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Deconstructing and unpacking scientific controversies in intensification and sustainability: why the tensions in concepts and values?

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Assuming 'ceteris paribus' in terms of the viability of the planet during the coming half-century or so, the rising needs of a burgeoning, but also increasingly rich and demanding world population will drastically change agriculture. Crop yields and animal productivity will have to increase substantially, with the risk of further depleting the resource base and degrading the environment, making food production both the culprit and the victim. Future food security therefore depends on development of technologies that increase the efficiency of resource use and prevent externalization of costs. The current trend is towards intensification, especially more output per production unit so as to increase input efficiency. Whether that trend is sustainable is a matter of strong debate among scientists and policy-makers alike. The big question is how to produce more food with much fewer resources. Sustainable intensification (i.e., increasing agricultural output while keeping the ecological footprint as small as possible) for some is an oxymoron, unless real progress can be made in ecological intensification, that is, increasing agricultural output by capitalizing on ecological processes in agro-ecosystems. Definitions of intensification and sustainability vary greatly. The way these concepts are being used in different disciplines causes tensions and hides trade-offs instead of making them explicit. Inter-disciplinarity and boundary-crossing in terminology and concepts are needed. Implicitly, the operationalization of intensification and sustainability implies appreciation of and choices for values, an issue that is often overlooked and sometimes even denied in the natural sciences. The multidimensional nature of intensification needs to be linked to the various notions of sustainability, acknowledging a hierarchy of considerations underlying decision-making on trade-offs, thus allowing political and moral arguments to play a proper role in the strategy towards sustainable intensification. We make a plea to create clarity in assumptions, norms and values in that decision-making process. Acknowledging that win-win situations are rare and that (some) choices have to be made on non-scientific grounds makes the debate more transparent and its outcome more acceptable both to the scientific community and society at large.

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Introduction

The majority of the world's population is affected by poor nutrition. During the period 2011–2013, 0.84 billion people were chronically hungry [1]. Most recent data show that over 2 billion suffer from micronutrient deficiencies [2], while 1.4 billion adults are over-nourished [3]. More people are obese than chronically hungry, but those with micronutrient deficiencies equal the sum of those who eat too much or too little. In total, over half of all deaths worldwide are associated with malnutrition. Poor quantity and quality of food production and nutrition have very high societal costs.

The societal costs of current ways of using technology for producing food also are substantial. From an agronomic and environmental perspective these include depletion and spillage of resources such as water, degradation of agro-ecosystems and natural ecosystems, decline in ecosystem services, loss of biodiversity, emission of greenhouse gases and toxic waste, post-harvest loss, among others, all contributing to agriculture's ecological footprint.

Future trends are unclear: although population growth might level off by 2050, in some parts of the world the population will age rapidly inducing large changes in diets, irreversible climate change and sea level rise will affect agriculture in many densely populated countries, degradation of natural resources might accelerate in fragile environments, among others. Although some of the worrying trends will slow down or come to a halt, the processes described will give even inveterate optimists gloomy moments.

These trends make it necessary to put much more efforts into the analysis of trade-offs and bring this analysis into the complex societal debate on decision making towards sustainable agro-ecosystems. Trade-offs, that is, compromises between desirable but incompatible features, are ubiquitous in agriculture, under a wide range of resource availabilities. They are also present at different hierarchical levels and across temporal and spatial scales. Therefore they also have moral dimensions and political consequences.

From the end of the Second World War until about 1980, agricultural research in the developed world focused on increasing productivity per unit of land or labour, whereas from 1980 until 2000 that focus shifted to limiting the ecological footprint of agriculture [4]. During the latter period, agriculture became unpopular among donors and policy-makers. In the wealthy First and Second Worlds, further investment in an economic activity that produced in excess to requirement at the cost of a large ecological footprint was considered unnecessary. In the poorer Third World, with the exception of Africa, the Green Revolution was considered a success. The period from 1980 until 2000 was marked by the common notion that hunger was no longer caused by a combination of poverty and lack of production — as in the past [5] — but by a combination of poverty, poor governance of resources, speculation, and competition between food, feed and fuel. Agriculture only regained prominence in the international political agenda after the United Nations Millennium Development Goals had been agreed upon [6], and after the food crises in the periods 2007–2011 [7,8]. Influential publications by Beddington *et al.* [9,10] helped to put agriculture on the climate change agenda of the United Nations Framework Convention on Climate Change.

