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A framework for priority-setting in climate smart agriculture research

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ABSTRACT

Climate-smart agriculture (CSA) is widely promoted as an approach for reorienting agricultural development under the realities of climate change. Prioritising research-for-development activities is crucial, given the need to utilise scarce resources as effectively as possible. However, no framework exists for assessing and comparing different CSA research investments. Several aspects make it challenging to prioritise CSA research, including its multi-dimensional nature (productivity, adaptation and mitigation), the uncertainty surrounding many climate impacts, and the scale and temporal dependencies that may affect the benefits and costs of CSA adoption. Here we propose a framework for prioritising agricultural research investments across scales and review different approaches to setting priorities among agricultural research projects. Many priority-setting case studies address the short- to medium-term and at relatively local scales. We suggest that a mix of actions that span spatial and temporal time scales is needed to be adaptive to a changing climate, address immediate problems and create enabling conditions for enduring change.

1. Introduction

By 2050, agricultural production will need to increase substantially to feed growing and urbanising populations, particularly in sub-Saharan Africa (SSA) and South Asia.Estimates of the increase needed vary between 25 and 70%, depending on the assumptions made about efficiency and consumption pattern changes (Alexandratos and Bruinsma, 2012; Hunter et al., 2017). Increased food production will have to be done in the face of a changing climate and increased climate variability (Porter et al., 2014), while improving nutritional outcomes and reducing the carbon cost of farming and its contribution to greenhouse gas emissions (Tubiello et al., 2015). This cannot be achieved simply by farming at lower intensity and taking more land; there is not enough land to convert at acceptable economic and environmental cost (Lambin et al., 2013; Tscharntke et al., 2012; Karlsson et al., 2017; Keating et al., 2014; Searchinger et al., 2015).

One response to these recognised needs has been the development of approaches such as sustainable intensification (SI) (Garnett et al., 2013; Montpellier Panel, 2013) and climate-smart agriculture (CSA) (Lipper et al., 2014). Such approaches have brought recognition that there will

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be multiple alternative pathways to sustainable agricultural systems, and their suitability and outcomes will vary, depending on agro-ecological zone, farming system, resource endowment, cultural preferences, institutions and policies. Another response has been to seek better understanding of the current and likely future structure of farming. Currently, 30% of most food commodities in Africa and Asia are produced on farms of < 2 ha, and 60–75% is produced on farms of < 20 ha (Herrero et al., 2017; Ricciardi et al., 2018). Industrialisation of agriculture will accelerate in some places, but in others, smallholders' contributions will remain critical, at least in the short to medium term.Although widespread intensification of production is urgently needed in SSA and elsewhere over the next 20 years, smallholders will still form the key target group for agricultural research for development (Masters et al., 2013).

How well are smallholders in lower-income countries adapting to the many challenges they face?Agricultural research for development has resulted in many different interventions over the last decades. A recent analysis of case studies across the tropics shows that only 16% of households have been actively intensifying their production in the last 10–15 years (Thornton et al., 2018a). There are many constraints facing smallholders regarding adoption of agricultural technology; so how are interventions to be taken to the scale needed if food and nutrition security is to be achieved? Given what is known about the importance of local context in smallholder systems, which interventions should be the focus? This highlights the need for prioritising different interventions, whether technical or policy-related, based on impact assessment (Raitzer, 2009). Such studies can provide information to assist in the allocation of scarce resources to research and scaling-up activities that best match funders' and governments' development objectives. This is increasingly important as many countries seek finance to implement their prioritised nationally determined contributions (NDCs) to achieve mitigation, adaptation and land degradation neutrality (LDN) targets as well as the Sustainable Development Goals (UN, 2015; Richards et al., 2015; Orr et al., 2017).

Here we consider prioritisation of research interventions in relation to CSA. While there is a growing literature on CSA prioritisation, with a wide array of different approaches and methods, we currently lack a flexible framework for assessing and comparing different interventions and investments that addresses the key elements of CSA.Here we propose such a framework. In the next section, CSA is outlined, describing some of its features that make prioritisation a challenge. Section 3 lays out a suggested framework for doing this in relation to CSA, and its use is illustrated in Section 5 based on a brief review of existing tools and methods for priority setting in agriculture and some case-study examples. We conclude with a consideration of remaining challenges.

2. Climate smart agriculture

CSA is an approach for transforming and reorienting agricultural development under the realities of climate change (Lipper et al., 2014). Its goal is to achieve sustainable agricultural development for food security via three “pillars”:

- Sustainably increasing agricultural productivity from crops, livestock and fish, to contribute to achieving food and nutritional security as well as higher incomes, but not at the expense of the environment;
- Adapting to climate change, with a focus on reducing exposure to short-term risks, enhancing capacity to adapt and develop in the face of shocks and longer-term stresses, and maintaining healthy ecosystems that provide environmental services to farmers;
- Reducing and/or removing greenhouse gas emissions where possible, including through reduced emissions for each kg of food, fibre and fuel produced, avoiding deforestation from agriculture, and managing soils and trees in ways that enhance their potential as carbon sinks, thereby absorbing CO_2 from the atmosphere.

