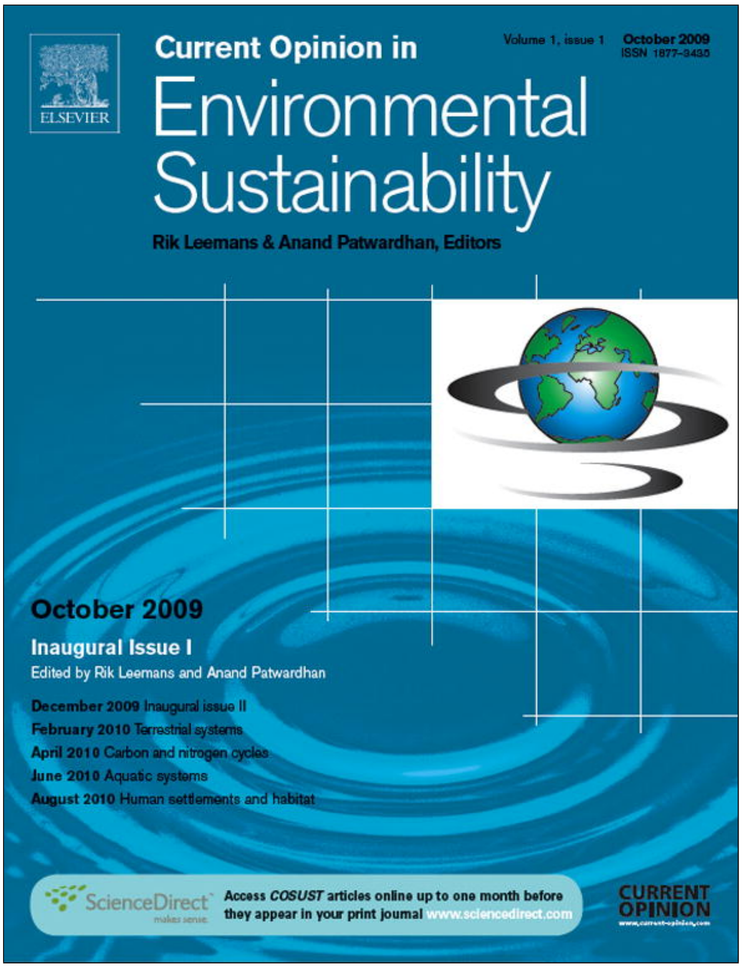
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Adaptation science for agriculture and natural resource management — urgency and theoretical basis

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The urgency for adaptation actions in response to climate risks is rapidly growing and climate change mitigation efforts alone are insufficient to avoid further, and often negative, impacts. Although most agricultural producers respond rapidly to changes in their external environment, science needs to play an important, partial role in instigating adaptation actions that go beyond the ongoing, experience-based response process. This requires well-structured, conceptual frameworks that connect science with action. These frameworks must also ensure that the scientific input into the adaptation process remains salient, credible and legitimate. For the field of agriculture and environmental sciences we review the urgency and the theoretical basis for such engagement processes. On the basis of this we propose an adaptation cycle that first, provides a reflective analysis-action continuum; second, ensures broad-based scientific input and feedback; and third, helps to increase the adaptive capacity of everyone involved (including farmers, policy-makers and scientists).

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Towards adaptation science

For most of human history, adaptation has largely been an intuitive response to changing conditions, the climate being one of many variable factors. For agriculture, which is arguably one of the most climate sensitive sectors, climate variability and risks have always been major drivers for reactive adaptation (for an anatomy of adaptation see [1]). Today the impacts of climate change on many natural and managed systems are well documented [2•]. Past emissions of greenhouse gases have already committed the globe to further warming of around 0.1°C per decade for several decades, if not centuries [3,4••,5•], making some level of impacts and associated adaptation responses unavoidable [6]. For these reasons, a new focus on proactively planned adaptation has emerged that specifically addresses climate change ([6]; see also 'The coming climate crunch', Nature 30 April 2009, Vol. 458 and many articles within). However, many recent impacts have not yet led to appropriate adaptations, in part because the experiential knowledge is lacking. For instance, in the Netherlands, the crop growing season is currently approximately one month longer than it was 30 years ago, enabling changes in crop choice, cropping practices and crop genotypes that have not been exploited let alone scientifically investigated. In Australia as in other parts of the world, whole industries are on the move, relocating across regions and even countries in response to current and expected changes in the availability of resources such as water. However, most of these responses are based on 'gut feeling' rather than on thorough, quantitative systems analyses. Likewise, and worldwide, changes in impact of pests, diseases and weeds are only slowly being addressed [7].