As a result, food and agriculture are definitely back on the societal and political agenda. Renewed donor attention to persistent hunger and malnutrition and political cognizance of the global drivers that create or reinforce food crises reframed the case of food security as an urgent and highly complex problem with technical, economic, and social dimensions that affect world trade and geopolitics. The urgency is underlined by population growth which increases demand, political realities that undermine production in key production areas, and increasing competing claims on natural resources. The re-emergence of food and nutrition on the political agenda is strengthened by climate change [11,12], resource depletion (e.g., phosphorus [13]; water [14]; energy [15] and the loss of agro-biodiversity [16•]), questioning the sustainability of current trajectories [17••]. A common response from scientists to such threats is to plead for paradigm shifts and scientific revolutions, or at least (and perhaps a bit more realistic and devoid of empty rhetoric) to call for changes in scientific concepts, practices and approaches, as well as new research agendas.

This response has come in different appearances. Cassman [18] coined the term ecological intensification to frame the challenge of increasing attainable yield and narrowing yield gaps by implementing new insights in precision agriculture, plant and crop physiology, and soil science, acknowledging that approaches and strategies should be different for favourable and unfavourable agricultural conditions. Meinke *et al.* [11] made a plea for 'adaptation science' to develop climate-robust agriculture and management of natural resources. Keating *et al.* [19] suggested options for making agriculture more 'eco-efficient': based on the simple notion that efficiency refers to output per unit of input, 'eco-efficiency' is the output of food and fibre relative to the input of ecological resources, including land, water, nutrients, energy, and biological diversity. Brussaard *et al.* [20•] made a case for a science that develops the best ecological means for food production with less negative or even positive impacts on biodiversity and ecosystem services. They proposed that trait-based ecology offers opportunities to design agro-ecosystems that contribute to both biodiversity conservation and food security. In the social realm, Khoury *et al.* [16•] noted that over the past 50 years considerable change has occurred in the composition of national food supplies, whereas diets around the world have become more similar. This resulted in several pleas to pay more attention to crops that are less favoured in terms of international research funding ('orphan crops'), for example towards the Consultative Group on International Agricultural Research (CGIAR) [21]. Recognizing that the concept of ecological intensification has been adopted, but also adapted over the last decade, Tittonell and Giller [22] re-defined the concept as ''a means of increasing agricultural output, while reducing the use and need for external inputs, and capitalizing on ecological processes that support and regulate primary productivity in agro-ecosystems''. Finally, it has been emphasized that new directions towards food and nutrition security require simultaneous change at the level of formal and informal social rules and incentive systems (i.e., institutions) that orient human interaction and behaviour, and hence that 'institutional innovation' should be a key entry point to addressing threats [23–25]. This is important for science to be able to contribute to international policies for food security and protection of natural resources that appear to rest on three pillars: right to food, intensification of agriculture, and sustainability. The three pillars are briefly described in the next section. Following that section we describe the need for intensification, how to evaluate intensification, the need for sustainability, which problems are encountered on the way towards sustainable intensification, and the nature of these problems and possible solutions. We also stress the importance of thorough analysis of trade-offs in agro-ecosystems.

The three pillars of food security and resource management: right to food, intensification, and sustainability

The Special Rapporteur of the United Nations on the Right to Food, Olivier De Schutter, defined *the right to food* as [26]: ''the right of every individual, alone or in community with others, to have physical and economic access at all times to sufficient, adequate and culturally acceptable food that is produced and consumed sustainably, preserving access to food for future generations.''

Sustainability is included to indicate that the right cannot be pursued at the expense of present or future others. In his final report, De Schutter joins many scientists in calling for a 'new paradigm'. The new paradigm should focus on well-being, resilience, and sustainability and stimulate effective production and processing for local use, based on agro-ecological modes of production. Successful co-existence of small-scale production with large-scale, export-oriented agriculture in Brazil is acknowledged, but export-oriented agriculture is not advocated. Earlier reports by the same Special Rapporteur had already emphasized agro-ecology and organic forms of agriculture as the best route for agricultural development [27]: in various countries and environments, agro-ecology can contribute to rapid realization of the right to food for vulnerable groups and has additional advantages beyond what can be achieved with conventional agriculture. The FAO (Food and Agriculture Organization of the United Nations) has responded to this idea by paying more attention to agro-ecology and conservation agriculture, and by searching for win-win situations in resource use [28].