In some situations, CSA may produce triple-win outcomes: increased productivity in combination with reduced impacts to climate risks and shocks, and mitigation of climate change through reduced GHG emissions. Often, however, implementing CSA will involve addressing trade-offs between the three pillars and weighing the costs and benefits of different options based on stakeholders' objectives. Furthermore, CSA is context specific and although some interventions may be climate-smart in some places there are no interventions that are applicable to all situations, in all ecosystems, and in all sets of different institutional arrangements and political realities. But CSA is more than a set of practices or technologies; it is rather an approach for integrating multiple interventions across a range of food systems, landscapes, value chains and government regulation or policy (Lipper et al., 2014). The range of CSA interventions is wide, from soil, water management to carbon finance and incentive systems for low-carbon agriculture, for example (FAO, 2013). Its entry points range from the development of technologies and practices to the elaboration of climate change models and scenarios, information technologies, insurance schemes, and processes to strengthen the institutional and political enabling environment, particularly for marginalized groups. The breadth of possibilities and the context-specificity of much smallholder agriculture underline the importance of the role of priority setting in resource-constrained research settings.

The CSA approach has gained considerable traction in recent years, but it has been heavily contested, particularly with respect to social equity. There are concerns that CSA may transfer the burden of responsibility for climate change mitigation to marginalized producers and resource managers, and that CSA gives little attention to entrenched power relations that may block the emergence of more equitable agricultural systems (Karlsson et al., 2017). At the same time, support for CSA has come from many countries, particularly in Africa, that include agricultural adaptation and mention of CSA in their nationally determined contributions in the wake of the Paris Agreement (Richards et al., 2015). The inclusion of equity considerations in CSA remains a work in progress, but research is now emerging on the politics and governance of adaptation and the transformations that will be needed in farming systems in the future (Chandra et al., 2017; Purdon and Thornton, 2017).

3. A framework for CSA prioritisation

In this section, we propose a conceptual framework for the prioritisation of CSA research. The framework was developed in a workshop setting, informed in part by case studies developed by some of the participants (see Section 5.2 below). Before presenting the framework, we list some of the special challenges that CSA prioritisation can present.

3.1. Special challenges of CSA

CSA presents special challenges to priority setting, including the following.First, what is “climate smart” in relation to practices, technologies, and policies is heavily influenced by local context (Duong et al., 2016; Wreford et al., 2017). Smallholder farming systems are highly heterogeneous even over short distances, both biophysically and socio-economically. Second, climate smartness needs to be assessed in relation to three dimensions (productivity, adaptation and mitigation). Priority setting thus needs to address these different dimensions using what may be multiple metrics, so that resulting trade-offs and synergies can be evaluated (Bell et al., 2018). In addition, the importance placed on each dimension by different stakeholders is strongly dependent on context and objectives. Third, the size and nature of the benefits and dis-benefits that arise from CSA adoption may have both scale and temporal dependencies (McCarthy et al., 2018). Scale dependence may arise in relation to the aggregated regional impacts of the adoption of an intervention on production and prices, such as seasonal weather forecast. Temporal dependence may arise owing to the dynamic interrelationship between the three pillars of CSA through time; for instance, interventions that build up soil organic matter may translate into substantial production, carbon sequestration, adaptation and income benefits several years into the future, but at the cost of income foregone in the short term. Fourth, the impact pathways for CSA interventions can span a broad range of decision makers, from individual farmers and value-chain participants, to regional and national governments and organizations, and ultimately to the full set of international actors engaged in negotiating collective action to combat climate change (Lipper et al., 2014).The challenge here is dealing with the multiple and sometime competing objectives of all the relevant stakeholders. Fifth, temporal variability may be high in agricultural systems and trajectories of climate change locally uncertain (Porter et al., 2014). CSA outcomes related to productivity, adaptation and mitigation may be heavily dependent on this variability and uncertainty. All these factors may present challenges to the way in which the effects of different alternatives on livelihoods, markets, economies and the environment are conceptualised and evaluated.

3.2. A conceptual framework

Here we outline a conceptual framework for prioritising different CSA research activities, to assist in making decisions about the allocation of research and implementation resources. A workshop-based participatory process involving the authors was used to identify six elements in the framework, illustrated in Fig. 1.We include feedbacks between the different elements to highlight the fact that priority-setting processes are generally non-linear and iterative. Above all, Fig. 1 presents a general “map” of the elements that need to be taken into account in prioritising CSA research at different spatial and temporal scales, along with the major questions to be addressed for each element. The six elements in the framework are outlined below.

3.2.1. Identify system entry points and impact pathways

All research activity should be planned based on a clear understanding of the problem being addressed and the way in which research may be able to contribute to finding a solution. Achieving consensus among the stakeholders involved may be greatly facilitated using participatory diagnosis as part of community baselining (Goudou et al., 2012) or through scenario-based approaches (Zougmoré et al., 2017), for example. Entry points for intervention in the system then need to be identified, along with the hypotheses and assumptions regarding the way in which research inputs, activities and outputs can lead to outcomes (behavioural change) and thence to impacts. Appropriate entry points may relate to specific challenges of nutrient depletion or inadequate water supply in cropping systems, for example. They may also relate to challenges beyond the farm gate regarding markets, value chains and governance, for example. The planning of agricultural research is well-documented (e.g., Gijsbers et al., 2001), with increasing attention being given to program theory (and theory of change) as a way to make it more effective and efficient in terms of contributing towards longer-term development goals (Vogel, 2012). Approaches based on theory of change, or the ways in which change is expected to occur from research output to outcome and impact, combine ways of tracking progress in research along with indicators of change aimed at understanding the factors that enable or inhibit the behavioural changes that can bring about development impacts. Setting out explicitly what these impact (or causal) pathways might be at the start of a research activity provides testable hypotheses about how research outputs may help to foster change, thereby helping to bridge the gap between knowledge generation and development outcomes (Douthwaite et al., 2003). Dealing with this element of the framework highlights the need for monitoring and evaluating the progress of the research itself, so that if early piloting of an intervention fails, for example, the theory of change can be adjusted and activities modified appropriately.