Beyond direct climatic factors, the vulnerability to climate-related impacts of individuals, sectors (including agriculture) and societies is also increasing. An example is rapid population growth along coastal and urban areas, where water supplies are becoming limited as a consequence of accelerated global change [8•]. Particularly for agriculture in tropical and subtropical regions, there is a need to maintain access to water resources and increase water use efficiency [9•]. Clearly, there is urgency for targeted, well-planned adaptation action for agriculture and natural ecosystems management. Increasingly, resources are made available for what is already called 'adaptation financing' (e.g. the 2009 US federal budget contains $2.0 billion to help poor countries adapt to climate change; http://www.scribd.com/doc/12515797/Budget-of-the-United-States-Government-Fiscal-Year-2009), without having frameworks in place to strategically guide targeted research for adaptation actions in agriculture and natural resource management.

Here, we define adaptation science as the process of identifying and assessing threats, risks, uncertainties and opportunities that generates the information, knowledge and insight required to effect changes in systems to increase their adaptive capacity and performance. Adaptation science can be seen as a specialised form of sustainability science that occupies the boundary space between science and society. It is our objective to provide the theoretical basis of adaptation science by reviewing part of relevant literature concentrating on publications since 2006. However, some of the fundamental work needed to build a coherent framework was published earlier and is therefore also included. On the basis of this we advocate for *adaptation science* as a solution-oriented, scientific endeavour in the global agenda to facilitate adaptation actions.

In contrast to conventional science, adaptation science analyses the problems without a predefined disciplinary lens. It tests the hypothesis that science can play an important role in problem solving. Adaptation science differs from science for adaptation by testing alternative solutions and developing adaptation pathways or processes as opposed to generating more data.

In some cases the main issues might be outside the scientific realm, for example in cases where political controversies exist, but value positions of the political opponents are not well articulated [10••]. In such instances, scientific engagement might be premature, as it contains the danger of the controversy being 'scientized', whereby science is used to advance partisan, political goals on the basis of ill-defined value propositions. This undermines the independence and legitimacy of the scientific process.

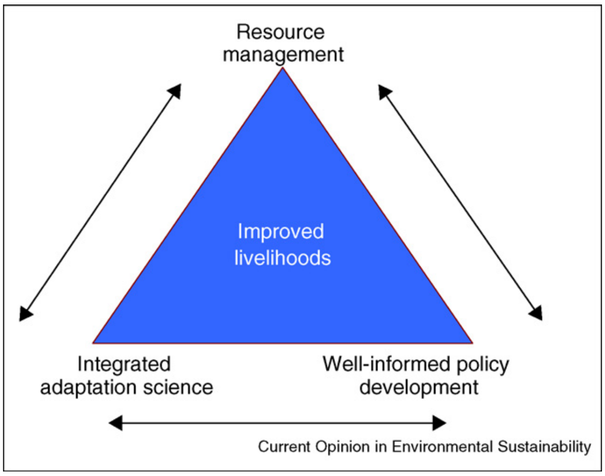
To avoid scientization, adaptation science needs to ensure that societal controversies are fully articulated and adjudicated through political means before science can play an effective role in problem solving (for a comprehensive discussion of this issue see [10••]). The next step — the selection of the disciplinary science mix needed to address the issues — is taken only if and when the hypothesis that science can play an important role in problem solving is confirmed. The main distinguishing feature of adaptation science from 'conventional' science is that testing this hypothesis takes place at the highest level of integration, at the interface between science and society and without the consideration of disciplinary confines.