Intensification, literally 'making more intense', can be defined as increasing the level of input of any kind to increase physical or economic productivity. In agriculture, intensification usually refers to an increase of input per unit of land, but it can also be used in a much wider sense. Intensification can refer to making more use of internal and external inputs, such as land, seed, manure, fertilizer, water, and credit; labour and other human resources; fossil fuel and mechanization, knowledge and communication; institutions; or a combination of all these. In fact, intensification of the use of one type of input can be associated with reduced intensification of the use of another input: capital-intensive agriculture will allow a high labour productivity and thus a low labour input. Simultaneous increases in land productivity and labour productivity will assist the farmer in capitalizing on the benefits of the economies of scale in farming. The main driver of intensification is efficiency: per unit of product, intensification increases efficiency.

Sustainability refers to the principle that people's needs must be met without compromising the options of others or those of future generations to meet theirs. Many definitions of sustainability exist. One early, commonly cited, definition, coined in the 'Brundtland report' [29], captures the dynamism and process orientation implied in the concept: ''Sustainability should be seen as a dynamic, progress-oriented strategy: it is not a fixed state of harmony, but rather a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional changes are made consistent with future as well as present needs''. Given such a dynamic and strategic process of change, making considerate choices and decisions becomes an important challenge. According to some, the biophysical limits of Planet Earth impose a hierarchy of criteria on the definition of sustainability: sustainability is not a relative concept or an act of balancing competing claims; it sets absolute biophysical limits. Only within those strict limits can social and economic trade-offs be assessed [17••]. Defining such a hierarchy of considerations requires agreement on ethical and normative dilemmas in our current and future life styles and production systems, in compliance with biophysically meaningful, explicit and ambitious sustainability targets so as to devise concrete actions to maintain an effective life-support system [17••].

All three pillars trigger hefty debates about the technology, ethics, ecology, and economics of the production of food among scientists, practitioners, and policy-makers.

This contribution to the special issue analyses the scientific controversies concerning intensification and sustainability, while taking the right to food as a given. Agricultural intensification is a process; hence the debate is by definition a debate on transitions (to greater food and nutrition security). But does this transition process result in *sustainable* intensification? Why the scientific controversies concerning intensification and sustainability, when the overall objectives are commonly shared? What is the role of norms and values in these controversies?

The need for intensification

The efficiency of natural resource use has always been a central concern in agricultural practice [19]. Drivers of that concern could be scarcity (e.g., nutrients in agricultural systems in Africa [22,30], water in Australia [31]), or financial resources (cost reduction). In conventional high-input agriculture, however, another concern features prominently: to avoid risk, farmers often apply more crop protection chemicals [32] and more fertilizers (which are relatively cheap and often subsidized) [33,34] than needed. Farmers at different stages of intensification may differ in their perception and management of risk. Risk perception and risk management are therefore also dimensions of intensification based on the farmer's short-term concern for economic sustainability.

The types of inputs of which use per production unit (usually a farm) can be intensified are diverse and include land, water, energy, nutrients, seeds, crop protection chemicals, labour, equipment and facilities, and financial capital. Some of these resources are man-made (inorganic fertilizers, biocides), many are part of the ecological resource base (phosphorus, water, land, biodiversity). Outputs are also diverse and not only concern quantity of produce, but also loads on the agro-ecosystem (pollution with nutrients, toxification with chemicals, erosion, salinization, depletion of aquifers, among others), the wider ecosystem (such as nitrate in surface water, reduction of biodiversity), or ecosystem services (such as maintaining the hydrological cycle, greenhouse gas control). In animal husbandry, animal welfare has to be weighed against cost efficiency.

In his famous paper on resource use efficiency in agriculture, De Wit [35••] gave the following agronomic argument for intensification:

''It may be concluded, with some reservations regarding the control of pests, diseases and weeds, that no production resource is used with any less efficiency and that most production resources are used more efficiently with increasing yield level due to further optimizing of growing conditions.''

