Mol Breeding (2013) 32:743–770
DOI 10.1007/s11032-013-9915-z

REVIEW

Building bridges: an integrated strategy for sustainable food production throughout the value chain

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Received: 31 March 2013 / Accepted: 1 July 2013 / Published online: 24 July 2013

Abstract The food production and processing value chain is under pressure from all sides—increasing demand driven by a growing and more affluent population; dwindling resources caused by urbanization, land erosion, pollution and competing agriculture such as biofuels; and increasing constraints on production methods driven by consumers and regulators demanding higher quality, reduced chemical use, and most of all environmentally beneficial practices 'from farm to fork'. This pressure can only be addressed by developing efficient and sustainable agricultural practices that are harmonized throughout the value chain, so that renewable resources can be exploited without damaging the environment. Bridges must, therefore, be built between the diverse areas within the food production and processing value chain, including bridges between different stages of production, between currently unlinked agronomic practices, and between the different levels and areas of research to achieve joined-up thinking within the industry, so that the wider impact of different technologies, practices and materials on productivity and sustainability is understood at the local, regional, national and global scales. In this article, we consider the challenges at different stages and levels of the value chain and how new technologies and strategies could be used to build bridges and achieve more sustainable food/feed production in the future.

Keywords Food · Farming · Sustainable

Introduction

The world's population is expected to increase by one-third (more than 2 billion people) over the next 50 years (US Census Bureau 2004), but the amount of land and water available for agriculture will not increase (Connor and Minguez 2012) and is more likely to decline due to urbanization, land erosion and pollution (IAASTD 2009; Royal Society 2009; FAO

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2011). Land and water will become even more precious as resources and there will be intense competition for different agricultural uses as the demand rises for food and feed, fiber and energy, space to rear livestock, and innovations in the use of plants to manufacture pharmaceuticals, industrial and specialty chemicals and other materials. Further increases in productivity are needed to satisfy the demand for agricultural products driven by the growing world population and the improved standard of living in many emerging economies (Rosegrant and Cline 2003; Tilman et al. 2011), but environmental sustainability is also seen as an increasingly important issue globally (Edwards et al. 1990; Evans 1998; Charles and Godfray 2011; Tilman et al. 2011).

These pressing issues can only be addressed by developing efficient and sustainable agricultural practices, and it is important to harmonize these practices throughout the value chain so that renewable resources can be exploited without damaging the environment further (Fig. 1). Therefore we must build bridges between diverse areas of food and feed production, including plant and animal production systems, food processing and food distribution networks. We must carry out research to understand the interactions between these components and to ensure that cutting-edge technologies are used to maximize yields, protect the environment and minimize waste, while maintaining the nutritional quality and safety of food and feed.

In this article, we consider the challenges affecting different components of the food, feed, raw materials and energy value chains and discuss how technology can help address these issues and provide the tools and strategies for a more sustainable agriculture in the future.

The environment

Overview

The environment encompasses all the abiotic and biotic factors and their interactions that affect us as living organisms, ranging in scale from the immediate surroundings of an individual organism (microenvironment) to the entire biosphere (global environment) (Peart and Shoup 2004). In the context of crops, the abiotic factors in the environment include edaphic conditions (the physical and chemical properties of the soil, such as its texture and structure, pH, aeration, water and mineral content), atmospheric conditions (e.g. radiation and CO_2 levels) and physical conditions that affect the use of edaphic and atmospheric resources (e.g. temperature and day length). The latter are considered in a broad sense (climate) or as short-term events (weather). The biotic factors include microbes that interact with crops in the soil or that cause plant diseases, animals such as insects, nematodes and earthworms, and competition with other plants (Nelson and Spanner 2010).

Any crop-management intervention affects either the capacity to deal with biotic and abiotic factors or the factors themselves, altering the edaphic/atmospheric conditions regulating crop productivity

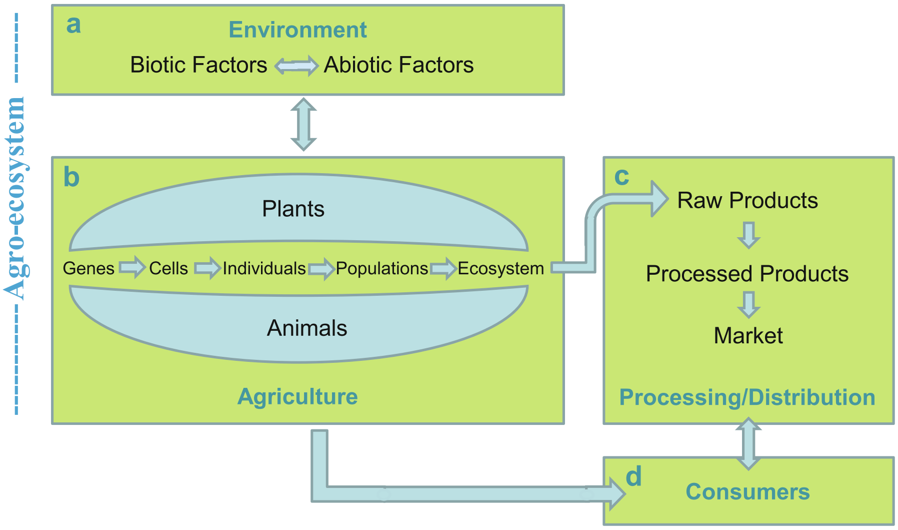

Fig. 1 Interacting factors that affect the food production and processing value chain. Panel **a** refers to the environment including biotic and abiotic factors; panel **b** represents plants and animals from genes to ecosystems; panel **c** represents processing and distribution of raw and processed products from agriculture; and finally panel **d** represents the consumers

(Loomis and Connor 1992). In many cases, these interventions have effects exceeding the crop itself, altering the wider components of agricultural systems, and thus innovations must accommodate soil and climate/weather characteristics either by exploiting their positive effects or mitigating their negative effects (Connor et al. 2011).

As well as being dependent on the environment, agriculture and food processing/distribution can also negatively or positively affect the biotic and the abiotic environment. Environmental pollution is among the most common negative consequences of agriculture and food processing whereas biodiversity reduction may have potentially both positive (e.g. less pests or less competition from weeds) and negative effects (e.g. less stability of agroecosystems or less food for birds). Therefore, the most valuable innovations prevent or even remedy environmental damage caused by conventional agriculture, as shown by the arrows leading to panel (a) in Fig. 1 or exploit its positive environmental effects. The remainder of this section focuses on measures to achieve environmental sustainability during the production of food, feed, fiber and bioenergy, through the rational use of natural resources. We consider the nature and impact of human activity on the environment, including the impact of agriculture and industry, and the development and implementation of novel technologies to facilitate interactions with the environment and thus promote sustainability.

Rational use of natural resources

The sustainable and efficient use of finite natural resources is necessary to guarantee our long-term survival, and thus rational and balanced use is necessary to achieve productivity targets while maintaining the environment, exploiting by-products and minimizing energy costs. The soil may contain large amounts of nutrients, but their bioavailability can be limited by soil properties, including the pH, water and organic matter content, temperature and the presence of particular salts. We can use nitrogen as an example, because this is an essential element needed for the synthesis of nucleic acids and proteins. Although nitrogen is abundant (nearly 80 % of the atmosphere is nitrogen), the primary productivity of both marine and terrestrial ecosystems is limited by nitrogen bioavailability, because this depends almost entirely on microbial redox processes. The fixation of atmospheric nitrogen using the Haber–Bosch process to produce nitrogenous fertilizers is recognized as a key step that facilitated the steady increases in agricultural productivity from 1860 onwards (Evans 1998). However, the increasing use of fertilizers has an important impact on the nitrogen cycle: nitrogen use efficiency is typically less than 40 %, and thus surplus nitrogen in agricultural runoffs initiates a cascade of events with a negative effect on the environment, such as the eutrophication of inland and coastal waters. The anticipated population increase over the next 50 years will only strengthen this demand for fixed nitrogen, so it will be essential to improve access to this key resource while minimizing its impact on the environment. This will require integrated and interdisciplinary research aiming to develop new strategies to reduce nitrogen waste in water resources and the integration of technologies to improve nitrogen use efficiency in crops (Galloway et al. 2008; Canfield et al. 2010). Similar challenges are evident with phosphorus, which is also required for agricultural productivity due to its presence in nucleic acids and its role as an energy currency in eukaryotic cells, but only a small fraction of total soil phosphorus is bioavailable and tens of millions of tons of phosphorus eventually end up in lakes and rivers, leading to eutrophication (Dumas et al. 2011).

Although not required in such large quantities, many trace elements are also essential nutrients with toxic effects when they accumulate as pollutants. Many areas of the world are polluted with heavy metals (particularly near mines and heavy industry) whereas others lack essential trace elements, resulting in malnutrition. For example, iron and zinc deficiencies are prevalent in developing countries because they lack infrastructure for the conventional fortification of processed food, but in many cases there can be a deficiency in the plant even if the minerals are present in the soil, because they are not present in a bioavailable form (Berman et al. 2013; Gómez-Galera et al. 2010). The uptake of metals depends largely on the free metal ion concentration and not on the total metal concentration, according to the paradigm of the free ion activity model (FIAM) which relies on internalization as the rate-limiting step (Anderson et al. 1978). Many techniques can be used to quantify metal ions in soil and water, including ion-selective electrodes (Bakker and Pretsch 2007), the Donnan membrane technique (Temminghoff et al. 2000) and absence of gradients and Nernstian equilibrium stripping (Galceran et al. 2004; Chito et al. 2012).