Risk management and adaptation at different scales

Decision-makers habitually manage risk holistically and often intuitively [11,12•], whilst science tends to provide (scale-)specific, detailed and generally technical information for clearly identified and foreseeable sources of risk. This narrow focus on specific risks can have the unintended consequence of under-emphasising longer term and more holistic opportunities to build adaptive capacity [13]. Hence the demand for science input is often broad, general and vague, whilst the supply is narrow, specific and precise. This creates a (perceived) lack of science relevance that John Maynard Keynes (1883–1946) supposedly captured in his statement '*It is better to be roughly right than precisely wrong*' [14]. The current supply-driven approach tries to fit the problem to the available methods or tools at hand [15]. To increase relevance, scientific approaches should be embedded within context-specific, multi-stakeholder dialogues that match the most suitable tools and approaches to the issues [16]. Such participatory processes can translate scientific information into real life action by paying attention to salience, credibility and legitimacy as proposed by Cash *et al.* in 2003 [17]. The field of adaptation science provides this translation by matching technical options with socio-economically feasible solutions at relevant scales. This requires science disciplines to be modest, that is acknowledge and recognise the specificity and hence limited applicability of specific methods and tools. Yet, it also requires boldness and a willingness to step forward, taking on the challenge, once a science knowledge gap is identified. New insights are created through a multi-directional knowledge exchange that values the contributions of all participants (including scientists) leading to improved livelihoods through dialogue and negotiation informed by science (Figure 1).

Adaptation is a multi-scale process made up of individual choices; sometimes collective action can be an appropriate response [18]. Adaptation takes place within specific social and institutional settings that provide the framework within which actions have to be taken. Adaptation also occurs within a global setting, whereby global and national policies can strongly influence adaptation options and actions. Adaptation science therefore aims to assist practitioners and policy-makers to make appropriate choices and to help them negotiate the complexity of

Figure 1



The role of integrated adaptation science as a communication tool to inform policy as well as practice and to facilitate co-learning of all partners.

management-by-policy interactions from a position of increased knowledge and improved insight. Quantitative knowledge about the function, use and consequences of enabling and transformational approaches and technologies is part of a proactive adaptation process and supplements the already existing empirical knowledge based on years of experience, expert judgement, insight and intuition.

New technologies or changes in management can be either 'enabling' (i.e. facilitating improvements to existing systems or practices), or 'transformational' (introduction of new systems or practices) depending on the level of stress experienced, the intrinsic robustness of the system and the attractiveness of alternative options [19••,20]. Greater transformational change is required if, for instance, the current performance of a system is already marginal and more sensitive to a stressor such as climate variability and climate change.

Adaptation science creates synergy between knowledge and action by facilitating communication

Adaptation science is designed to create synergies from seemingly unconnected and divergent issues and goals. For instance, Huang [21] successfully applied a solution-oriented, multi-level, transdisciplinary research paradigm to connect the diverse fields of environmental sustainability and obesity. Such approaches are the key to generating the much-needed public and political support for solutions that can have large societal impacts. Here we propose a similar approach for agriculture and the natural resource management by expanding on the ideas summarised by Howden *et al.* [22]. We have modified the original version and suggested that for adaptation science to be successful in managing and transforming agriculture and natural ecosystems it requires that we (Figure 2):

1. understand the existing system and scope possible changes to norms and values,
2. identify likely core issues and decision criteria; clarify: who, what and when,
3. assess (climate) impacts and trends, including their uncertainty,
4. evaluate if impacts matter,
5. assess the adaptation options, their broader consequences and links,
6. design and evaluate implementation options.

This cycle of understanding and implementation is perpetual and participants choose whether or not they want to be part of this process. However, to have impact, involved scientists need to seek feedback *at each step of the cycle* and engage with the people and institutions that will ultimately act on the newly created knowledge. It is also evident from Figure 2 that each context and step requires a different disciplinary mix. No single scientific discipline or stakeholder dominates and not all of them need to be involved all the time. Ostrom [16] called for the creation of institutional structures and incentives that enable scientists from diverse disciplines and agencies to flexibly and continuously integrate formal scientific knowledge with local knowledge to support collective action.