In other words: the totality of resource use is most efficient when all inputs are applied in quantities that are close to the level at which yields are maximized. This translates into land use efficiency, water use efficiency, nutrient use efficiency, in general: yield per amount of input (e.g., kilograms (kg) of dry matter yield per ha, per kg of water transpired or per kg of nutrient taken up or supplied). It is therefore often claimed that intensification improves the efficiency of resource use, a win-win situation. However, De Wit's concept is also often contested, for many reasons, including agronomic ones.

Certainly, farmers may optimize other values than agronomic efficiency, including, for example, independence of input markets, income from non-agricultural sources, peace of mind, cultural heritage or short-term economic gain [36–38].

In addition, De Wit's law on resource use efficiency goes against the law of diminishing returns, which states that for a single input the highest efficiency (i.e., increment of output per increment of input) is reached at lower ranges of input [19]. Tilman *et al.* [39] calculated that between 1960 and 1995 global use of N fertilizer in cereal production increased sevenfold, while cereal yields only doubled: the number of kilograms grain produced per kilo of N fertilizer decreased from 70 to around 25. For China, recent figures show that increases in rice yields are levelling off while fertilizer use is still increasing in a linear fashion (Bingqiang Zhao, personal communication, 2014). Similar efficiency calculations can be made for other resources, supporting the diminishing returns to investment scenario rather than De Wit's early win-win optimism. In this respect, agronomic intensification obeys the same principle as economic intensification. In both forms of intensification, more gains can be obtained by intensification in less intensified systems. This implies that — in a diverse and relatively open global economy — it is difficult to achieve higher resource-use efficiency in the more intensive systems.

Nonetheless, Cassman *et al.* [40] conclude that increased nitrogen-use efficiency and improved soil fertility are essential elements in making agriculture more sustainable while meeting human needs and protecting natural resources. Spiertz [41] concludes that more resources are required for meeting the demands of the growing human population. According to Tilman *et al.*'s [42] calculations, in order to feed the global population without degrading natural ecosystems and ecosystem services, during the next decades agro-ecosystems need to be re-designed so as to make efficiency gains in agriculture worldwide. This will not be possible without new incentive systems and policies that support yield increases without compromising environmental integrity or harming public health.

How to evaluate intensification?

Population growth, globalization, urbanization and changes in diets and life styles increase the demand for agricultural products and thereby drive agricultural intensification: to satisfy the increased demand farmers start to produce more by using more inputs and/or by using those inputs more efficiently. They do so in a way that makes economic sense to them. Moreover, there is another economic driver of intensification in agriculture, often called the technology treadmill. This term, first coined by Willard Cochrane [43], identifies a cyclic process of generating new technology, reducing costs of production, and increasing farm sizes. The process of diffusion of innovations favours the early adopters of a new technology: they profit most from the efficiency gain. Late adopters finally also have to adopt the new technology because market conditions force them to do so [43]. The Dutch dairy industry is a good example where such mechanisms played a major role during the last 50 years, revolutionizing the industry, increasing its productivity, while decimating the number of dairy farmers. This illustrates that intensification (and agricultural innovation in general) is not a neutral technical activity, but that it is associated with (deliberate or un-intentional) re-configurations in society that may be valued differently by stakeholders with different interests (e.g., consumers getting cheaper milk, dairy farmers getting squeezed out of farming, non-governmental organizations concerned about vanishing landscapes and biodiversity).

Although agronomists tend to promote intensification based on increasing efficiency of biophysical resource use, many farmers tend to opt for maximizing financial gain by increasing cost effectiveness, the so-called profit maximizers, despite the fact that there are different styles of farming, characterized by different short-term and long-term objectives [36]. As mentioned earlier, these different approaches to efficiency are not always closely aligned. Economic efficiency is often calculated in an incomplete manner by not taking all costs into account, or by externalizing them to the public space. For example, costs of cleaning drinking water are not included in the price of pesticides. Agriculture emits greenhouse gasses without any costs to farmers. Some inputs are too cheap relative to the limited supplies available or the high requirements for scarce natural resources to produce them. Other resources are very expensive but also very renewable such as labour. In industrial agriculture, the replacement of labour by mechanization and non-renewable fossil fuels has been phenomenal but seems unsustainable. Some inputs can be replaced by labour (e.g., herbicides can be replaced by mechanical or hand weeding) but others cannot (e.g., irrigation water). Scarcity of inputs but also unwise use of inputs or unsuitable cropping systems can even force farmers to leave their land (e.g., as a result of soil erosion, land degradation, fertility loss, salinity, or infestation by persistent pathogens) [44].

