scarcity. For Suharto pesticides became a major political risk. FAO's ICP programme in Indonesia started in 1989 (paid for out of abolished pesticide subsidies): the scientists were called in after the decree was issued.

The examples mentioned above show that the focus on technology often is not sufficient and that institutional factors such markets and politics can play crucial roles in achieving success (van Huis, 2009). Even the involvement of farmers as a stand-alone effort may not be enough (Hounkonnou et al., 2012). It is true, farmers might be knowledgeable, skilled, motivated, and empowered, and have participated in developing technologies that are suited to their circumstances and farm management objectives. However, if opportunities are lacking, these technologies still allow only marginal improvement. Therefore, from 2005 onwards the focus shifted to innovation systems. In the Convergence of Sciences programme we showed that smallholders are unable to benefit fully from appropriate and desirable technologies because of their limited opportunities. Our analysis showed that African smallholder farmers lacked an enabling institutional context. This probably is the cause of the sub-optimal impact of agricultural research. How can one enhance that impact? In the Convergence of Sciences programme 'research on agricultural research' was the main focus. Farmers need reasons to innovate. Hence, we looked at issues beyond farm gate. Innovation and technological change can be considered to be the outcomes of complex interactions among actors in the system, which includes farmers, private enterprises, universities, research institutes and others. We brought these stakeholders together in innovation platforms, which proved highly successful at low costs (CoS, 2013). Such results require working with social and economic disciplines (inter-disciplinarity) and with non-academic stakeholders (trans-disciplinarity). I could give eight examples of success, but limit myself to one. In Ghana, female artisanal processors were able to produce higher quality palm oil after having implemented improved processing techniques. Through district and national innovation platforms they were able to access more remunerative markets to fetch a higher price. The success changed the focus of Ghana's Oil Palm Research Institute, which now takes on board institutional issues, in addition to its usual purely technical (agronomical) mandate (Osei-Amponsah et al., 2014).

If Wageningen University and Research Centre is serious about "Science for impact" then inter- and trans-disciplinarity should receive much more attention. Impact can only be achieved when investing in identifying and understanding the stakeholders in some domain or arena of endeavour, and in facilitating informed interaction among these often diverse actors. There are large paradigm differences in the approaches of natural and socio-economic disciplines. Prof. Niels Röling once told me: for many natural scientists the truth is the 95% probability outcome of a randomized block design; for many social scientists the truth is the outcome of negotiation among key actors. Innovation occurs at the interface among disciplines. In the Convergence of Sciences programme we are proposing new pathways for agricultural research in West Africa so as to effectively create conditions for innovation. Frankly I am amazed that universities that have research as their mandate and that advocate 'science for impact' do not have a meta-discipline that focuses on pathways of research: research of research

7. Insects as food and feed

My interest in insects as food and feed was triggered during a sabbatical in 1995, during which I interviewed people in a number of African countries about the cultural aspects of insects. In 2008, FAO organized a regional conference on edible insects in Thailand. In 2010, I took a sabbatical to work on the topic at FAO Headquarters in Rome, focusing on its global significance. Since then the interest for edible insects has been growing exponentially with new enterprises and projects starting up all over the world. In 2013, we published a book with FAO, which has been downloaded 6 million times. The edible insect conference in May 2014 in the Netherlands attracted 450 people from 45 countries. Why does the subject draw so much attention?

Compared to 2005/07 the demand for animal protein is expected to grow by about 75% by 2050 (Alexandratos & Bruinsma, 2012). This leads to a worldwide realisation that we need alternative sources of animal protein. However livestock production currently already uses 80 percent of all agricultural land available. Increasing yields on existing agricultural land is a possibility, but there are limitations to further intensification of the use of croplands. One of the options is to use insects as food and feed.