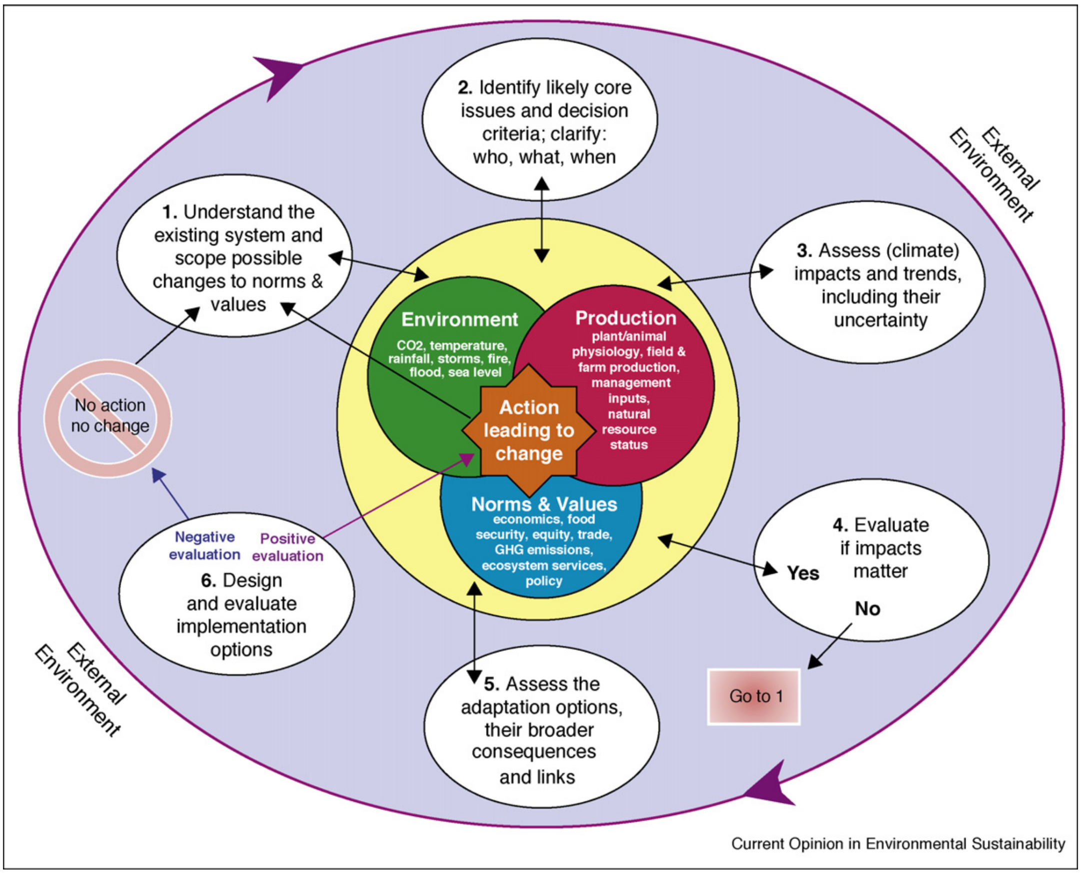
One way to facilitate such collaboration is through the process of developing outcomes-focussed models,[a] and embedding these in participatory and adaptive governance and decision-making processes. We stress the importance of modelling as a joint, participatory process, rather than taking a positivistic approach in which scientific knowledge is combined into a model that provides information for an often faceless or even non-existent 'user'. This also means that decision-makers need to be involved in the design of the tools that ultimately will provide them with information on which they might base their decisions [22]. The cycle proposed here functions in a way that is similar to that of the 'rapid prototyping' method that is now frequently applied in the development of consumer products, especially computer software (e.g. [23]; see also http://www.instructionaldesign.org/models/rapid_prototyping.html). The outcome-oriented process captures the synergies that arise when natural and social sciences are seamlessly combined to address pertinent issues of living rather than individually pursuing the disciplinary interests of academic inquiry [24••]. Thus viewed, model-building facilitates transdisciplinary communication whilst model application facilitates the discussion about possible actions and its consequences ('discussion support' [25]).