Efficiency is thus clearly a complex concept that requires an integrated approach: all inputs should be used as efficiently as possible and all aspects of efficiency (at least including economic, agronomic, environmental, social, trans-generational, and global aspects) are relevant. Therefore, intensification is a multi-faceted process that requires the implicit trade-offs to be analysed explicitly and the arguments to be weighed. Intensification should be based on an all-inclusive cost–benefit analysis, in which all inputs, outputs and consequences (the desirable and the undesirable, as well as the externalized costs) are taken into account. Economic efficiency does not always drive intensification into the same direction as resource scarcity because scarcity of inputs (e.g., phosphorus, fossil fuels) is not always fully accounted for in their pricing.

Intensification strategies often include specialization, concentration and scale enlargement. Specialization, not only in primary production, but also further along the value chain can be a source of sustainability problems because each link in the chain seeks to optimize its own efficiency (in terms of biophysical resources, costs, or both) [45]. Concentration of production also leads to concentration of negative outputs, and increases the chances of over-taxing the carrying capacity of the local environment. An increase of scale can also increase problems when some values and costs are systematically left out of the equation, resulting in wicked problems and organized irresponsibility as elaborated below.

Overall, it seems safe to say that intensification is not automatically associated with an increase in efficiency of all inputs or that it always is consistent with the need to reduce the negative side effects of production. Trade-offs among different dimensions of efficiency (e.g., economics or use of biophysical resources), and values such as the right to food, wealth and (animal) welfare, environmental quality, social equity, nature conservation, biodiversity, dietary quality, poverty alleviation and food safety are complex and require normative choices. Realizing this is only one step. Creating the tools and data to reach an informed agreement on how the different aspects could be weighed is quite another. Even when both economic and environmental quality indicators are favourable for intensive systems, other sustainability indicators might not be. To avoid that direct costs become the common denominator, we need to construct a hierarchy in the indicators of resource use efficiency. In such a hierarchy, the biophysical limits set by the carrying capacity of Planet Earth and the availability of non-renewable resources set the parameters that frame the playing field within which production, profit and efficiency goals must be met. Even when based on costs, it is imperative that the hierarchy takes into account all costs (including, for example, negative impacts on ecosystem services), future scarcity (e.g., of phosphorus) and the need for an economy based on closing the hydrological, carbon, and other cycles [45]. Creating a hierarchy implies dealing with norms and values. These become even more important if intensification also needs to ensure societal sustainability.

The need for sustainability

Garnett and Godfray [46•] realized that, given the fact that supplies of many resources are limited and currently even shrinking rapidly (fertile arable land, phosphorus, energy, fresh water), the task of meeting current resource needs and product demands without compromising the ability of others and future generations to do so is virtually impossible. It is therefore imperative to develop some form of stewardship that allows us to improve our act substantially. Minimally, we need to design agricultural systems that allow us to use resources judiciously, to ban wastage and spillage, and to create an internationally agreed system for sharing resources (cf. [47]). The pursuit of sustainability can focus on conservation and stewardship in ways that can easily become counter-productive and result in following existing pathways towards fixed solutions. Resilience can become narrowly defined as returning to existing situations and base lines. To cope with such eventualities, Jackson *et al.* [48] claimed that ''Rapid changes in land use, food systems, and livelihoods require social–ecological systems that keep multiple options open and prepare for future unpredictability''. They coined the term 'sustainagility', which refers to ''the properties and assets of a system that sustain the ability (agility) of agents to adapt and meet their needs in new ways." Concern for sustainable agriculture and agricultural sustainability can therefore not be limited to agronomic and economic aspects. It is not just a matter of inventing new incentives and designing policies that ensure the sustainability of agriculture and ecosystem services [42]. Rather, sustainable agriculture is about food and nutrition security and food safety, based on the right to food and on compliance with three other goals: environmental, economic, and social sustainability. The complexity of this statement already indicates that sustainability involves a diversity of practices, policies, norms and values, and ways of thinking, and a large support network of practitioners, policy-makers, scientists, consumers and citizens. In line with Fischer *et al.*'s [17••] conceptualization of sustainability as a hierarchy of considerations, we propose that sustainability can only be addressed by a systems approach that allows the construction of a widely shared hierarchy of different subsystems. Useful biophysical layers that can be recognized in this hierarchy are the individual field, farm, cropping system, local ecosystem, landscape, region, and planet Earth. The social layers in this hierarchy include individual farmers, households, consumers and citizens, communities, and society at large.