The bioavailability of metals in soil, and the corresponding nutritional and/or toxic properties towards different organisms, is determined by a set of linked events whose equilibrium values only represent simplified limiting cases within the general dynamic processes in the environment. Analytical dynamic techniques such as diffusion gradient in thin films (Davison and Zhang 1994) and voltammetry techniques such as gel-integrated microelectrodes (Noel et al. 2003) or scanned stripping chronopotentiometry (van Leeuwen and Town 2002) measure the available metal flux over different spatial and temporal ranges. A physicochemical framework for the interpretation of bioavailability data is also necessary, and this can be another limiting step in the development of suitable environmental chemistry methods. The speciation (distribution of chemical species) of metals needs to be characterized in addition to the dynamic and kinetic behavior of each system (Galceran et al. 2003; Mongin et al. 2011). Poorly-defined species such as humic and fulvic acids, polysaccharides, gels, nanoparticles and colloids can act as metal ligands under differing pH and ionic strength conditions, preventing the hydroxylation and precipitation of minerals and playing a key role in the circulation and ecotoxicological properties of metal species in natural media. Thermodynamic or statistical mechanics methods (Puy et al. 2008) are required to account for the heterogeneity and polyfunctionality of such macromolecular ligands, including their polyelectrolytic and electrokinetic characteristics, competition effects and the aggregation/dissolution of particles and colloids. Transport phenomena also need also to be considered, including dynamic speciation (i.e. moving beyond FIAM and relating bioavailability to metal fluxes).

Recent research on the bioavailability of nutrients and contaminants has focused on microbes as individual organisms, but many species form aggregated communities or biofilms protected by an array of gel-like extracellular polymeric substances. Metal bioavailability has also been assessed in higher plants such as perennial ryegrass (Kalis et al. 2008), wheat and potato (Perez and Anderson 2009), common dandelion and narrow-leaf plantain (Muhammad et al. 2012). Various strategies have been developed to increase the uptake of nutrients into plants by enhancing their bioavailability in the soil, such as the use of metal-chelating ligands to release metal ions bound to soil particles (Lucena et al. 2008). Likewise, transgenic plants have been developed which synthesize and secrete metal-binding ligands that are subsequently reabsorbed, or that secrete enzymes that convert trapped metal species into bioavailable ones, e.g. by reducing Fe^{3+} to Fe^{2+} (Berman et al. 2013; Farré et al. 2011). Lability criteria, indicating which physicochemical phenomena limit metal uptake, must be assessed to mitigate or eliminate these bottlenecks.

The challenging compromise of sustainable food/feed and bioenergy production

The amount of land required for biofuels to meet 20–30 % of International Energy Agency projections for transport fuel demands in 2050 ranges from 7 to 45 % of current global arable cropland (Murphy et al. 2011). Reasons for the wide range of these estimates are the uncertain yields of energy crops and the variable conversion efficiency of crops to biofuel. Therefore, it is unclear how the expanding bioenergy sector will interact with other land uses (Berndes et al. 2003; Dornburg et al. 2010). The recent large-scale acquisition of land in many parts of the developing world by foreign entities in the food/feed and biofuel sectors, frequently characterized as ‘land grabs’ by the media, provides an example of this complex setting, with many governments promoting foreign direct investment (FDI) in land with the presumption that it can contribute towards agricultural modernization and poverty reduction (Cotula et al. 2009). These practices often result in conflict between local populations and their governments (Habib-Mintz 2010). The ongoing debate also extends to the scientific community, with proponents of FDI arguing that it increases productivity and generates economic growth (e.g. Li and Liu 2005) and opponents arguing that lax FDI regulation could exacerbate food insecurity (Habib-Mintz 2010).

When increased demands for food, feed and energy coincide, there will be additional pressure to convert land for agriculture, leading to the loss of biodiversity and increased deforestation, as well as intense competition for water resources (Searchinger et al. 2008). This in turn affects productivity and land availability, so creating a potential vicious circle which has been described as the food, energy and environment trilemma (Tilman et al. 2009). It is unclear to what extent bioenergy agriculture can harmonize with other environmental goals such as biodiversity and sustainability (Berndes et al. 2003). Large-scale monocultures of bioenergy crops are devastating to natural habitats, so there is concern that such vast areas of land would be difficult to find without interfering with the production of strategic crops or natural ecosystem conservation measures (Tirado et al. 2010). One solution is to develop and reclaim degraded lands and wastelands or to use marginal lands rather than agricultural lands or natural forests, but it is uncertain whether such lands would achieve the yields required by investors, who tend to establish energy plantations on fertile forestry and agricultural lands where it is most profitable to do so (Azar and Larson 2000).

The global potential of bioenergy agriculture has been challenged in a debate calling for the prioritization of food production (OECD-FAO 2008). It is unclear whether there is a direct connection between biofuel production, food prices and the expansion of cultivated land (Gilbert 2010; Harvey and Pilgrim 2011; Henn 2011), but recent food price hikes have increased pressure to develop bioenergy crops only if they do not impinge on conventional agriculture for food and feed. Current (first-generation) energy crops are bred to produce starch and sugar for conversion into bioethanol, or oils for conversion into biodiesel, but these could be replaced with second-generation lignocellulosic biofuels from biomass that are thought to provide better gross energy yields with considerably lower energy and greenhouse gas input costs compared with traditional sources of bioethanol. This would allow the production of fuels from the non-consumed parts of food and feed crops, e.g. straw and wood chippings (Woods et al. 2010). Although second-generation bioethanol would not directly interfere with food production, it could affect food production sustainability in some cases; for example, straw is often used in developing countries as feed for grazing livestock (Cooper et al. 1987) and crop residues also maintain soil quality by sequestering carbon into humus (Lal 2007a). Under conservation agriculture systems, maintaining crop residues reduces soil erosion, increases water storage and crop water use efficiency, enhances soil biodiversity and increases soil organic matter (Cantero-Martínez and Gabiña 2004; Cantero-Martínez et al. 2007). Lignocellulosic feedstock should therefore be assessed in relation to competition for land, water, energy and biodiversity (Lal 2007b).

Trees are potentially sustainable as feedstock for biofuel and they can be grown on degraded or abandoned lands unsuitable for food crops, thus minimizing conflicts with food production (e.g. Campbell et al. 2008; FAO 2008). However, the bioenergy potential of abandoned agricultural land is small, although it may account for a significant fraction of global primary energy consumption in developing regions (Campbell et al. 2008). Accordingly, the intensification of agriculture on current arable land is likely both for food/feed and biofuel crops (Pretty 2008). This could be a sustainable approach with additional biodiversity benefits (Pretty et al. 2006) that might also reduce greenhouse gas emissions (Burney et al. 2010). The promotion of environmental, economic and social sustainability through good agricultural practice (GAP) standards (FAO 2003) and forest certification programs (e.g. the Forest Stewardship Council's Program for the Endorsement of Forest Certification) is necessary for the harmonious development of biofuel/bioenergy agriculture. In the long run, managing the interaction between food/feed and biofuels must be understood as an opportunity to improve food and energy security rather than a threat to the current status quo (Woods et al. 2010).

Some challenges and opportunities in the development of bioenergy crops are linked to other components of the food value chain. GAP refers to "… practices that address environmental, economic and social sustainability for on-farm processes, and result in safe and high-quality food and non-food agricultural products…" (FAO 2003). GAP codes may serve as the benchmark for deciding, at each step in the production process, on practices that are environmentally sustainable and socially acceptable. Indeed, GAP may serve as a baseline for the assessment of future developments in agriculture, but the challenge is to embed them in the framework of agricultural intensification, so that future food and energy demands can be met. Such approaches include integrated production and pest management and integrated water resources management to increase water use efficiency in areas with water shortages. Breeding crops using tools such as marker-assisted selection (MAS) and genetic engineering could also have a major impact by allowing the development of novel biofuel crops (Harfouche et al. 2012). For example, the controlled modification of lignin biosynthesis and degradation could encourage the use of cellulosic feed stocks for sustainable biofuel production (Ye et al. 2011).

Agriculture

Overview

Agriculture is any human activity that uses domesticated living organisms as sources to produce food/feed, fiber, fuel or raw materials that are necessary to sustain a human population. Agricultural systems are transformations of natural ecosystems with varying degrees of intensity, and are therefore immersed in the biosphere and dependent on the environment (Loomis and Connor 1992).

Agricultural productivity is determined by potential productivity and the extent to which this potential is limited by abiotic and biotic stresses (Lobell et al. 2009; Mueller et al. 2012). Research at different levels of organization (genes, cells, organs, individuals, populations and ecosystems) aims to improve agricultural productivity both by increasing the potential of crops and by reducing the impact of stress directly (mostly through crop management) or indirectly (by providing crops with tolerance, mostly through crop breeding in its broader sense). Research has focused on resource-use efficiency in agro-ecosystems, e.g. through the use of genetics (conventional and biotechnology-based breeding) to optimize resource utilization by manipulating developmental attributes and the partitioning of dry matter (Kropff et al. 2001; Reynolds et al. 2012). Focused crop physiology, genetics and biotechnology are required to reduce stress levels or increase stress tolerance, and here genetics must be combined with crop management at the population and ecosystem levels, including the likely impact on the environmental health and sustainability of the agro-ecosystem.