3.2.2. Define the spatial and temporal scales of the research

Specific research activities have different spatial and time scale dimensions.For example, a varietal improvement intervention may operate by utilising current crop varieties based on refined recommendations that can deliver a specific adaptation needed in a particular place. In such a case, the time scale is short and the spatial scale is relatively local.Activities in “Climate Smart Villages” provide an example, involving applied research around knowledge and local institutions, climate services, climate smart technology and village development plans. Some activities might be focused on implementation and attempting to scale out interventions across space (Aggarwal et al., 2018). Alternatively, other breeding investments may be much larger-scale and longer-term, such as a breeding program designed to develop new varieties with complex adaptation traits. An example is the development of drought tolerance in common bean, which has taken > 30 years of effort and may have very wide applicability (Beebe et al., 2013). A key part in defining the scale of the research activity relates to the costs required for the research itself and deploying the research outputs, and the adoption expected, such as the percentage of farms adopting in a village, landscape or region. This stage in the process will also involve a consideration of the scaling strategy to be used, if deployment is to happen over large areas, as there may be considerable costs involved.

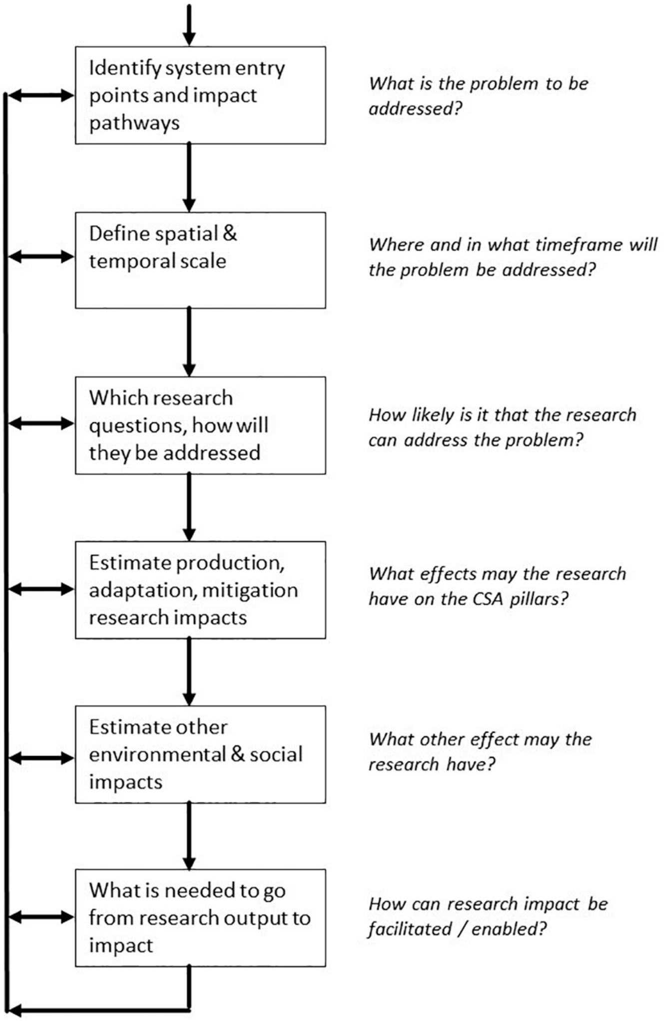

Fig. 1. Elements in the CSA priority setting framework and the questions to be addressed.

3.2.3. Which research questions, and how will they be addressed

For this element of the framework, questions are asked about the nature of the work being planned, and whether research outputs are feasible, in the light of the spatial and temporal scale of the research activity proposed. The work may relate to the evaluation of existing technology in different locations or to more upstream research activities where the research outputs are uncertain. One important question may relate to the likely conditions in future that may need to be adapted to, such as weather patterns characterised by more extreme drought and more frequent high-temperature events, for example.This may involve assessing whether the research proposed fits within the bounds of theoretical possibility; for example, the climate expected in future in the research location may be above the thresholds of high-frequency, high-temperature events that induce crop sterility. The practical viability of the research will also need to be assessed; for example, whether the research proposed is practicable given the state of current knowledge and the research's likely levels of resourcing. Such considerations are needed to estimate the probability of success in producing the research outputs envisaged, which may be quite high for applied research activities (and lower for more uncertain, upstream research).

3.2.4. *Estimate production, adaptation, mitigation research impacts*

In this part of the framework, estimates have to be made as to the likely effects that the proposed research may have on the CSA pillars.Different metrics will be needed to describe the "climate smartness" of the research products. This includes estimates of the likely changes in productivity such as more yield and income (P), metrics that describe elements of adaptation such as a decrease in the variability of yield and income (A), and metrics addressing mitigation such as marginal or absolute changes in GHG emissions or changes in GHG intensities per kg product (M).The literature around such indicators is already quite extensive (Hills et al., 2015; Braimoh et al., 2016; FAO, 2017; Chaudhary et al., 2018), and there are many from which to choose. Depending on the priority-setting tools being used, some of these metrics may be expressed as probability distributions of outputs such as yield, income and GHG emission intensities, particularly in situations where the analysis is addressing risk and its influence on stakeholders' behaviour.