Towards sustainable intensification

According to Spiertz [41], sustainability represents a balance between short and long-term objectives with respect to profitability, ecological health, and socio-ethical acceptability, allowing intensification as long as the system remains healthy and acceptable. By contrast to this optimistic scenario, Fischer *et al.* [17••] posit the concept of a 'sustainability gap'. They state that there is a widening gap between what is done and what needs to be done to realize sustainability. Their concept involves a hierarchy of considerations within the ultimate bio-physical limits of the Earth. These authors therefore introduce norms and values into the debate. The question is whether their notion of 'economies' embedded in 'human societies' applies to major food production systems, which are driven by 'free trade' at a global scale, or at least by price setting mechanisms over which most 'human societies' have no control. Transitions in agriculture are unavoidable as a consequence of population pressure, global climate change, developments in markets and prices, and new technologies [41]. Such transitions could intensify agriculture and food production to a more advanced stage of sustainability. To achieve that, the world community needs solutions that are more radical than the current more-of-the same intensification.

A totally different take on sustainable intensification is to see it as an intellectual framework, a process of enquiry and analysis for navigating and sorting out the issues and concerns, rather than a 'hard' set of principles and practices [46•]. In this definition it is not technology, which is dominant but a process of societal negotiation, institutional innovation, and adaptive management.

We need to sustain our efforts to design intensive systems that are sustainable in all aspects of the term (certainly within the limits that are perceived as being imposed by the carrying capacity of Earth) and to unravel the mechanisms for realizing sustainable intensification as they vary from system to system and from one social context to the next. But we also need to continue developing conceptual frameworks within which we can pose and answer the ethical and normative questions on the desirability of each proposed form of sustainable intensification.

Despite their consensus with respect to some of the sustainability issues at stake, scientists still have difficulty in defining the playing field. They are not always able to define the scientific discourse, identify sustainability indicators, quantify sustainability thresholds, work out the way science should play its role within the scientific and societal debate, or the role of individual scientists in the debate, both towards the policy-makers and the general public. Quantifying sustainability thresholds can be especially tricky: it will depend on norms and values, and will require quantification of trade-offs and hierarchies among sustainability aspects (e.g., how to weigh animal welfare against cost efficiency), and will often be case-specific.

Summarizing, sustainable intensification sets three major challenges, partly within the domain of dealing with our bio-physical environment and partly within the domain of developing appropriate social and economic institutions:

1. Consensus on values and norms to be taken into account whenever choices have to be made on the feasibility and desirability of intensification, and the processes and methodologies to reach agreement within and among societal actors. And from there: consensus on how to make choices, on the processes and criteria to decide on unavoidable trade-offs, and on the relative weight or hierarchy of sustainability goals.
2. Scientific consensus on the sustainability issues that are at stake, based on precise definitions and indicators, detailed contextualization, reliable quantification of sustainability thresholds and on a hierarchy of issues causing the sustainability gap.
3. Creation of conducive institutional environments to realize consensus and change.

Trans-disciplinary research programmes and societal debates are needed to create these forms of consensus [17••]. Garnett and Godfray [46•] speak of the need to balance the two terms in 'sustainable intensification' so as to prevent the phrase from becoming an oxymoron. That balancing act requires not only the input of scientists and practitioners, but also of other stakeholders and society at large. They raise the following issues:

- Society should decide whether sustainable intensification is merely an environmental issue or whether it also includes a broader range of social and ethical concerns. In embarking upon the process, it needs to take into account social and ethical concerns and be aware of trade-offs and possibly perverse outcomes.
- Technical, social, economic and moral trade-offs are especially prevalent in industrial production systems with high levels of external inputs.
- Transforming thinking about sustainable intensification into its practice requires a process of identifying and realizing the proper mix of local, national, and international policies, institutions, and governance structures. Such a mix is only possible if the values that shape the different attitudes of the diverse stakeholders towards (the future of) the agricultural production and food systems can be mapped and analysed and if that knowledge can be used to come to a shared in-depth insight in the challenges at hand and possible ways of dealing with them. Who is taking the lead in such a process of creating and transferring knowledge is a (value-laden) question in itself.