As well as affecting the environment, agriculture is also dependent on the environment and its combination of biotic and abiotic factors (bidirectional arrows between panels (a) and (b) in Fig. 1). In this section, we discuss the nature of abiotic and biotic stresses that affect crops and livestock at the genetic, cellular, individual and population levels, including the impacts of different forms of agriculture on each other, the impact of agricultural practices on the environment and the development of sustainable technologies to improve the performance of crops and livestock.

Progress at the molecular, cellular and individual levels: crop biotechnology

Crop biotechnology encompasses a wide range of approaches that rely on the use of molecular biology to generate crops with enhanced properties. Some of these approaches are used to augment trait-based selection (e.g. MAS and advanced mutagenesis approaches such as TILLING), whereas others involve the direct introduction of recombinant DNA into crops to make specific alterations that improve the phenotype. Genetic engineering in crops is therefore one of a broad selection of strategies that can be combined to provide a sustainable solution to the challenge of food and energy insecurity (Christou and Twyman 2004; Farré et al. 2010, 2011).

The first generation of transgenic crops was developed to modulate input traits, thus reducing the use of toxic herbicides and pesticides (Christou 2013). The ability to generate crops that tolerate broad-spectrum herbicides has reduced the use of more selective but more environmentally-damaging chemicals, and the ability to generate crops with built-in pest resistance has reduced the need for chemical pesticides and has also reduced fuel consumption and CO_2 emissions by limiting the need for spraying and plowing. This also conserves soil and moisture by encouraging reduced-tillage agriculture. The cumulative reduction in pesticide use for the period 1996–2008 achieved by deploying Bt crops (i.e. transgenic crops expressing pesticide genes from the bacterium *Bacillus thuringiensis*) was approximately 356,000 tons (8.4 %), which is equivalent to a 16.1 % reduction in the associated net environmental impact as measured by the Environmental Impact Quotient (EIQ). The corresponding data for 2008 alone revealed a reduction of 34,600 tons of pesticides (9.6 %) and a reduction of 18.2 % in EIQ (Brooks and Barfoot 2010). In countries such as India, China, Argentina and Brazil, which are the most enthusiastic adopters of Bt agriculture after the US and Canada, the greatest impact of Bt has been the reduction in the number of pesticide applications (from 16 down to 2–3 per growing season) and a concomitant reduction in the number of poisonings caused by chemical exposure. These factors, together with average yield increases of up to 10 %, have raised net incomes by as much as 40 % (Subramanian and Qaim 2010). Although the vast majority of first-generation transgenic crops are herbicide-tolerant, pest-resistant or both, a new wave of first-generation crops is approaching the market led by a drought-tolerant corn variety (http://www.agricorner.com/syngenta-rolling-out-drought-tolerant-corn-cuts-losses-15/ and http://blogs.desmoinesregister.com/dmr/index.php/2013/05/22/dupont-pioneer-sees-strong-demand-for-drought-tolerant-corn-seed/article?nclick_check=1). There are also transgenic varieties of crops with inbuilt disease resistance, such as rice resistant to bacterial blight (Zhang 2009), and virus-resistant varieties of papaya (Fitch et al. 1992), plums (Monticelli et al. 2012) and beans (Bonfim et al. 2007). Some of these varieties are already grown commercially whereas others are on the brink of commercial release.

The principal benefits of first-generation crops are yield increases achieved by reducing crop destruction by pests and pathogens (i.e. allowing the crops to reach their potential, as discussed above) but there is also an indirect impact on quality. For example, Bt corn confers resistance to corn borers, thus reducing quantitative loss due to pests, but the reduction in damage also prevents colonization by fungi and therefore indirectly reduces mycotoxin contamination. Field trials of Bt corn at 288 separate test sites have shown that harvested kernels have significantly lower fumonisin levels than non-Bt counterparts, typically 2–4 μg/kg dry weight (Wu 2006).

There has also been significant progress in the development of second-generation transgenic crops, which have enhanced output traits (e.g. nutritional properties). The principal example is Golden Rice, a transgenic rice variety containing an imported carotenoid metabolic pathway that promotes the accumulation of β-carotene (required by humans to produce vitamin A) in the endosperm. Normal cultivated varieties of rice contain negligible levels of β-carotene in the polished grains because a key rate-limiting enzyme, phytoene synthase, is inactive (Ye et al. 2000). The Golden Rice project was the first significant application of carotenoid metabolic engineering in plants and was envisaged as a humanitarian mission to alleviate vitamin A deficiency, which results in millions of cases of preventable blindness every year in developing countries (Bai et al. 2011). The first Golden Rice line contained three transgenes: the daffodil gene for phytoene synthase together with the bacterial genes *crt*I and *crt*Y, which encode downstream enzymes required to synthesize β-carotene from phytoene. The grains accumulated up to 1.6 μg/g dry weight of β-carotene, which was not sufficient to provide the recommended daily intake of vitamin A from a reasonable rice meal (Ye et al. 2000). A more active phytoene synthase gene was therefore used in place of the daffodil gene, resulting in Golden Rice 2 containing up to 37 μg/g dry weight of β-carotene (Paine et al. 2005). The introgression of the same traits into locally adapted varieties will allow the commercial deployment of Golden Rice in the next few years (Potrykus 2010). One of the reasons it is taking so long for Golden Rice to be made available to farmers is the excessive regulatory burden for deregulating transgenic crops in general, and negative campaigns by politically motivated pseudo-environmental organizations (Farré et al. 2010, 2011).

The power of second-generation transgenic crops has recently been demonstrated by the development of multivitamin corn. An important future trend is the move away from plants engineered to produce single nutritional compounds and towards those simultaneously engineered to produce multiple nutrients, a development made possible by the increasing use of multigene engineering strategies (Zhu et al. 2008, 2010). In this context, transgenic corn plants simultaneously enhanced for carotenes, folate and ascorbate provide the first example of a nutritionally-enhanced crop targeting three entirely different metabolic pathways, going some way towards the goal of nutritionally-complete staple crops (Naqvi et al. 2009). This was achieved by transferring four genes into an elite white South African inbred corn variety, resulting in a 407-fold increase in β-carotene levels (57 μg/g dry weight), a 6.1-fold increase in ascorbate (106.94 μg/g dry weight) and a twofold increase in folate (200 μg/g dry weight).

Mineral nutrients are another key target of genetic engineering, but this requires a distinct set of strategies because minerals need to be sequestered from the environment rather than synthesized de novo (Gómez-Galera et al. 2010). For example, the hyperaccumulation of iron in rice plants has been achieved by the expression of two transgenes, one encoding nicotianamine synthase (which is required for iron transport through the vascular system) and the other encoding ferritin (which increases the capacity for iron storage) (Wirth et al. 2009).

Any long-term strategy to address food insecurity in the developing world must tackle the underlying problem of poverty by increasing agricultural productivity in a sustainable manner (Islam 2008; Yuan et al. 2011; Berman et al. 2013; FAO 2011). In part this can be achieved by growing crops that are engineered for pest and disease resistance, drought tolerance and herbicide tolerance (Maqbool et al. 1998; Loc et al. 2002; Christou and Twyman 2004; Pérez-Massot et al. 2013) but the production of crops with higher nutritional value would mean that a smaller proportion of each farmer's output would need to be consumed to sustain the family and more could be sold at market, and there would be a lower burden of disease caused by malnutrition (Zhu et al. 2007, 2013).

Natural antioxidants from crops

Epidemiological studies have shown that the consumption of cereals, fruits, berries and vegetables lowers the risk of certain chronic diseases, and that the protective effect is conferred by bioactive compounds such as antioxidants (Esfahani et al. 2011; Finley et al. 2011). The potential benefits of antioxidants have attracted much attention from both consumers and the food industry. Phenolic compounds (tocopherols, polyphenols, phenolic acids and lignans) and ascorbic acid are the most important natural antioxidants, but carotenoids, Maillard reaction products, phospholipids and sterols in foods also possess natural antioxidant activity.

The antioxidant content and composition of plant foods are influenced by a range of factors including the plant variety, growth conditions (climate and soil), crop management (irrigation, fertilizer use and pest management), state of maturity at harvest, postharvest handling, storage and food processing (Bendini et al. 2007; Hollman et al. 2011). Even the simplest foods may contain hundreds or even thousands of interacting components differing in stability (Pastoriza et al. 2011). For these reasons it is difficult to estimate the total dietary intake of antioxidants. However, modern analytical methods such as liquid chromatography coupled with tandem mass spectrometry (LC–MS/MS) can identify and quantify low concentrations of phytochemicals in complex matrices such as plant tissues (Ignat et al. 2011; Smyth et al. 2012). Such analytical methods need to be validated in terms of selectivity, sensitivity, analysis time, peak efficiency, operating costs and quality parameters such as linearity, reproducibility, detection limits and quantification limits (FDA 2001; Vogt and Kord 2011).

To investigate the antioxidant mechanisms of food components and their role in disease prevention, it is necessary to understand the factors that affect bioaccessibility and bioavailability (Manach et al. 2004; Crozier et al. 2010). Nutrient bioaccessibility can be defined as the fraction of the ingested nutrients that is released from the food matrix and is accessible for intestinal absorption from the lumen, and this can be equal to or less than the total amount that is released from the food matrix (Stahl et al. 2002). In contrast, nutrient bioavailability also includes the limitations of nutrient absorption, tissue distribution and metabolism (Liu and Hu 2007) and therefore requires the measurement of absorption, transport through the circulatory system and delivery to the site of activity (McGhie et al. 2003).