About 2,000 insect species (list compiled by the taxonomist Yde Jongema)[1] are eaten worldwide, mostly in tropical countries. There is an erroneous assumption in the West that people in tropical countries eat insects out of necessity. This is because we in the West have never looked at insects as food. In fact, we have a negative attitude towards insects, which may not be justified considering that only 0.5 percent of the total estimated insect species in the world are harmful for plants, humans and animals (Van Lenteren, 2006). People eat representatives from almost all insect groups, including beetles, caterpillars, wasps, bees, and ants, crickets, grasshoppers, locusts, true bugs, termites, dragonflies, and flies. Up till now most of this food is collected from nature.

Why should we promote the use of insects as food and feed? I will list a number of advantages.

With respect to nutritional value, it is difficult to generalize across 2,000 species. However, in general, compared to conventional meat, the protein content is similar but contains more unsaturated (good) fatty acids (Rumpold & Schlüter, 2013). Insects

1 *http://www.wageningenur.nl/en/Expertise-Services/Chair-groups/Plant-Sciences/Laboratory-of-Entomology/Edible-insects/Worldwide-species-list.htm*

also contain more minerals such as iron and zinc. This is quite important considering that anaemia affects one quarter of the world's population and is concentrated in preschool-aged children and women (Christensen et al., 2006). Zinc deficiency results in a substantial disease burden predominantly among children less than 5 years of age, resulting in close to half a million deaths annually (Fischer Walker et al., 2008).

There are also a number of environmental reasons for replacing meat with alternative protein sources. Livestock is responsible for about 60% of all global emissions of ammonia (NH_3), an atmospheric pollutant. NH_3 is returned to the surface by deposition, which is known to be one of the causes of soil acidification, eutrophication of natural ecosystems and loss of biodiversity. Globally, livestock systems contribute to 14.5% of anthropogenic greenhouse gas (GHG) emissions (Gerber et al., 2013; Steinfeld et al., 2006). The main GHG emissions from livestock systems are methane from animals (25%), carbon dioxide from land use and its changes (32%), and nitrous oxide from manure and slurry (31%). To reduce them, a number of mitigation strategies have been proposed to increase the efficiency of the food chain from 'field to fork": better quality diets for ruminants, more productive livestock breeds, and changing from cows, sheep and goats to pigs and poultry (Gerber et al., 2013; Steinfeld & Gerber, 2010). But, a change from livestock species to mini-livestock species such as insects has hardly been considered.

Are insects doing environmentally better than conventional livestock? Studies show that a number of insects species used for human consumption such as crickets, mealworms and locusts produce considerably less GHG and that mealworms produce considerably less ammonia than pigs (Oonincx et al., 2010). A life cycle analysis (that takes into account the whole production process) for mealworms showed that the area needed to produce one kg of protein is 18 m^2, while for cattle it is ten times as much (Oonincx & de Boer, 2012). Another environmental benefit is the high feed conversion efficiency, i.e. the number of kgs feed needed to produce one kg of edible bodyweight. Producing one kg of beef requires 25 kg of feed, while a kg of edible crickets only requires 2.1 kg (van Huis, 2013). This lower feed requirement probably is due to the fact that insects are cold-blooded and do not need to maintain a body temperature higher than their environment.

There is one other advantage of insects. A number of species can be grown on organic side-streams, which is particularly important considering that one third of all our agricultural produce and food is wasted. This is globally 1.3 billion tonnes each year annually (FAO, 2011) costing 750 billion US$ (Economist, 2014). Insects can convert low value organic by-products into high value proteins.

We can also use insects to feed pets, livestock and fish. This is important as current protein feed ingredients, such as fishmeal, are becoming increasingly expensive. For example, fish farming (the aquaculture industry) now supplies more than 50 percent of the total amount of fish consumed and that percentage is increasing by about 6% a year (FAO, 2014). However, the supply of fishmeal used to feed carnivorous fish species (e.g., carp, salmon, tilapia and catfish) is becoming limited and therefore expensive. Fishmeal is extracted from fish caught in the wild, a source that is becoming increasingly scarcer as a result of overexploitation of the oceans. Vegetable feedstuffs, such as soya, can be used but the amino-acid profile, anti-nutritional factors, low palatability, and a high proportion of fibre limit their use as feed. Insects appear to be a sustainable source of protein with an appealing quantity and quality and acceptable nutritional properties. Promising insect species are the Black Soldier Fly and the Domesticated House Fly.