3.2.5. *Estimate other environmental and social impacts*

As usually conceived, CSA does not explicitly address certain environmental and social dimensions of interventions that may be important to address. These include metrics for environmental changes that may be brought about by the intervention, such as biodiversity, water quality and air quality (E); and metrics for social changes such as gender and income equity (S). This category may also include metrics related to the economics of interventions at different scales, including returns on investment to government or private sector programs, and gross margins for smallholders, for example. Another element to consider are the changes in these metrics at different scales and the investments and actions that may be needed to bring about the scaling up required to reach the adoption targets identified above. For example, farm ponds may need massive investment, while micro-dosing of fertilizers may need very little. Some research activities involve bundles of different CSA options; in these cases, changes in some of the metrics through time may need to be estimated and activities sequenced appropriately.

3.2.6. *What will be needed to go from research output to impact*

Here, the likelihood of achieving outcomes and impact has to be estimated in relation to the scale of the research activity. This likelihood may be highly context specific and will depend on the scale of impact along the impact pathway, such as household income effects compared with national food security impacts, for instance. This also requires a consideration of the factors that can enable change. For example, in places where maize is well established as a crop, the swapping of one variety for another may be relatively straightforward, although there are often important nuances around texture, consistency and taste. Other enablers such as conducive policies, informational requirements, and markets will need to be considered, and all these can affect the likelihood of reaching adoption targets and achieving impact. Activities designed to facilitate uptake may have costs that need to be considered. As noted above in relation to element 1, if the impact pathway originally envisaged no longer appears to be appropriate, the theory of change may need to be adjusted, a modified impact pathway developed, and activities adjusted accordingly.

4. Setting priorities

In this section we discuss use of the framework presented above. We first outline existing tools and methods that in the past have been used to set priorities in agricultural research, and then we relate these to the six elements of the framework in Fig. 1.

4.1. *Approaches supporting priority setting in agricultural research*

In reviewing existing approaches to priority setting in agricultural research, a workshop-based participatory process was set up to identify examples from the literature that were representative of a wide range of different approaches. Participants (including the authors) had a broad range of expertise, including plant breeding, economics, policy and ecology, as well as experience working at spatial scales ranging from the plot level to global-scale analysis. In this way we could reduce bias towards specific methods at the same time as having a broad coverage of approaches. Although it is difficult to categorize published work owing to significant methodological overlaps, Table 1 presents nine major approaches currently used for priority setting, some of their advantages and disadvantages, and examples of each from the literature. It should be noted that in all cases, these tools and approaches may be used for a whole range of different purposes, not just priority setting. The approaches identified vary widely in complexity, as well as in the type and nature of information required for their use.No one approach will suit all contexts or interventions. Most methods have already been used for assessments of productivity, adaptation or mitigation effects in agriculture, sometimes all three together. They all have one characteristic in common: many variables and dimensions can be included and weighted according to the context or question being addressed.

4.1.1. *Simulation modelling*

The types of simulation models applied to understanding the impacts of various CSA interventions are generally flexible frameworks which can consider numerous factors of the given production system including the effects of varying biological, technical and physical processes. These models have been used to investigate agricultural production at various levels of research, including crop, livestock, and farming system level. In contrast to statistical methods such as econometrics, dynamic simulation models can describe the changes in systems states in response to external environmental drivers (e.g., weather and management practices), and how those changes are affected by other components in the system (Jones et al., 2017). Examples of dynamic models include APSIM (Holzworth et al., 2014), DSSAT (Hoogenboom et al., 2017), CROPSYST (Stöckle et al., 2014), and EPIC (Williams et al., 1989). Models are typically highly complex, containing many descriptive variables and parameters. Reduced-form models of larger more complex models have been used in the past for specific purposes (see, for example, Chikowo et al., 2008; Dzotsi et al., 2013). This approach is particularly useful when integrating agronomic or livestock models in a broader agricultural systems framework such as economic analyses at farm, regional, national, or global scales (Lisson et al., 2010). Recent years have seen several international collaborative efforts to improve the state of agricultural simulation and to understand climate impacts on the agricultural sector at global and regional scales (Rosenzweig et al., 2014).Whole farm modelling approaches that combine both biophysical and economic elements have gained more relevance in the recent times (Robertson et al., 2012). These models have been used to prioritise alternative crop-livestock enterprise systems, to capture management differences, risk and resource trade-offs

Table 1
Existing tools and approaches that can be used for setting priorities among agricultural technologies.