Sustainable intensification: controversy and wicked problem

These challenges and issues are pressing, because intensification and sustainability have developed into controversial subjects. In this introductory article we have shed some light on why this is the case. We have seen that terms like 'intensification' and 'sustainability' can be defined in different ways, and that any operationalization of these terms in society goes along with normative choices and trade-offs between the use of resources but also trade-offs between different values. These are not just 'technical' trade-offs (e.g., between energy efficiency and water efficiency) but they are linked to, and have real and perceived consequences for, social values and outcomes. Choices regarding, for example, the desirable scale at which farming is to take place, the relative importance of animal welfare, the importance of farmer autonomy and peace of mind, appropriate rules and standards, or the distribution and use of resources need to be made in society and have important consequences for its organization. Thus, competing social values and normative interests are at the heart of the issue. And since a large diversity of values and interests exists, this goes along with different problem definitions in society. Although applied scientists may aim to produce insights and facts that are replicable, transparent and 'objective', they cannot avoid that their research questions are inspired by value-laden problem definitions, and subsequently that stakeholders may strategically select those facts and arguments that (are seen to) further their cause in what is eventually an inherently political societal debate about the future, and about who determines it. When the stakes are high — such as around the future of agriculture — the debate can easily turn into controversy. Our role as scientists is primarily to enhance the transparency of the debate. This means among other things interacting intensively with society, collaborative experimentation with new social and technical options [49], and taking trade-offs seriously, so as to increase the decision space of actors in the joint quest for sustainability.

A related observation is that sustainable intensification may require radical transformations in the social and economic organization of agriculture. At the same time we know that it is notoriously difficult to orchestrate such change since dominant socio-technical configurations (including the technology treadmill) are highly institutionalized and supported by existing lobbies and infrastructures. Moreover, it can be very hard to break out of the path paved by previous decisions and investments, causing a situation of lock-in [50]. Thus, we may be dealing with what has been labelled as wicked problems [51], that is, problems that are difficult to resolve due to contradictory problem definitions, complex or unknown interdependencies, legacies of decisions and investments, and resistance.

The quest for sustainable intensification in agriculture indeed has characteristics of a wicked problem. Within the current incentive systems and frameworks, specific values tend to be optimized while others tend to be systematically overlooked and externalized, leading to what Beck called a situation of 'organized irresponsibility', that is, a situation whereby interactions in the system lead to the emergence of socially-created risks that are offloaded to society as a whole (or to specific 'risk victims') and that may pose serious threats to sustainability [52].

Even before the scientific and societal debates can begin, clear definitions and proper contextualization are needed to ensure that the right questions are asked to stimulate a productive debate oriented towards gaining insight and reaching consensus. This debate should go beyond instruments (e.g., on agronomic resource-use efficiency) and not make a priori assumptions (e.g., on the value of economic efficiency).

An innovation in our thinking about sustainability is the recently developed Water-Energy-Land-Food nexus [53,54]. Identifying the linkages across key natural resources and simultaneously improving their efficiencies was considered a win-win-win strategy that would benefit current and future generations by creating sustainability, while allowing intensification. However, trade-offs are much more common than synergies and dealing with them requires a completely different approach. Certainly in a diverse and relatively open global economy, it is difficult to achieve higher resource-use efficiency in the more intensive systems. Klapwijk *et al.* [55•] reviewed the state of the art of trade-off analysis. On the basis of the example of the diverse use of crop residues in mixed smallholder farming systems, they showed that, by combining different techniques, aspects of system behaviour can be assessed and analysed via various perspectives; by doing so complementary knowledge can be generated. Trade-off analysis also provides a useful tool to support discussions with stakeholders rather than for decision support [55•]. This exciting new field might contribute significantly to our insight into systems behaviour and create analytical tools to realistically design systems that can combine sustainability with high productivity. Such scientific developments can facilitate the scientific and societal debates, add credibility to nexus concepts, and even shift the balance from trade-offs to synergies so as to gain efficiency in the use of what is most precious and scarce. Moreover, such trade-off analysis can be usefully embedded in broader procedures and frameworks for 'responsible innovation' [56] that have emerged recently.

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References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

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