Most data concerning the fate of antioxidants in humans are based on blood and urine analysis, but little is known about the concentration of antioxidants or their metabolic derivatives in different tissues. Even less is known about the kinetics of antioxidants and the equilibrium among different tissues and organs, but such information is required to evaluate the efficacy of bioactive compounds (Stahl et al. 2002). It is therefore necessary to develop and validate rapid, selective and sensitive methods for the quantitative analysis of low concentrations of antioxidants and their metabolic derivatives in different biological samples obtained throughout the food value chain. For example, these techniques could be used during food production to identify foods and feeds with high concentrations of bioactive compounds, and during secondary production to improve the control of food manufacturing processes, thus reducing the loss of bioactive compounds during processing and throughout the marketing chain (transport, storage, distribution and consumption). Further research on this topic will be of particular interest to the food industry. The development of healthy or functional foods will require the redesign of dietary sources to improve the delivery of beneficial compounds.

The future commercial/economic benefits of bioactive compounds as functional food ingredients can be realized by adopting the following strategies: (1) the selection/creation of cultivars, agronomic practices and animal feeds to produce foods with the highest content of bioactive compounds, either for fresh consumption or as ingredients in food formulation; (2) the development of validated, standardized and selective methods for the analysis of bioactive compounds in food and the establishment of real food composition databases; (3) the development of methods to determine the effects of formulation and processing on bioactive compounds to arrive at realistic intake levels; and (4) the analysis of food processing and matrix effects on bioavailability and the impact of common metabolic pathways producing bioactive compounds, to investigate their health-promoting effects.

Plant and animal productivity: crop physiology

Crop physiology aims to increase our understanding of the physiological basis of crop productivity and quality (Reynolds et al. 2009; Sadras et al. 2009). This is achieved by integrating physiological processes and plant community responses in agricultural settings, so that the impact of genetic and environmental factors on yield and quality can be understood and managed. Ultimately, by improving the efficiency of resource capture and utilization by crops, it may be possible to create more sustainable agricultural systems.

The physiological basis of productivity and quality in grain crops must be understood in order to improve breeding and management decisions (Slafer and Araus 2007), but it is also important to appreciate the factors that become relevant when scaling up from laboratory research to large-scale production in the field (Passioura 2010). Crop physiology, therefore, focuses on the precise level of organization required to provide knowledge and tools that are readily applicable to crop breeding and management, particularly when seeking improvements in complex traits whose impact during large-scale production may be uncertain (Slafer 2003; Wollenweber et al. 2005).

An understanding of traits at the physiological level helps to predict synergies and bottlenecks (e.g. interactions between new environments and breeding strategies, between agronomy and breeding, and between biomass and partitioning traits). Over the last two decades, significant progress has been made in a number of research areas that have the potential to boost crop productivity, particularly in major crops such as wheat (Araus et al. 2008; Reynolds et al. 2009; Foulkes et al. 2011). The efficiency of breeding for increased yields and other complex traits will benefit from the combination of conventional empirical approaches and new knowledge arising from the analysis of relatively simple traits at the crop level of organization (Slafer 2003; Slafer et al. 2005; Fischer 2011).

There are many successful examples of the selection of physiological attributes, such as the optimization of flowering time in grain crops by manipulating developmental characteristics. In environments characterized by terminal stress, the yield of cereal crops is often improved by earlier flowering. Improved drought tolerance has been achieved by phenological modifications that allow crops to escape stress (e.g. Araus et al. 2002). An informative example is the shorter anthesis–silking interval (ASI) in corn, a monoecious crop in which yield depends on axillary female inflorescences whose development is delayed compared to the apical male inflorescence. This results in an interval between pollen release (anthesis) and silking, which is prolonged by drought stress (e.g. Hall et al. 1982). Selection for reduced ASI has been successful because ASI is negatively related to yield and has a much higher heritability (Bolaños and Edmeades 1996; Chapman and Edmeades 1999).

Another more complex example is selection for reduced capacity to discriminate against ^{13}C during photosynthesis in Australian wheat (Rebetzke et al. 2002). There is a negative relationship between transpiration efficiency and discrimination against ^{13}C in C3 crops (e.g. Farquhar et al. 1982; Farquhar and Richards 1984). Under severe drought conditions, better transpiration efficiency can increase yields, and thus a breeding program was set up using backcrossing to introgress relatively low discrimination into a well-adapted cultivar with relatively high discrimination against ^{13}C. This resulted in a commercial cultivar (Drysdale) with consistently better performance under stress compared to high-discrimination sister lines and the widely-recommended cultivars for that region (Richards 2006).

Understanding physiological processes determining yield and quality in crops will become even more important in the future because physiological tools will be required to interpret the relevance of phenotyping strategies based on levels of organization much lower than the crop itself.

Plant health in agro-ecosystems

The biotic factors affecting crop yields (arrow from panel (a) to panel (b) in Fig. 1) include three major groups with negative impacts, namely weeds (mainly causing competition for resources), pests (causing damage and loss of biomass) and pathogens (causing diseases that interfere with the physiology of healthy crop plants).

Weeds are plants that coexist with a crop in the agricultural setting and establish some form of competition for nutrients, water, light and/or space, resulting in a lower crop yield. Therefore, although the term ‘weed species’ is often encountered, this is in fact meaningless because a weed is defined more by the setting than the species. Any plant can be classed as a weed if it grows where it is unwanted and has a detrimental effect on other plants that are wanted. Weeds not only reduce yields by competition, they can also act as alleleopaths by releasing chemicals that directly inhibit the growth of crops or they can disrupt harvesting and contaminate harvested products (Sanyal et al. 2008).

Pests are organisms that cause damage to plants either by feeding on them or interfering with their growth and development in a way that reduces yields and/or quality. Examples of interference with normal crop development and growth caused by pests include the injection of toxins or pathogens, honeydew deposits that reduce photosynthesis, or the mutilation of plant tissues for nesting. Most pests are arthropods, but other herbivorous invertebrates and vertebrates can also be regarded as pests. Pathogens are generally fungi, bacteria and viruses that cause crop diseases, but some plants that directly parasitize the crop may also be classed as pathogens. Both weeds and pests can also act as reservoirs for disease-causing bacteria, fungi and viruses. These invade the plant and utilize plant resources for growth and reproduction, often causing visible disease symptoms and a loss of yield and quality.

Weeds, pests and pathogens are serious constraints preventing the improvement of agricultural productivity, currently accounting for the loss of more than two-thirds of the attainable yield (67 %) on a global scale (Oerke and Dehne 2004); this means that crop yield might be increased by more than 67 % if 100 % effective control measures could be applied. The loss is made up of 17 % lost to pests, 18 % lost to diseases and 32 % lost to weeds. The comparison of loss potential and actual losses shows that plant protection is only just above 50 % efficient (Oerke and Dehne 2004), with weed control the most efficient component (70 %) and disease control the least efficient (13 %). In southern Europe, including Mediterranean regions, the percentage of yield losses due to pests is still significant (40–45 %) despite the extensive use of chemicals (Oerke 2006).

The increase in agricultural productivity over the last 50 years has been mirrored by a parallel increase in pesticide use, which is environmentally unsustainable. Research into novel pest control methods has therefore focused on understanding the causes of infestations and attempts to replace conventional pesticides with biological and genetic methods. Other investigators have looked at genetic engineering (Benbrook 2012) or systems-based approaches which involve the replacement of current pesticides with more sophisticated agents (Lewis et al. 1997). This means that the fundamental challenge is not the typical low long-term efficacy of pesticides, but understanding why agricultural pests exist at all and using this understanding to manage them more appropriately.

Such an apparently simple question can only be addressed by analyzing pests as a symptom within the framework of the overall agro-ecosystem (Fig. 1). Agro-ecosystems differ from natural ecosystems in several ways, including the need for energy input in addition to sunlight (e.g. fuel for agricultural machinery) and the focus on a specific crop leading to the simplification of biodiversity within the producer and consumer food web levels. A simplified agro-ecosystem is shown in Fig. 2, indicating the components linked to plant health and pest control. Productivity is maximized by increasing the proportion of sunlight energy that is fixed as biomass by the crop, reducing the level of interference caused by weeds, and reducing the damage caused by pests and pathogens.