The promotion of insects for human consumption and their utilization in animal and fish feed means that they must be mass-produced. Experience is available. In Asia silk is produced on a large scale. Companies worldwide produce insects as fish bait and as feed for birds and reptiles. In the West, companies produce beneficial insects and market those to control arthropod pests of agricultural crops. However, feedstock companies that produce for aquaculture and the livestock industry need to be ensured of a large and continuous quantity of standard quality. The cost price of insect products needs to be competitive with current protein sources. This is possible by automating the production process. Insects for human consumption are farmed especially in Thailand. In that country about 20,000 medium and large-scale enterprises produce 7,500 tonnes of crickets per year; also other species are reared by using simple techniques (Hanboonsong et al., 2013). In Thailand, economic growth has been accompanied by a rising demand for insects for human consumption.

Is it safe to eat insects? Livestock and humans are similar in that they can share many diseases. A new disease strains in livestock may be lethal for humans. However, insects are very different from humans, so we expect this risk to be much lower. The few instances of food safety problems with insects relate to contamination with pathogens. For that reason, insects need to be reared under hygienic conditions. Similar to other animal-derived products, insects are susceptible to microbiological hazards and, therefore, proper heat treatment or storage conditions are required (Klunder et al., 2012). Could people allergic to seafood and to house dust mites face problems when eating insects? Laboratory studies have demonstrated that such cross reactivity is possible (Verhoeckx et al., 2014) and currently tests are being carried out in vivo (with humans) to ascertain this. If these tests are positive, proper labelling of insect products will be required. In Western countries legislation lags behind developments because rules and regulations were formulated before insects were considered as food and feed.

How to get the consumers, in particular those in Western countries, to eat insects? When we interviewed him for The Insect Cookbook, the former Secretary General of the UN, Kofi Annan, told us "*it is a matter of educating the public*" (van Huis et al., 2014). Even when stressing the environmental, nutritional and food safety aspects, and even when the product has an excellent taste, consumers may not be convinced. In the western world, insects have never been considered food. Cultural acceptance has to do with emotions and with psychology. However, with globalization it is possible that consumers may adapt, as has been shown in the case of sushi.

In 2008, the Laboratory of Entomology suggested in a press release that edible insects would be in the shelves of supermarkets in 2020. The events last month indicated that it happened five years earlier.

Insects provide many services to mankind. The benefits of using insects as food and feed over conventional meat are numerous (Van Huis et al., 2013). Insects have high potential of becoming a new sector in agriculture and the food and feed industry.

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and veterinary entomology. I started it up, but the medical and veterinary entomologist Willem Takken replaced me in 1997, when I became unable to work for a whole year as a result of a plane crash in Kenya (together with Joop van Lenteren). It is a pleasure to see that Medical and Veterinary entomology is flourishing and has a prominent place in the chair group. Joop van Loon, joined me during the last years in supervising PhDs on edible insects. He always impressed me with his knowledge of insect physiology. Of course I have to thank everybody in the chair group, in particular all PhD students. However, I need to mention one person in particular and this is Gerard Pesch, my assistant. He has been with me ever since my appointment in 1985, and has continued after his retirement. Numerous cups of coffee were brought to me, and meters of documents have been photocopied and scanned. He has been extremely loyal during all those years; being available all the time.

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'Insects are the most abundant and most diverse group of animal organisms on earth. The economic benefits of the ecological services provided by insects are enormous. Examples of two pest species with a global impact are given. During the last 30 years Integrated pest management projects started all over the world, but institutional contexts are often not conducive to success. The topic of insects as food and feed is conquering the world and the numerous benefits for satisfying the world's increasing demand for proteins are outlined.'

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