Approach	Pros	Cons	Examples/key references
Simulation modelling[a]	* Efficiently assessing spatio-temporal variability. * Allows comparison across different contexts * Allows exploration of a wide range of scenarios	* Complexity and uncertainty can be high, precluding decisions * Calibration and validation are challenging * High data intensity	* Assessing adaptation strategies in Kenya (Claessens et al., 2012) * Prioritisation of agronomic practices in north-eastern India (Shirsath et al., 2017) * Assessing the value of 19 agricultural technologies under climate change globally (Rosegrant et al., 2014)
Mathematical Programming/ Optimization methods	* Consideration of multiple system objectives * Flexibility in defining system's objectives	* Data intensive, time consuming, difficulty of eliciting household objectives and representing them appropriately (Thornton et al., 2003) * Difficult to address hypothetical situations, other contexts or scenarios.	* Multi-objective optimization and design of farming systems (FarmDESIGN, Groot et al., 2012) * Identification of optimum management adaptations in Western Switzerland (Holzkämper et al. 2015) * Developing water resources plans under climate change (Borgomeo et al., 2016) * Bio-economic evaluation of dairy farm management scenarios using integrated simulation and multiple-criteria models (Herrero et al., 1999)
Cost-benefit analysis	* Applicable in different contexts * Low data intensity	* Difficult to capture all benefits and costs (e.g. bank account or insurance aspect of cattle) * Difficult to include multiple criteria or system's objectives (e.g. poverty, nutritional outcomes)	* Assessment of climate policy (van den Bergh, 2004) * Cost-benefit analysis for climate change and climate variability adaptation (Leary, 1999) * Cost-benefit analysis for CSA technologies in Telangana, India (Kumar et al., 2018)
Economic surplus	* Requires less information than other (i.e. econometric, optimization) models. * Widely used to estimate impact of agricultural technologies	* Required information on price responsiveness of consumers and producers often not available. * Difficult to incorporate non-marketed benefits and hidden costs * Difficult to include non-economic outcomes (e.g. poverty, nutrition).	* Measuring the returns on research on African animal trypanosomiasis (Kristjanson et al., 1999) * The impact of high-end climate change on agricultural welfare (Stevanovic et al., 2016) * Economic impacts of improved pigeonpea varieties in Tanzania (Shiferaw et al., 2008) * Study of the impact of EMBRAPA technologies (Wander et al., 2004)
Econometrics	* Allows estimating direct impacts at multiple levels (farmer, county or state) * Allows statistical testing of economic theory	* Limited ability to extrapolate responses outside estimation sample (Antle and Capalbo, 2001) * Restrictive assumptions associated with choice of functional form (work on flexible technology representations, Carter, 1984) * Data intensive: requires detailed survey data	* Global warming impacts on US agriculture (Schlenker et al., 2006) * Ricardian analysis of the impact of global warming on agriculture (Mendelsohn et al., 1994) * Economic-process models for integrated assessment of agricultural production systems (Antle and Capalbo, 2001).
Participatory/ranking[a]	* Incorporates expert and stakeholder views, often reflective of realities in the field * Flexibility to incorporate multiple variables and systems' objectives * Various existing examples in CSA research * Many methods exist, with varying degrees of complexity and ease of implementation * Linkable to other approaches (e.g. modelling)	* Difficult to compare across different groups of experts or contexts * Difficulty in relating expert-based scores to measurable variables * There can be considerable variation across experts or communities * Subject to bias if groups are dominated by certain individuals (e.g. women left out) or if stakeholders deliberately mislead organizers (i.e. tell organizers 'what they want to hear')	* Participatory monitoring and impact assessment in agriculture (Guijt, 1998) * Comparative analysis of eight CSA technologies in Guatemala (Sain et al., 2017) * Participatory evaluation of CSA technologies, practices and services in Rajasthan (India) (Khatri-Chhetri et al., 2017) * Rapid appraisal to prioritise CSA interventions in Uganda and Tanzania (Hareau et al., 2014; Mwongera et al., 2017) * Participatory ranking of CSA technologies in Telangana, India (Kumar et al., 2018)
Meta-analysis/systematic review[a]	* Can include multiple sources of potentially disparate (e.g. experimental, model-based) evidence, seeking consensus among these * Can combine multiple indicators into aggregated dimensions, hence useful for CSA * Systematic review can include adoption rates of practices and factor this into analysis	* Difficult to draw generalized conclusions or reach consensus when context-specificity is high or evidence is limited * Time consuming if the systematic review is too long and complex (many variables, many studies) * Difficult to draw conclusions on underlying processes	* Global meta-analysis of crop yield under climate change and adaptation for rice, wheat and maize (Challinor et al., 2014) * Systematic review protocol for climate-smart agriculture (Rosenstock et al., 2016) * Prioritisation and potential impact of climate-smart agriculture practices in Tanzania and Uganda (Lamanna et al., 2016)
Spatial analysis/GIS/ Remote sensing[a]	* Allows delineation of target zones or recommendation domains * Simplicity	* Dependent on good spatial datasets * Often difficult to include socio-economic aspects at high resolution * Difficult to incorporate systems dynamics, or to assess mixed systems	* Identifying recommendation domains for maize-based interventions in East Africa (Notenbaert et al., 2013) * Development domains for Ethiopia (Chamberlin et al., 2006) * Prioritisation of climate-smart interventions in the livestock sector in sub-Saharan Africa (Notenbaert et al., 2017) * Characterization of areas for improving agriculture-based livelihoods (Farrow et al., 2007) * Recommendation domains for conservation agriculture in Ethiopia, Kenya and Malawi (Tesfaye et al., 2015)

(*continued on next page*)

Table 1 (*continued*)

Approach	Pros	Cons	Examples/key references
Integrated assessment modelling	* Allows integration of a suite of different models to evaluate synergies and trade-offs * Can provide outputs in several dimensions relating to land-use, commodity prices, and environmental and health impacts, for example	* Complex and skill- and time-consuming to carry out * Conceptual difficulty of model validation and calibration * Uncertainty bounds on model outputs are often unknown; when known (e.g. Nelson et al., 2014) they may be very large	* Assessing the impacts on production and GHG emissions of shifts from livestock only to mixed drop-livestock farming systems (Havlík et al., 2014) * Evaluating the adaptation costs and mitigation benefits of livestock systems shifts (Weindl et al., 2015) * Evaluating different research strategies for CGIAR commodities (Rosegrant et al., 2017)

[a] Existing studies have used the method for the prioritisation of climate-smart agriculture practices.

between scenarios reflecting crop, feed, livestock, labour and economic outcomes (Lisson et al., 2010; Komarek et al., 2015). With dynamic linkages among crop, livestock and socio-economic components, these models are a valuable tool to assess the impacts of climate smart interventions on resource use and household cash flows and help extension agents and farmers as decision support (Kumar et al., 2017). Simulation modelling, although widely used, is often complex and the uncertainty associated with the results may be considerable.