The complex nature of the agro-ecosystem demands an integrated approach to managing all the potential multitrophic interactions, noting that changes to individual components may upset the whole system. For example, tritrophic interactions between plants, insect herbivores and their natural enemies are being investigated to devise strategies for crop protection based on the attraction of enemies of pest species. However, even when just a few elements in the three trophic levels are considered, complexity

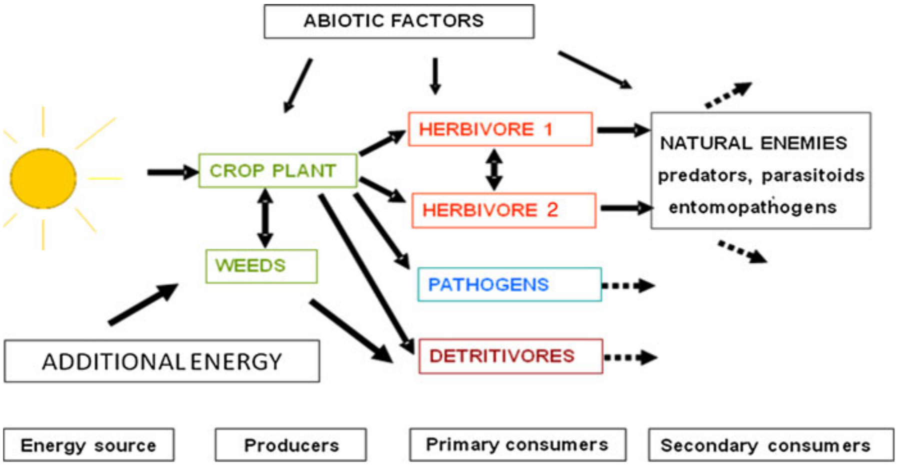

Fig. 2 Agro-ecosystem showing components and relationships related to crop pests and their control. *Arrows* show the direction of energy flow between components of adjacent trophic levels. *Double arrows* show competition between components within a trophic level. *Broken arrows* show that energy flow continues but the components involved are not represented

increases enormously and translation to agro-ecosystem management practices has been remarkably slow and ineffective. A truly integrated approach to agro-ecosystem management not only requires a comprehensive understanding of the ecological parameters, but also organizational knowledge at the molecular level from gene to individual. This would allow the two approaches to be combined in a strategy known as integral quantification of biological organization (IQ_{BIO}) to enhance our ability to generate improved crops (Keurentjes et al. 2011).

This multilateral approach to agro-ecosystem management provides new selective intervention methods that keep sensitive components within tolerable limits, taking into account that agriculture is driven by economic, social and environmental forces. Initial economic analysis (considering the costs and benefits of any measure to reduce the impact of pests) uses a simple economic threshold to make pest control decisions (Higley and Pedigo 1999). The economic threshold is the point at which the estimated benefit in yield improvement covers the cost of the intervention. This simple parameter conceals how challenging it can be to understand the relationships between pests and yields, reflecting the wider and more complex interactions within the agro-ecosystem. Western society demands sustainable and environmentally-responsible agriculture, but the costs of interventions that control pests are poorly described because they do not consider effects on related ecosystems or the global environment. Furthermore, the long-term consequences of current pest control methods must be taken into account when considering control costs because some of the side-effects of current methods only become visible later when the cumulative effects are manifested or when buffering factors are no longer able to cope (Higley and Pedigo 1999).

Modern pest control methods recognize the need for integration and the desire for synergistic or at least complementary efficacy. Improved pesticides, pest-resistant crops and biological control methods are the cornerstones of innovation in pest control, but other non-chemical methods may also be integrated to implement efficient Integrated Pest Management (IPM) systems that, in addition to higher agricultural productivity, reduce the environmental impact of pest control (Brewer and Goodell 2012).

Beyond pesticides (and herbicides to control weeds), new strategies have been incorporated into integrated weed management programs that use multiple management tactics and incorporate knowledge of weed biology and crop physiology (Sanyal et al. 2008). Recent research has focused on the development of engineered crops with intrinsic herbicide resistance, although the adoption of these new varieties will oblige growers to modify their current cultural practices substantially (Vencill et al. 2012). The restriction of chemical pesticide use, particularly in Europe, is a major force driving innovation in the field of pest control. In a few years, most of the pesticides/insecticides available at the end of the last century will be withdrawn or marked for withdrawal from the market, increasing the necessity to find novel non-chemical methods to control pests, diseases and weeds. Surprisingly, this restrictive policy on pesticides has not been accompanied by a corresponding change to the regulatory framework in Europe to allow the development and rapid deployment of biological and biotechnology-based methods (Masip et al. 2013).

Animal health in agro-ecosystems

The sustainability of livestock production in the context of global climate change, population dynamics and agro-ecosystem quality is a matter of intense debate (Casasús et al. 2007). The report "Livestock's long shadow" (Steinfeld et al. 2006) evaluated the impact of the livestock sector (and feedstock agriculture) on the environment and suggested technical and policy approaches to help mitigate its negative effects. However, because livestock farming systems differ widely in terms of intensity and resource-use efficiency, a uniform approach is unlikely to succeed (Casasús et al. 2007). Meat, dairy and egg production in many parts of the world has become industrialized, and large numbers of animals are raised in confined facilities with specialized forage and grain-based diets to maximize productivity (Hogberg 2010). In contrast, pasture-based livestock production is both socially and environmentally beneficial and enjoys significant cultural diversity (Gibon 2005).

Before 1950, most animals were raised on small, diversified farms with access to pasture. Following the industrialization of crop production, the traditional livestock business was replaced with an industrial model reflecting the increase in grain production, more efficient transport and other technological developments (Mallin and Cahoon 2003). Animal production also became more specialized, e.g. large farms that focus on a single production phase have replaced farrow-to-finish farms where all stages of production are carried out (Key and McBride 2010). These changes improved efficiency and revenue while reducing the footprint of livestock production, encouraging the adoption of novel technologies (Steinfeld et al. 2006). More recently, the livestock industry in developed countries has focused on animal well-being, environmental issues, food safety and human health more than improving the efficiency of production (Hogberg 2010).

The livestock sector is currently a major source of environmental damage, contributing significantly to land degradation, greenhouse gas emissions, water pollution and loss of biodiversity (Steinfeld et al. 2006). There is a complex relationship between climate and infectious diseases, based on the distribution of disease vectors, deforestation, economic development, animal movement, habitat destruction and drug resistance (Torremorell 2010). These issues need to be addressed urgently through the development of more sustainable industry practices, which would result in a massive positive effect on the environment in the short term at a reasonable cost. Production is currently shifting away from ruminants (cattle, sheep and goats) raised on pastures and towards monogastric species (pigs and poultry) raised indoors or in batteries (Steinfeld et al. 2006). These changes increase efficiency and land use but marginalize smallholders and pastoral farmers and increase inputs, waste and pollution, particularly the larger volumes of wastewater (manure and liquid waste) which requires specialized animal waste management systems (Kanwar and Burns 2010). On the other hand, increased industrialization does reduce the rate of deforestation and pasture degradation, but this can also be addressed by restoring historical losses of soil carbon through measures such as conservation tillage, cover crops and agroforestry, which could sequester up to 1.3 tons of carbon per hectare per year with additional amounts available through the restoration of desertified pastures. Methane emissions can be reduced by improving diets to reduce enteric fermentation and improving manure management (Steinfeld et al. 2006; Kanwar and Burns 2010).

Intensive livestock farming has become important in developed countries and also in emerging economies because the demand for meat and dairy products is increasing and is expected to double by 2050 (Tilman et al. 2002). Research is required to ensure that the livestock sector can respond to a growing demand for animal products and at the same time contribute to poverty reduction, food safety, environmental sustainability and human health. The environmental footprint of livestock production must also be reduced because consumers in many countries are increasingly concerned about the environmental impact of farming in addition to food quality (Tilman et al. 2002; Gerber 2010) and ethical standards for animal welfare (Johnson 2010a). The industry must also respond to volatility in the price of raw materials and exchange rates, the competition between biofuel and feed crops, and competition between different market sectors (Coma 2010). In developing countries, almost 50 % of people living in absolute poverty are livestock keepers and they often depend on livestock to live above subsistence level by generating off-farm income from chickens, sheep, goats, pigs or cattle (Herrero et al. 2009; Kristjanson 2010).

The complex challenges of livestock agriculture must be addressed through multidisciplinary research with a strong grounding in ethics (Hogberg 2010). Animal genetics plays an important role in livestock production, particularly genome analysis to improve and redesign breeding programs, e.g. by selecting bulls for breeding at a young age rather than waiting for progeny (Schaeffer 2006). Female genomic selection can also reduce generation intervals compared to current breeding programs (Schaeffer 2006; Dekkers 2010). The control of reproduction can also enhance livestock productivity sustainably. In effect, animal wellbeing can be related to the highest levels of production and fertility thus improving the efficient use of natural resources (López-Gatius 2003; López-Gatius et al. 2006; García-Ispierto et al. 2007).

Different nutritional strategies are available to reduce the emission of nitrogen, phosphorus and methane in animal waste, such as the efficient use of byproducts in the feed industry (Coma 2010) and the use of transgenic plants tailored for their nutritional properties (Farré et al. 2010, 2011; Kothamasi and Vermeylen 2011; Naqvi et al. 2009, 2010, 2011). Animal waste can also be managed by applying solid and liquid manure as fertilizer for crops, pasture grasses and forests (Lloveras et al. 2004; Powers and Burns 2007; Berenguer et al. 2008; Kanwar and Burns. 2010).

Plant breeding

Plant breeding is a key component of the food production and processing value chain, which interacts directly or indirectly with all four major areas shown in Fig. 1. Agronomists generally select varieties for cultivation based on their expected returns in the form of the highest attainable yields. Breeding programs aim to release cultivars that can be grown successfully over a large cropping area, varying in soil attributes and across several growing seasons, with interannual variations in climatic conditions. Cultivar selection is a critical factor that strongly determines the sustainability of the agricultural system, but this is not a trivial decision because it can be challenging to identify a cultivar that is ideal for diverse environments exposed to complex biotic and abiotic factors and interactions, and also tailored to processing and market needs. Therefore, any comprehensive breeding program requires a detailed understanding of the biotic and abiotic constraints in the relevant environment (Cooper and Hammer 1996), the factors that determine crop yield and quality at the gene, cell and individual plant levels (Sadras and Calderini 2009), the opportunities and requirements in the crop management and agricultural system (Denison 2009), and the technological, nutritional and sociological prerequisites imposed by processing, distribution and consumer acceptance (Sands et al. 2009).