Modelling, systems thinking and operational risk management

In this paper, we use the term 'model' to refer to any simplified representation of a system that enables the investigation of the properties of that system and, in some cases, allows prediction, projection or exploration of future outcomes [see (G. Kruseman, Bio-economic household modelling for agricultural intensification, PhD thesis, Mansholt Studies No. 20, Wageningen University, The Netherlands, 2000) for a typology]. This includes conceptual, socio-economic and bio-physical models. Although the adaptation cycle is generic, its success will depend on a clearly negotiated understanding of the system's boundaries: participants have to agree on what they regard as internal to the system (i.e. issues potentially under their control and influence) and what they regard as external to the system (issues dictated by external forces). This negotiation process will draw attention to contested norms and values. Differences in norms and values need to be either resolved or made explicit as part of this process. A greater diversity of the norms and

[a] For a definition of the term 'model' see following section.

Figure 2



The adaptation cycle, the 'engine' of adaptation science, is based on a reflective analysis-action continuum (modified from Howden *et al.* [22]).

value propositions treated as 'internal' results in increased complexity of the issues to be resolved and may reduce the opportunity for meaningful conclusions. Therefore, clearly articulating the system boundaries is perhaps the most important step. Often this can be facilitated through a quantitative, model-based systems analysis.

Modelling can also be applied to evaluate the effectiveness of potential innovations at various levels of integration: from genetic engineering, to phenotype expression, to crop and cropping system management, to regional governance and policy setting. Through modelling, scale-specific knowledge is integrated to generate insights into complex system interactions whereby systems interactions can create behaviours and outcomes that can be very different from viewing these components in isolation. Emergent properties, the hallmarks of complex, adaptive systems (CAS), can result in counter-intuitive but correct inferences. Agricultural systems are typical examples of CAS whereby: first, order emerges rather than being predetermined; second, the history of the system is largely irreversible; and third, the system's future can only be predicted probabilistically [26]. Systems thinking places as much importance on understanding dynamic interactions between parts as it does on understanding the functions of the parts themselves. The system(s) of interest (and its/their outputs) need(s) to be viewed and evaluated holistically, including the key linkages and interactions between system components.

The brief examples below [27–38] focus on the use of biophysical models with particular emphasis on the management of plant-based systems. By definition, this excludes other equally important players in the agri-food chain, for example those involved in food distribution, processing, retailing and related industries. Nor do we elaborate on the use of the adaptation cycle for natural resource management. In fact our choice is not important. Alternative examples would be equally valid. Our choice simply reflects that context matters and unless systems boundaries are agreed upon and made explicit, no meaningful discourse is possible.

To positively influence the behaviour of managed systems (i.e. agro-ecosystems), it is necessary to identify the leverage points where incremental or transformative intervention can be supported by an adaptive policy environment [27]. *Ex ante*, model-based evaluation of the technology-by-management-by-policy interaction 'landscape' assists in determining the likely risks and benefits of a myriad of potential adaptation options. At the field to farm level, models are already used for operational risk management (e.g. [28]) and for the design of more resilient farm business [29,30], whilst they have also become indispensible in plant sciences to understand and predict the emergent properties of complex biological systems [31,32]. Likewise, public as well as private sector policy decisions are increasingly informed by the design of and output from simulation models (e.g. [33–36]) including the development of new insurance products (e.g. [37,38]).

Adaptation science builds a bridge between practice and policy, but also needs to link with society

Particularly in developing countries, the coping capacity of farmers is often well aligned to past challenges but is limited by (and somewhat adapted to) first, lack of resources and infrastructure; second, poor levels of education; third, lack of institutional support; and fourth, in many cases ineffective policy including that brought about through inept and corrupt governance [39]. Therefore, any existing adaptive capacity that has evolved over time is unlikely to be prepared for unprecedented impacts, such as those brought about by anthropogenic climate change. Research underpinned by a human-centred sustainable livelihood approach can contribute to survival and help in the subsequent renewal and re-direction of livelihood options [40]. Without an effective and supportive policy framework for sustainable adaptation actions, farmers' adaptive responses will likely prioritise short-term gains at the expense of the long-term sustainability of the system. Hence, adaptation science needs to engage both sides (practice and policy) and both communities (agriculture and sustainable eco-systems management) simultaneously to iteratively improve the situations of resource poor farmers.