4.1.2. *Mathematical programming and optimization methods*

Agricultural systems modelling has evolved in line with several key events that drove the development and use of these models across several disciplines (Jones et al., 2017). Heady and Dillon (1960) were instrumental in establishing the application of optimisation techniques to estimate the economic benefit associated with rural development policy. Historically, optimisation models have used a linear programming framework to mathematically obtain the best solution for the problems in the systems of interest given an objective function such as input minimization or output maximization at the farm or household level. These models are generally developed for specific situations and are therefore less suited to studying consequences of a range of hypothetical investigations although methods have been developed using more flexible specifications than traditional linear constraints such as positive mathematical programming techniques (Howitt, 1995; Louhichi and Paloma, 2014).A recent example of the use of mathematical programming in prioritising CSA interventions is described in Dunnett et al. (2018). Such approaches to prioritising research alternatives tend to be data intensive, complex and time consuming.

4.1.3. *Cost-benefit analysis*

Cost Benefit Analysis (CBA) is an economic tool that can be used to assess the relative profitability of alternative investments comparing their different flows of costs and benefits over a specific time period. Many studies have employed CBA approaches to CSA prioritisation (for example, Sain et al., 2017; Nganga et al., 2017). In the context of CSA, a key strength of CBA lies in determining trade-offs between different adaptation options, thus playing an important role in justifying the case for a particular action, and for prioritising available resources to maximize social, environmental and economic benefits. However, the application of CBA in CSA prioritisation can be challenging. This is because CBA requires all costs and benefits to be expressed in monetary units; and it is difficult to attach monetary values to non-market social and environmental goods and services (Almansa and Martínez-Paz, 2011). CBA approaches have also been limited by conceptual difficulties in discounting future costs and benefits and integration of risk and uncertainty (Salci and Jenkins, 2016).

4.1.4. *Economic surplus*

Economic surplus methods have been used widely to assess the economic impacts of new agricultural technology, both ex-ante (e.g., Kristjanson et al., 1999; Rudi et al., 2010) and ex-post (e.g., Elbasha et al., 1999; Moussa et al., 2011), as well as for priority setting (You and Johnson, 2010). These methods are based on the premise that technology or policy shifts will affect the supply of the commodity being produced, which changes its price. Economic surplus methods quantify these shifts and estimate the impact that change has for both the producers of the commodity and consumers. Technical change may reduce production costs for farmers and increase production per unit of input cost. Consumers benefit because the commodity price has decreased. Farmers may be better off, if the quantity they are selling has increased, despite the decrease in the price they receive from the market per unit of production. The total economic benefit arising from the technology or policy change is usually partitioned between benefits to consumers and benefits to producers. The distribution of the benefits depends on the elasticities of the supply and demand curves and on the size and nature of the supply shift.Many extensions can be incorporated within the economic surplus framework, such as multiple markets for a single commodity, multiple commodities, and shifts in the demand curve because of quality changes (Alston et al., 1995). While economic surplus methods are relatively straightforward from a conceptual point of view, a problem with the approach from a practical standpoint is that the effort needed to collect, process and analyse the technical and economic data required is not trivial.

4.1.5. *Econometric methods*

Econometric methods involve the use of mathematics and statistics to represent an economic system, such as a farming household. Both single-equation and simultaneous system models that represent input demand and output supply behaviour have been developed in the literature, along with both static and dynamic models. Early studies looked at single crop production functions estimated directly from data on the physical quantities of inputs and outputs observed from experimental plots.As econometric methods developed, multi-crop production studies were undertaken, drawing on data from more comprehensive farm production surveys. Most studies specify a quadratic or Cobb Douglas form for the production functions, which place restrictive assumptions on the production technology. Later work has emphasized various more flexible technology representations (Carter, 1984). Econometric models have also been limited in their ability to extrapolate results on biophysical processes and economic conditions outside the sample of observable behaviour. Antle and Capalbo (2001) highlighted these limitations whilst developing economic simulation models that combine econometric and other disciplinary simulation models. This framework allows outputs such as crop yields from process-based crop growth models to be used to both estimate and subsequently simulate econometric production models using site-specific data.Such an approach was used by Claessens et al. (2012) to evaluate and prioritise different alternatives of sweet-potato utilisation in farming systems in western Kenya, for example.

4.1.6. *Participatory and ranking methods*

Participatory methods have also been applied to CSA prioritisation (e.g. Mwongera et al., 2017; Sain et al., 2017). Many different implementations exist, but they all have a common thread: they enable people to play an active role and to influence the results obtained, or the decisions made, thus factoring their opinions, views and visions into the research outputs (Guijt, 1998). Participatory assessments are flexible with respect to how many and which variables are included, as well as with respect to the number of stakeholders involved. For instance, Mwongera et al. (2017) gathered both qualitative and quantitative data from farmers, local leaders, researchers, local-level agricultural experts, private sector actors, donor organizations, and policy implementers, to assess vulnerability, prioritise CSA interventions, and assess constraints to such interventions.In their study of two farming systems in Uganda and Tanzania, Mwongera et al. (2017) triangulated data from multiple sources to validate research findings for discussion in the case-study communities.While flexibility and ease of implementation are major advantages of participatory methods, their major caveat is the difficulty to compare assessments that have been conducted across different groups of experts, in different contexts, or at different times. Care is also needed in such approaches to address adequately issues that may arise in relation to representativeness and power dynamics (Barnaud and Van Paassen, 2013).