Plant breeding focuses on the identification of advanced genotypes broadly or narrowly adapted across a wide range of target environments, as ascertained by means of genotype × environment interaction (G × E) studies (Romagosa et al. 2009). Well-adapted cultivars with improved yields and quality are always welcome, but breeders must also address the greater social awareness of environmental issues, which restricts the use of pesticides, growth regulators and chemical fertilizers (Delmer 2005; Beddington 2010; Brummer et al. 2011). Breeding can address some of these issues in a sustainable manner by incorporating increased tolerance to abiotic stress (Cattivelli et al. 2010; Passioura and Angus 2010), protection against pests and pathogens (Niks et al. 2011), and by increasing yield potential by modifying plant growth, development, architecture and input use efficiency (Sadras and Calderini 2009). Breeding objectives have also changed from predominantly focusing on yield to including quality and value-added traits (Baenziger et al. 2006). These challenges require that plant breeding is integrated into the rest of the food production and processing value chain as a combined multidisciplinary endeavor, involving the coordination of efforts from genetics, molecular biology, biotechnology, conventional breeding, mechanization, integrated pest and fertility management, and food/feed transformation so that agricultural research can address food and energy security at a societal level (Godfray et al. 2010; Tester and Langridge 2010).

Plant breeding is a rapidly-evolving discipline, which uses germplasm as a central resource (Rasmusson 1996). Whereas selection was formerly achieved directly at the phenotypic level, plant breeding now embraces more advanced genotypic selection methods such as MAS (Xu and Crouch 2008; Collard and Mackill 2008). Markers are deployed in commercial breeding programs as routine tools to identify specific genotypes and to select genes linked to known markers (Thomas 2003; Johnson 2010b; Foolada and Pantheeb 2012). Markers also facilitate the dissection of complex quantitative traits through association mapping, particularly the analysis of quantitative train loci and as an intermediate step towards the identification and isolation of candidate genes (Salvi and Tuberosa 2005; van Eeuwijk et al. 2010). Whereas genomics data was a scarce and expensive resource in the past (particularly for non-model species), the advent of next-generation sequencing now provides rapid and relatively inexpensive access to a large number of novel markers (Stratton et al. 2009). The combination of accessible genomic data and sophisticated statistical methods is also providing novel strategies for genome-wide selection, the location and isolation of useful genes, and the integration of genomic data with RNA and protein expression profiles, protein structures and interactions, metabolite profiles and phenotypes (Granier et al. 2006; Bernardo and Yu 2007; Montes et al. 2007; Cooper et al. 2009; Heffner et al. 2009; Jannink et al. 2010; van Eeuwijk et al. 2010). Even so, it remains challenging to convert the mass availability of molecular data into meaningful and measurable breeding practices (Hammer et al. 2006).

Strong bridges are therefore required between plant breeding and related disciplines such as high-throughput phenotyping schemes, which are currently applied to individual cells, tissues, organs or plants, and which therefore may have little impact on crop breeding. Scaling up from processes that take place in a few seconds observed in small isolated tissues, and applying the principles to crops growing for months over large areas, has been consistently unsuccessful and remains one of the most difficult and obscure aspects of crop breeding. Crop physiology may play a key role in understanding multi-trait interactions when scaling down from the phenotype to the underlying molecular mechanisms or scaling up from the gene to crop breeding programs (Chenu et al. 2009; Slafer and Araus 2007; Spiertz et al. 2007). One worrying development is that traditional plant breeding, like most classical agricultural disciplines, is becoming unattractive to funding agencies and younger scientists. However, without breeders and agronomists these "…new genetic approaches might never bear fruit…" (Knight 2003). There is no clearer demonstration of the need to build bridges within public and private institutions to create added value from complementary disciplines in order to improve agricultural productivity as a whole.

Agronomic practices and food safety

Agronomic practices

Our food production and processing value chain originates with crops, and although the properties of these crops and their interactions with the environment are critical components of sustainable agriculture, the development and optimization of integrated agronomic technologies is also necessary to achieve sustainability and productivity. Indeed, improvements in agronomic techniques have been responsible for 50 % of the yield increases achieved over the last 50 years (Hobbs et al. 1998). Research in the field of agronomy should focus on four key attributes, which can be summarized as follows:

(a) The development of new agronomic practices that promote sustainable soil management, efficient nutrition, crop productivity, the control of pests and diseases and the use of sustainable materials (Tilman et al. 2002).
(b) The implementation of technologies that promote the conservation of natural resources, especially soil and water (Lal 2000).
(c) The development of strategies to increase carbon and nitrogen fixation, reducing greenhouse gas emissions through the sink and increasing the fixation capacity of crops and soils (Lal 2007b).
(d) The development of strategies to determine the impact of different agronomic technologies on biodiversity conservation in agricultural systems (Cardador et al. 2012).

More than 80 % of our food is produced on large-scale farms but much of the population lives in communities that could be sustained by small-scale local farms, and thus crop management and technology should be addressed towards farms at different scales and not solely focused on the larger and more industrialized ones (Lauer et al. 2012). Agronomic practices include all operations that are used to manage crops or crop combinations, and in a wider context also farming operations that include the rearing of livestock (which may or may not be related to the management of crops) and the environmental, social and economic impact of farming (Golley 1995). Typical crop management practices include soil management (e.g. tillage), applying fertilizers, irrigating crops that are not rain-fed, sowing, pruning, harvesting and the management of pests, diseases and weeds.

After selecting the appropriate crop variety/cultivar and crop rotation strategy, soil management becomes an important decision issue for producers using different combinations of tools benefiting significantly from recent advances in soil science. Soil provides a physical substrate to anchor plants in the ground, but each type of soil also has a unique profile of physical, chemical and biological properties that supports the existence of a discrete community of living organisms (including the crop) which develop complex relationships and interdependencies (Lal 2007b). This community effect is difficult to recreate, suggesting that a greater demand for food could only be satisfied by the provision of more agricultural land. However, land erosion and the loss of topsoil is accelerating, with almost one billion hectares lost due to water erosion, 450 million ha by wind erosion and 75 million ha by salinization over the last few decades (Oledeman et al. 1991; FAO 2011). The nitrogen lost by erosion must be replaced using fertilizers, and therefore proactive soil management is required to halt and reverse land degradation and the consequential need for chemical fertilizers (Kirchman and Thorvaldsson 2000).

Water supplies are also affected by agronomic practices. Depending on the crop, 200–600 L of water is required to produce 1 kg of dry biomass (Sadras et al. 2007). In both rain-fed and irrigated crops, water availability can be a significant productivity constraint. Crop and soil management strategies that promote efficient water utilization and water retention in the soil are therefore valuable. The conservation, restoration and enhancement of soil and water resources are essential to ensure sufficient yields (Lal 2007b).

Crops also require nutrients that are present naturally in the soil but augmented by fertilizers. Sustainable agriculture demands that nutrient management should be fine-tuned to optimize agricultural productivity while minimizing the loss of nutrients and their impact on the environment. This may involve the regulation of nutrient applications and strategies to recycle nutrients to maintain soil fertility while limiting the impact of leaching and run-offs. Intensive livestock farming has increased the number of animals and the amount of manure produced without increasing the capacity for recycling. This should be addressed by developing management practices that balance the requirements of crops, nutrient inputs and outputs, nutrient availability and uptake, and soil–plant and atmospheric transformation of the nutrient products. For example, legumes provide up to 400 kg of nitrogen per ha by fixing atmospheric nitrogen. Furthermore, additional nutrients can be reintroduced into the soil by using animal manure as fertilizer, either in addition to or instead of chemical fertilizers (National Research Council 2010).

Agricultural productivity can be limited by certain environmental and technological constraints, and agricultural technology must therefore adapt to maximize resource use (such as soil, water, the climate and biodiversity). Several niche production systems have been developed in response to this challenge, including organic farming and other alternative agriculture concepts. However, we need to broaden the impact of sustainable agriculture by defining locally-optimized production systems for different environments and developing interactions between different sustainable agricultural practices to form an integrated food production and processing value chain with sustainability as a key principle (Hendrickson et al. 2008).

This will require the integration of agronomic research with related disciplines such as soil science, crop physiology, plant breeding, biotechnology, engineering (irrigation systems) and pest management, and to consider these integrated disciplines in the wider scope of agro-ecosystems. Crop management can be considered as part of the environment effect in the analysis of G × E interactions, but different practices such as soil management, plant nutrition and crop rotation have different effects. For example, there are major interactive effects between soil management systems and fertilizer use because most of the nutrients come from the soil, which also regulates nutrient uptake. Plant pathologists, entomologists and weed scientists consider agronomic practices to be cultural (without distinguishing between practices such as tillage and irrigation) and do not consider the impact on the interactions between plants and pests/pathogens. More integrated research and improved knowledge systems are therefore needed, especially in the most vulnerable socioecological systems (Beddington et al. 2010).