Even in developed economies, proactively designed adaptation does not come easily to agricultural sectors that value short-term economic incentives, experience and tradition and whose decision needs are rarely directly met by the science community. Adaptation action requires changed attitudes and practice by all participants, including the science and policy communities [34,35] and the recognition that science will only ever provide partial answers to societal problems [41••]. The pervasive nature of ongoing climate variability and change poses a particular challenge: climate is a widely acknowledged risk factor for most agricultural activities, but without being the sole or even dominant driver for most of them. Yet without due consideration of climatic impacts, the dual goals of agricultural production — profitability and sustainability — cannot be achieved. Conversely, the considerable opportunities that are created by more favourable climatic conditions and new, climate-related policy measures often fail to translate into real benefits.

Science promises a wide range of technical innovations that could potentially provide partial solutions for more sustainable production. However, such technical solutions need to be assessed against their broader biological, economic and social consequences [28,42•]. For instance, modern gene technologies and breeding techniques now enable the rapid development of highly specialised agricultural products (food, fibre or fuel crops) that are purposely designed to perform well in certain environments and in conjunction with specific management options (e.g. herbicide-tolerant crops). As impressive as some of these technical advances are for farmers [43•], they are often viewed with suspicion by a sceptical public unconvinced that the benefits outweigh the concerns about real or perceived risks. To many scientists such scepticism is sometimes surprising and often frustrating given the 'obvious' (from a scientific perspective) advantages of technological advance. This further highlights the existing relevance gap between science and society that can only be bridged if all sides are willing and able to actively engage in debate.

Adaptation science and modelling create social capital and connect scientists with decision-makers

Social capital can be defined as the norms and networks that enable people to act collectively. There are three components of social capital: bonding, bridging and linking [44]. Bonding refers to the interactions characterised by personal trust and reciprocity within homogenous social networks. Bridging refers to interactions characterised by trust and reciprocity that extends beyond homogenous social networks to members of heterogeneous social networks. Whilst the bonding form of social capital permits cooperation, and bridging connects people with new ideas, the linking form of social capital facilitates access to the resources necessary to implement collective action on those ideas.

Effective climate risk management depends on various dimensions of social capital including peer groups, networks, trust, collective action, social inclusion, information and communication. Successful integration of climate risk management into social systems involves implementing both the structural form and cognitive function of social capital [45]. Participatory research and systems modelling approaches are a means by which science can build social capital by bringing together researchers, policy-makers and practitioners to construct, analyse, discuss and learn from relevant quantitative data and scenario analyses as part of an adaptive process of directed adaptation or adaptation by design (Figure 2).

Such relationships are a prerequisite for effective, multi-scale modelling that leads to action. It opens the possibilities to use models for first, upscaling from an understanding of crop physiological responses to enterprise-scale options and second, downscaling from an understanding of global (climatic) conditions to 'quantities' that motivate farmers: farm income and the long-term sustainability of their resource base [46]. Such multi-scale modelling can provide the quantitative information needed for sustainable and profitable management and inform the various forms of capital for rural livelihood analyses [47,40]. This includes the under-exploited heuristic value of modelling [48] given that education, both formal academic education and work-place skills, is a crucial dimension of human capital required for improving livelihood prospects [40].

Participatory modelling exercises can also facilitate debates between scientists and a public critical of new technologies by considering multiple evaluation criteria (economic, environmental and social). In such cases, the model replaces traditional, *in vivo* approaches to data collection (i.e. experimentation) with *in silico* approaches, given that experimental (*in vivo*) approaches are not feasible due to time scales or costs involved. As one Australian farmer said: 'Modelling provides hindsight in advance and farming with hindsight makes things a lot easier'.