4.1.7. Meta-analysis and systematic reviews

Meta-analysis, or 'the analysis of analyses', focuses on gathering and reconciling existing evidence for the problem of interest, particularly when the problem is complex or the research environment is difficult to control (Wolf, 1984; Brockwell and Gordon, 2001). The complexity embedded in the concept of CSA and the rapid expansion of literature on climate change impacts, adaptation and mitigation, make meta-analysis a useful alternative to more classical approaches to assessments of agricultural technologies (e.g. Kristjanson et al., 1999; Shiferaw et al., 2008). In a meta-analysis, a systematic review of published studies is conducted, followed by a data gathering process from the identified studies (i.e., the meta-data, or primary analysis results); finally, statistical methods (e.g., mixed-effects models, Monte-Carlo simulation) are applied to draw general conclusions based on the meta-data. Data gathering can target any variable of interest, focus on peer-reviewed and/or grey literature sources, can be done for a long period of time or large geographic area, and can focus on model- or observation-based studies. If a sufficiently large number of studies is available, the analysis can be done by 'strata' (e.g., country, agro-ecological zones, farming systems). For instance, Challinor et al. (2014) compiled > 1700 published maize, wheat and rice crop simulations across the globe to draw generalized conclusions on the impacts of climate change on these crops in tropical and temperate regions. To the best of our knowledge only one application exists for CSA research that uses meta-analysis to estimate the impact of different CSA technologies and prioritise among them. Lamanna et al. (2016) reviewed and systematized 6342 observations from 175 studies on CSA practices in Uganda and Tanzania for maize and bananas. The analysis included the three CSA pillars (productivity, adaptation and mitigation) and concluded that CSA is possible in these two countries, though reported adoption rates strongly condition the potential impact of practices at scale. Other examples of meta-analysis have focussed on single technologies such as conservation agriculture (Corbeels et al., 2014; Rusinamhodzi et al., 2011).

4.1.8. Methods using spatial analysis and remote sensing

The rapid development of GIS, remote sensing and spatial analysis over the last decades has resulted in a range of good quality global and regional datasets that are now readily available from various sources (e.g., Monfreda et al., 2008; Herrero et al., 2013). This is especially true for bio-physical data, while slower progress is made with the availability of socio-economic data (Notenbaert et al., 2017). GIS technology and these datasets have facilitated the construction of recommendation domains (RDs) which correspond to the delineation of geographical locations with a specific combination of bio-physical and socio-economic factors which can form the basis for priority setting and outscaling of research findings, and hence facilitate the targeting of agricultural research and development efforts (Notenbaert et al., 2013). Generally, there are two different approaches for combining geographical data layers into RDs: similarity analysis and threshold-based approaches. Similarity analysis makes use of spatially explicit observations (e.g. research results, known successes), overlays those with the available geographical data layers, and identifies locations where similar combinations of these geographical attributes are present (Notenbaert et al., 2017). Threshold-based approaches generally define ranges for the attributes in the different geographic data layers based on likely adoptability of a specific intervention (Brandt et al., 2017). Spatially delineated RDs still need to be complemented with household-level information to match interventions to specific types of producers, as significant heterogeneity exists in farming styles and objectives, resource endowments and farm types within a certain region (Giller et al., 2011).

4.1.9. Integrated assessment models

A wide range of integrated assessment models have been used for prioritisation.One example is the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model, a global, partial equilibrium, multi-market, agriculture sector model, with links to crop models and hydrology and water-use models.Agricultural land use and land use change are modelled based on historical trends and expert opinion on responses to agricultural prices. Demand for food is simulated based on changes in income, population, and prices.IMPACT is solved by finding equilibrium prices that clear world markets, equating supply (cropped areas and yields for crops and numbers and slaughtered carcass weight for livestock) and demand in domestic and world markets for all commodities. Beyond equilibrium measures of food availability, water use, and land use change, IMPACT also estimates welfare measures such as supply of nutrients, population at risk of hunger and numbers of undernourished children in developing countries (Robinson et al., 2015).Other examples include the study of Havlík et al. (2011) looking at the global land-use implications of first-and second-generation biofuel targets, and the Australian National Outlook integrated assessment study of Hatfield-Dodds et al. (2015). Such studies often make use of the Shared Socio-economic Pathways (SSPs), a coherent set of descriptions of plausible alternative evolutions of society at the global level (O'Neill et al., 2017). Nelson et al. (2014) compared nine of the major integrated assessment models and highlighted the need for better understanding of the differences in key outputs from these models given ostensibly the same or very similar input data.Although Ackerman et al. (2009) caution against the use of integrated assessment models for informing policy decisions, largely on the basis that their empirical and philosophical assumptions may be untenable, there is a large literature on the application of such models to the decision-making space, including analysis of a broad range of research alternatives (see Table 1 for some examples). These methods are complex and may be time-consuming to carry out.

4.1.10. Choice of approach

There are some examples of priority setting exercises that rely wholly on one approach; Thornton et al. (2008) used a participatory approach to prioritise research topics around livestock and climate change, for instance. Even in that case, however, quantitative information from a wide variety of sources, including data previously derived from spatial analysis and simulation methods, was used as input to the process. In most situations, the various elements of the framework will involve different tools and methods. Table 2 maps our assessment of the general suitability of the tools and methods of Table 1 against the elements of the framework shown in Fig. 1. Table 2 shows that different tools may be appropriate for different purposes, choice of method depending not only on suitability but also on the time, resources and skills available for any specific priority-setting study.

Table 2
Suitability of tools and methods in relation to the different elements of the framework (authors' evaluation).