The sustainable control of microbial hazards in food

Fruits and vegetables are an important part of the human diet because they provide vitamins and essential mineral nutrients as well as beneficial compounds such as antioxidants. Consumers are concerned about the safety of the fresh products they eat and expect them to be free from pesticide residues, toxins and harmful microorganisms. However, damage caused by pests and diseases in the field and during storage and transit can result in up to 25 % losses in the developed world and more than 50 % losses in developing countries, reflecting the lack of adequate storage facilities. It is essential to avoid the presence of pathogens in fruits and vegetables, and this is a basic requirement in food safety programs including GAP, good manufacturing practice and hazard analysis critical control point (HACCP) programs (IFPA 2001).

Synthetic fungicides are used to control postharvest diseases, but the appearance of resistant strains along with growing concern over the health and environmental hazards associated with pesticide use in fruits have generated significant interest in the development of alternative non-chemical methods for disease control. All pesticides on the market are currently under review by the European Commission and most will be withdrawn (Directive 91/414/CEE). Biological control methods using microbes have been investigated to identify environmentally-sustainable ways to control diseases (Pusey and Wilson 1984; Droby et al. 1992; Janisiewicz and Marchi 1992; Viñas et al. 1998; Teixidó et al. 2001; Usall et al. 2001; Chanchaichaovivat et al. 2007). The first generation of biological control agents consisted of single antagonists that lacked the consistent, broad-spectrum control achieved by synthetic fungicides (Droby et al. 2003). Single microbial antagonists have variable efficacy, their protective effect diminishes with ripening, and they usually cannot eradicate incipient or pre-existing infections or prevent fungal sporulation (El Ghaouth et al. 2002). The next generation of biological control agents comprises mixtures of antagonists that may have undergone physiological and/or genetic improvement through breeding or biotechnology (Janisiewicz and Korsten 2002). Their efficacy can be increased by combining field and postharvest applications, by developing innovative formulations, and by integration with non-biological methods such as physical decontamination and the application of low-toxicity compounds (Droby et al. 2003). Spadaro et al. (2004) suggest that current biological control agents must be used in combination with other methods of control in an integrated vision of postharvest disease management. The optimization of growth media and the cultivation environment can increase the stress tolerance of biological control agents and thus enhance their performance in practical situations, during formulation (Usall et al. 2009) and pre-harvest applications (Teixidó et al. 2009).

Ready-to-eat fresh fruit and vegetables represent an important area of potential growth in the food industry and the sale of pre-cut/pre-packed food is increasing all over the world. Although spoilage bacteria, yeasts and molds dominate the microbiota found on raw fruits and vegetables, the occasional presence of pathogenic bacteria, parasites and viruses that infect humans has also been documented, e.g. the bacteria *Salmonella* spp., *Escherichia coli* and *Listeria monocytogenes*, viruses such as Norwalk virus and hepatitis A virus, and parasites of the genera *Cryptosporidium* and *Cyclospora* (De Rover 1998). It is possible to reduce but not eliminate pathogens by washing in water, although chlorinated water (200 ppm, pH 6.5–7.5) can achieve a 1–2 log reduction in the microbial population (Beuchat et al. 1998). The inhibitory or lethal activity depends on the availability of free chlorine (in the form of hypochlorous acid, HClO) which depends on the pH and the exposure conditions. Chlorine is consumed by contact with organic matter and loses activity when exposed to air, light and metals. It is also highly corrosive, and may form potentially carcinogenic byproducts when it reacts with organic compounds. For this reason, the use of hypochlorite-based systems for fresh product washing is already prohibited in Denmark and Germany (Betts and Everis 2005). Alternatives that have been considered include chlorine dioxide, ozone, electrolyzed water, acidified sodium chloride, peroxyacetic acid, hydrogen peroxide, trisodium phosphate and organic acids (Betts and Everis 2005; Abadias et al. 2008; 2011; Viñas et al. 2010; 2011).

Biological control agents have also been used to preserve fresh or partly-processed fruits, reflecting the inhibitory effect of the agent (or its metabolites) on the growth and survival of a pathogen. Bacterial control agents are often added to minimally-processed fruits and vegetables, e.g. bacteriocin-producing lactic acid bacteria sometimes in combination with certain yeasts. Other biopreservation systems include the direct use of microbial metabolites (such as bacteriocins) or the addition of bacteriophages that are specific for selected pathogens without harming beneficial microbes.

Food processing and safety management

The sustainability of manufactured food products is more important to consumers than ever before. Consumers demand safe, high-quality and nutritious processed commodities and also expect them to be convenient and produced using environmentally-sustainable methods. Sustainability can only be ensured by reducing the ecological footprint of food production and processing by streamlining resource utilization, reducing the production of waste and finding novel uses for byproducts (Sellahewa and Martindale 2010). This is a significant challenge in the food industry but it can also be recognized as a welcome opportunity to reduce energy consumption, increase process efficiency and improve the quality of processed foods (arrows from panel (b) to (c) to (d) in Fig. 1). As part of this drive towards increased sustainability, certain key principles must be accepted so that the necessary foundations to achieve food safety objectives can be provided. These include an integrated farm-to-table approach, transparency, the application of risk–benefit analysis and the introduction of preventive measures throughout the food chain (FAO 2007).

Food processing

Sustainability in food manufacturing is driving research in related areas, and therefore beginning to build some of the bridges discussed in this article. But this will require the definition of standard parameters that allow the comparison of different products and processes, including energy efficiency, greenhouse gas emissions, water use and waste (Benoist et al. 2012). Life cycle assessment studies are useful for calculating gas emissions and water consumption during the production, storage and distribution of raw materials, the manufacture of processed goods, their distribution and storage, their consumption, and the disposal and recycling of waste (EC 2006; Edwards-Jones et al. 2008). Such studies will yield carbon and water footprints for processed food products, indicators that are often demanded by food distributors, retailers and consumer organizations. The influence of retailers has increased because they respond to the needs of consumers and address environmental issues by exerting pressure on food processors to adopt sustainable manufacturing practices. In turn, processors are starting to regard sustainability as a leitmotif driving innovation and competitiveness, thus undertaking work on corporate social responsibility (Dron 2012). Companies around the world are adopting sustainable business models and increasing their energy, water and resource utilization efficiency by introducing innovative processing and packaging technologies (Larson 2009).

Cutting-edge technology and research into novel processing methods offer the prospect of greater energy and resource efficiency. The latest processes and materials will be used to improve the energy efficiency of conventional food preservation methods, especially when these innovations can be implemented at a reduced cost. Such advances are driving the renovation of processing facilities, reflecting the immediate benefits of reduced energy costs. There have been incremental advances in conventional food preservation technologies because these are established and mature platforms, but more radical and disruptive innovations have been introduced in processing techniques. The development and application of advanced heating systems as an alternative to conventional heating, as well as non-thermal technologies such as high-pressure processing, pulsed light, pulsed electric fields, ultrasonication and cold plasma, offer new ways to reduce energy and water consumption that can be combined to generate innovative and sustainable processes (Toepfl et al. 2006; Morris et al. 2007).

Waste reduction and recycling is another area in which sustainability can be achieved in concert with significant cost savings (Sellahewa and Martindale 2010). Waste products can become useful byproducts if they contain compounds suitable as ingredients in other foods because of their organoleptic or nutritional properties. The valorization of plant and animal extracts containing compounds with useful properties (e.g. rich in dietary fiber, proteins, peptides, vitamins or phytochemicals) is currently a significant growth area (Galanakis 2012). The characterization of carbohydrates recovered from plant, animal and microbial sources can be important because these are useful as stabilizers or low-calorie bulking agents, or as substrates for bioenergy production.

The design of environmentally-responsible packaging systems is a field in which extensive research is expected during the next decade. The development of biodegradable packaging and the design of edible films and coatings are the two most promising areas for innovation. These systems can be used to reduce food deterioration during storage and distribution while minimizing the impact of packaging on the overall product life cycle (Brody 2009). There is also the possibility that novel packaging could be cast from waste products and could be reused for packaging or as fuel to increase sustainability (Verghese et al. 2012). It may also be possible to develop smart packaging systems that incorporate active ingredients into the polymer matrix, to be delivered to the food surface, e.g. to prevent spoilage (Rojas-Graü et al. 2009).

Finally, nanotechnology could have a significant impact on the sustainability of the food manufacturing chain, based on recent developments that promise to make energy conversion and storage more efficient or to improve product durability. The many potential applications of nanotechnology in the food industry include the detection of pathogens and other contaminants or the development of novel barcoding devices to track food products (Moraru et al. 2003). Nanoparticles can also be incorporated into packaging systems to improve food quality, or could be integrated as part of the food itself as novel food ingredients with improved functionality at low concentrations (Weiss et al. 2006).

Food safety management

Food safety has rarely been evaluated in terms of sustainability, but a new concept of sustainable food safety has recently been defined as ‘the complex of actions intended to minimize any adverse health impact on future generations associated with the safety and nutritional quality of food today’ (Frazzoli et al. 2009). Risk factors in early life are known to play a significant role in adult diseases, and therefore access to safe, affordable and nutritionally-adequate food will contribute to the health of future generations. Because of industrialization and environmental pollution, our food can be exposed to many chemical contaminants and there is growing recognition of the potential for long-term adverse effects from low-level, continuous exposure to many chemicals (Frazzoli et al. 2009). The assessment of long-term risks from chemical and/or nutritional imbalances is therefore a major component of the new food safety paradigm as implemented by international bodies such as the European Food Safety Authority.