Adapting to a changing physical and economic environment within policy frameworks that facilitate sound adaptation could be essential for the economic survival of some agricultural sectors whilst creating substantial development opportunities for others. Yet decision-makers' research needs on both sides — practice and policy — are often neglected as their interests fall in the gaps between existing disciplinary and institutional boundaries. In the early development of adaptation responses, it may be useful to nurture climate specific forms of interdisciplinary research to avoid them being swamped by other issues. This addresses the issue of climate as a major driver of risk explicitly before it can be 'mainstreamed' into a more general risk management framework [22]. As these forms of science develop, mainstreaming may be required to ensure adaptation responses consider climate as one of many possible drivers of change. Without mainstreaming, a lack of scale-transcending and discipline-transcending knowledge can lead to maladaptation, as shown by unintended consequences on food prices and ecosystems services of policies that encourage the expansion of maize-based biofuel production [49•]. Proactively designed and sustainable adaptation action will occur only if and when climate-related risks are treated holistically in conjunction with other drivers of risk (e.g. market, environment or social unrest, policy), supported by policies that take multiple domains and outcomes into account (e.g. facilitating transformational changes when required) [13]. Therefore, we call for adaptation science to provide integrated vulnerability and viability assessments that are policy relevant and trigger regionally specific and enterprise-appropriate adaptation and transformational responses.

Conclusions

Adaptation is rapidly emerging as one of the biggest, global agenda items for this decade, and possibly the century. The role of science in implementing this agenda is yet to be defined and requires well-structured, conceptual frameworks that connect science with actions whilst achieving desirable adaptation outcomes. Drawing on the existing literature, we contribute to the development of such a framework in the field of agriculture and natural resource management by developing early ideas of adaptation science, a process designed to create adaptation-supporting synergies from seemingly unconnected and divergent issues and goals. Such a framework will allow the evaluation of alternative adaptation approaches in a rigorous and contestable way. In this way, adaptation science will contribute to accelerate the rate of current adaptation in the face of an ever-accelerating global change process. The framework is designed to advance adaptation actions by overcoming existing barriers, mainly through the provision of 'alternative futures' that can be realised through the use of enabling (improvements of existing systems) or transformational (introduction of new systems) technologies.

We have defined adaptation science as the process of identifying and assessing threats, risks, uncertainties and opportunities that generates the information, knowledge and insight required to affect changes in systems towards increased adaptive capacity and performance. We have also proposed an 'adaptation cycle' as a multi-scale conceptual framework on which to base a reflective analysis-action continuum that connects science with society at every step in the process. We conclude that in order to make science more relevant for the process of adaptation we need to embed scientific approaches within context-specific, participatory dialogues that match the highly contextual needs of decision-makers to suitable tools. There must also be a recognition that science will only ever provide partial answers to societal problems. By adopting the adaptation cycle we ensure that no single scientific discipline and, in fact, none of the participants dominate the process.

We further conclude that for managed systems (e.g. agro-ecosystems) it is necessary to identify the leverage points where management intervention supported by an adaptive policy environment can positively influence systems behaviour and where technological options can either provide incremental or transformative improvements. Models are an essential tool for this process. Yet modelling can often be insular, esoteric and uncontaminated by real problems or actions. We therefore propose to use the adaptation cycle to engage with all the players, including the modelling community from all the relevant disciplines, in order to start the dialogue and to distil the best science has to offer for the task of highest priority: adaptation to improve livelihoods.

Acknowledgements

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According to Maxwell, the answer is 'yes'. He argues that science philosophy is partly to blame for the collective inaction in regard to the overwhelming evidence of global warming. For adequate action to have occurred we would have required traditions and institutions of inquiry devoted to helping humanity learn what are our problems of living and what we need to do about them. Instead science philosophy has promoted a mode of inquiry that is overwhelmingly devoted to acquiring knowledge. This, he argues, is disastrously irrational. If academic inquiry were to help promote human welfare rationally, it would give intellectual priority to the tasks of articulating problems of living and proposing possible solutions and real actions.

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Jasanoff takes scientists and policy-makers to task and argues that uncertainty has become the threat to collective action. This lack of action fails to recognise the inevitable partiality of scientific knowledge under irredeemable uncertainty. She therefore calls for 'technologies of humility', a plea for policy-makers to cultivate and for universities to teach complimentary modes of knowing. She argues that good science needs to be supplemented with the analysis of those aspects of the human condition that science cannot easily illuminate. Her paper is a call for policy analysts and policy-makers to re-engage with the moral foundations for acting in the face of inevitable scientific uncertainty.

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