The whole food production and processing chain contributes to the dietary intake of mixtures of chemicals, as described in the conceptual framework ‘from farm to fork’. Animal feed and human food may be contaminated in three ways: (a) consciously, i.e. authorized chemicals used incorrectly or insufficiently regulated to ensure the protection of susceptible population subsets; (b) fraudulently, i.e. the use of unauthorized chemicals; or (c) involuntarily, i.e. the accidental introduction of undesirable substances, including environmental pollution and mycotoxins.

Outbreaks of acute poisoning from chemical hazards in foods have been reported, but inadequate monitoring, identification and tracking prevent the assessment of chronic and trans-generational exposure. The latter is anticipated to be more prevalent, particularly in developing and transition countries where new and/or insufficiently-controlled chemicals may be introduced through rapid, unplanned and uncontrolled intensive farming, urbanization, industrialization and dumping (Frazzoli et al. 2009). There may also be a conflict between food safety and food security, e.g. a choice between going hungry or consuming a contaminated staple food. The awareness of long-term risks may cause further problems and a public health approach is required to detect minute amounts of contaminants that may prevent the use of food sources of substantial nutritional value. Health risk assessment, not merely chemical analysis, should be the driving force setting priorities for food control programs (Frazzoli et al. 2009).

The FAO has estimated that 25 % of crops are contaminated by mycotoxins in the field and in postharvest storage, and although food processing reduces the risk to humans much of the contaminated produce is used as animal feed. The risk of consuming animal products when the animals have consumed feed containing mycotoxins is unknown (Kabak et al. 2006; Schatzmayr et al. 2006). A consistent food safety management program is therefore required through the food production and processing value chain. The complete prevention of mycotoxin contamination in the field is not feasible, but GAPs can minimize the problem. Control measures have been extensively studied in cereals, the most efficient being pest control or the use of pest-resistant varieties, adjusting sowing and harvest dates, reducing plant density and ensuring balanced nitrogen fertilization (Blandino et al. 2008a, b, c). Pesticides, herbicides and fertilizers are not used in organic farming, so organic products might suffer from mycotoxin contamination. The prevention of mycotoxin contamination after harvest usually involves the careful selection of raw materials and the control of temperature/moisture. Many studies have been published on the effects of food processing on mycotoxins but precise details of the processing steps necessary to remove mycotoxins have not been established and the characteristics of any potential degradation products are unknown (Bullerman and Bianchini 2007). Notably, any prevention strategy applied during postharvest storage or afterwards will reduce dumping and lead to a more sustainable food production chain.

An integrated strategy

Bridges must be built between the diverse areas within the food production and processing value chain (Fig. 1), including bridges between different stages of production (plant breeding, livestock breeding, food processing, food distribution), bridges between currently unlinked agronomic practices (choice of crops and livestock, recycling of waste plant biomass, animal waste, and integration with fertilizer and energy cycles, agronomic technology, pest and disease management), bridges between the different levels of research (genetic, molecular, individual plants, whole crops, whole agro-ecosystems) and bridges between research areas (molecular biology, crop physiology, crop protection, breeding, engineering, environmental and soil sciences). These bridges are required to achieve joined-up thinking within the industry so that the wider impact of different technologies, practices and materials is understood at the systems level and choices can be made with environmental sustainability in mind at the local, regional, national and global scales.

The need for integration is driven by the realization that no area of the food and feed production and processing chain acts in isolation, so any decision at any level has a wider impact. Livestock production has an impact on crop production (40 % of crops are used for animal feed) and on environmental pollution (e.g. manure, slurry and methane) but careful choices can mitigate these impacts (e.g. growing feed crops that reduce methane production, and using waste animal slurry as fertilizer). The environment has an impact on plant health and on food and feed safety; e.g. high metal levels in the soil may result in contaminated food. Crop physiology and plant biotechnology may help to reduce the susceptibility of crops to fungi and mycotoxins, pathogens, weeds and abiotic stresses. Insects and other pests act as vectors for pathogens, so improved pest management can also help to reduce disease burden. Weeds, as well as causing crop yield losses, may act as a refuge for natural enemies of insect pests, but also for herbivores and plant pathogens. Therefore, knowledge of the interactions among biotic components in the agro-ecosystem should allow the development of integrated crop management practices that exploit natural resources more efficiently and prevent losses caused by pests, weeds and diseases. Molecular tools to study the mechanisms involved in the interactions among crop plants and their weeds, pathogens and herbivores may favor the identification of traits that can be introduced into the crop to reduce losses caused by these biotic factors. Furthermore, the development of crops with better nutritional properties (e.g. higher vitamin, mineral and antioxidant levels) may not only make the processed food more healthy and nutritious, but the crops themselves may be protected from microbes and fungi, reducing the disease burden and mycotoxin levels in the field and in storage. A better knowledge of fundamental thermodynamic and kinetic aspects of nutrient and pollutant behavior in crops can help to improve agronomic practices and reduce environmental damage while increasing the quality and nutritional value of food.

Bridges between the different areas of the food/feed chain are also important to achieve a productive and sustainable balance with other agricultural economies, particularly energy crops. For example, the integration of crop physiology can help to improve both the yield potential of lignocellulose crops under optimum conditions and their adaptation to marginal conditions (by identifying target traits for selection and breeding) whereas plant breeding could address the same aims, e.g. by accelerating domestication. Plant biotechnology is also useful in this context, to modulate lignin biosynthesis in a balanced and controlled way and improve the resistance of energy crops to pests and diseases. GAPs should be embedded in this framework of agricultural intensification to meet future demands for food and energy.

Plant breeding is a core component of any integrated strategy for sustainable food production because only an integrated approach will achieve sustainable higher yields. A key factor is that agriculture is, by its very nature, environmentally damaging, so we should marshal all available instruments at our disposal to reduce its impact, knowing that negative effects can never be entirely eliminated. Crop diversity is essential for environmental sustainability, and by integrating crop physiology and crop biotechnology it will be possible to provide essential knowledge and tools for plant breeding. One of the most environmentally sustainable ways to increase agricultural productivity and reduce the use of pesticides is through genetic engineering, which allows the direct improvement of cultivars that are already selected for their suitability in terms of agriculture and end-product processing. However, complex traits that are not yet amenable to genetic engineering can be investigated using emerging genomics-based breeding technologies such as markers identified by next-generation sequencing and the development of adequate phenotyping methods for complex traits.

To balance the concurrent desire for sustainable food processing and food safety, the whole testing and risk assessment process (additives, pesticides and mycotoxins) carried out by the scientific community should be evaluated according to the ability to identify and characterize possible hazards in susceptible life stages, including the impact of factors other than single chemicals administered in toxicology studies, i.e. it should include the overall burden of interactions with bioactive components (e.g. antioxidants) and nutrients (e.g. vitamins and trace elements) (Baldi and Mantovani 2008) and take into account that inadequate nutrition may affect susceptibility to toxic components in food (Olden and White 2005). Furthermore, the private sector must play an active role in the risk management of production and distribution processes. These must adhere to the relevant farming and harvesting practices, and must include adequate storage, transport and marketing facilities. Short food supply chains based on local resources may promote food safety by reducing the number of critical hazard points between the primary producer and consumer. Sustainable food safety management requires that HACCP strategies are prepared to include and evaluate hazards that are not related to acute foodborne diseases (Frazzoli et al. 2009).

The food production and processing value chain is facing greater demands in terms of yields, quality, regulatory scrutiny and consumer pressure for environmental benefits, while resources such as land and water are declining. Sustainable agriculture can be achieved by building some of the bridges discussed above through the development of complementary production technologies, agronomic practices and processing methods to form an integrated approach through the entire value chain, but this can only be implemented if there is a corresponding vision at the political level to ensure that agricultural, industrial and environmental policies are harmonized with trade and development goals on a global scale.

Acknowledgments Research at the University of Lleida is supported by MINECO, Spain (AGL2009-11006; AGL2009-11475; AGL2009-11964; AGL2009-13517-C03-02; AGL2010-21572; AGL-22050-C03-01; AGL2010-22084-CO2-O1; AGL 2010-22182; AGL2011-23996; AGL2011-24862; AGL2011-30529-C02-02; AGL2012-35300; AGL2012-40144-C03-03; BIO2011-22525; BIO2011-23324; BIO2007-61413; CTQ 2009-07831; CTM2009-14612 and PIM2010PKB-00746); EU FP7 Integrated Project 222716 SmartCell; EU FP7 European Research Council IDEAS Advanced Grant (to PC) Program-BIOFORCE; EU FP7 Large-scale integrated project KBBE 222738 Selection and improving of fit-for-purpose sampling procedures for specific foods and risks (BASELINE); EU FP7 Program-SICA project KBBE 222690; COST Action FA0804: Molecular farming: plants as a production platform for high value proteins; COST Action FA 1006: Plant Engine; COST Action TD1104: Development of electroporation-based technologies; Centre CONSOLIDER on Agrigenomics funded by MICINN, Spain; the HENUFOOD project (CEN-20101016) as part of the CENIT program and the INCOMES project as part of the INNPRONTA 2011 program funded by Ministry of Science and Innovation, Spain; RecerCaixa. An ICREA Academia Award has been presented to Prof. Martín-Belloso.

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