Framework element	Tools, methods								
	Simulation modelling	Mathematical programming	Cost-benefit analysis	Economic surplus	Econometric methods	Participatory & ranking methods	Meta-analyses & systematic reviews	Spatial methods	Integrated assessment modelling
1 Identify system entry points and impact pathways	**	**	**	*	*	***	***	**	*
2 Define the spatial and temporal scale of the research	*	*	*	*	*	***	***	***	**
3 Which research questions, how will they be addressed	**	*	**	*	*	***	***	*	*
4 Estimate production, adaptation, mitigation research impacts	***	***	**	*	**	**	**	*	***
5 Estimate other environmental and social impacts	**	**	**	**	**	***	**	**	**
6 What will be needed to go from research output to impact	***	***	**	**	**	***	***	**	*

Suitability: *** highly suitable; ** suitable; * marginally or not suitable, or highly context-specific.

4.2. *Using the framework*

Application of the framework outlined in section 3 above can assist in setting priorities by ranking a range of alternatives based on their potential impact as well as their effects on the pillars of CSA.It can help the user think about the context-specific impacts of different interventions, in relation to each intervention's current stage of development or implementation and a range of metrics that evaluate the potential contribution of the intervention to the CSA pillars and other metrics related to environmental and social impacts beyond the farm gate. It attempts to build in elements of monitoring, evaluation and learning through the use of theory of change to postulate a specific impact pathway for each intervention at the start of the research. During the process, lessons can then be learned about both success and failure, and adjustments made if appropriate. The framework encourages the user to consider what the explicit enablers of uptake may be, in relation to the returns on investment and the sequence of interventions and scaling pathways that may be needed. Because research activities are described in relation to temporal and spatial scales, it should be able to contribute to program design and evaluation where sequences of activities are required (i.e., specific activities may be dependent on the success of other activities before they can be developed or deployed at scale).

Prior to the workshop in 2017 at which the framework was developed, participants were asked to contribute short case studies of their own prioritisation activities. Six studies were contributed, and these are summarised in Table 3 in relation to what was being prioritised, the spatial and temporal scales of the work and its location, the methods used in the analysis (using the same classification as in Table 1), and current information gaps. More details can be found in the references shown in Table 3. The various priority-setting activities cover several types of study: identifying and prioritising the suitability of different locations and situations in which a well-developed intervention (supplemental irrigation) may be feasible; identifying specific crop traits and where they may be utilised most effectively (maize and sweet potato); identifying which combinations of different interventions are climate smart in which situations; and identifying which future agricultural system transitions may affect the three CSA pillars in specific ways and in specific locations. Below, the application of the six stages of the framework is briefly discussed in relation to these studies.

4.2.1. *Identify system entry points and impact pathways*

The system entry points for the six studies were quite different. The farm-level costs and benefits of supplemental irrigation, for instance (study 1), are well understood, but there are many challenges to adoption at scale related to the enabling environment (Nangia and Oweis, 2016). The prioritisation activity is thus concerned with identifying locations where supplemental irrigation will fit into the local agricultural, economic and socio-cultural system. In the case of drought-tolerant sweet potato (case 3), appropriate varieties for East and southern Africa do not yet exist, so the priority setting here is needed to help identify the specific traits that will lead to varieties that can be adopted in particular environments. For case 5, system entry points were identified through spatial and climate analysis that showed strong differentiation of climate vulnerability within the cocoa belt of West Africa, pointing to the need for spatially differentiated adaptation alternatives (Schroth et al., 2016).

4.2.2. *Define the spatial and temporal scales of the research*

Several of the studies address the farm or district scale, in which there may be several hundreds or thousands of households and communities in locations that share specific characteristics related to climate variability (study 4) or vulnerability (study 5), for example. The study on agricultural transitions (study 6) is global in scope and forward-looking (and model-based) over several decades into the future. Most of the other case studies have a medium-term outlook (3–10 years, Table 3), with study 1 (supplemental irrigation) a much shorter time

Table 3

Features of case studies on priority setting contributed by the authors at a workshop held in 2017.

Case study	What is being prioritised	Location of research	Spatial scale	Temporal scale	Approaches used	Examples of information gaps
1Supplemental irrigation: addition of small amounts of water to rainfed crops to improve and/or stabilize yields (Oweis and Hachum, 2012; Nangia and Oweis, 2016).	Where and under which conditions is it appropriate	Drylands of Middle East-North Africa	Plot, farm	Short	● Cost-benefit analysis ● Simulation modelling	● Mitigation co-benefits
2Climate-smart maize breeding: development of new or replacement varieties adapted to future climates (Atlin et al., 2017).	Which traits, where and when	East & Southern Africa	Farm, community	Medium	● Spatial analysis ● Cost-benefit analysis	● Nature of private- & public-sector incentives ● Mitigation co-benefits
3Drought-tolerant sweet potato: development of new varieties that are high-yielding under current drought conditions (Andrade et al., 2017).	Which traits and where	East, Central & West Africa	Farm, community	Medium	● Spatial analysis ● Simulation modelling ● Participatory methods	● Social impacts of adoption
4Bundles of Climate-Smart Agriculture options: scaling up CSA options to manage risks in different climatic environments (Kumar et al., 2018)	Which interventions, under which conditions of climate variability	Telangana State, India	District	Medium	● Spatial (climate) analysis ● Cost-benefit analysis ● Participatory methods	● Nature of private- & public-sector incentives ● Mitigation co-benefits
5CSA packages for cocoa production: Farmer innovation for adapting to new climate risks in cocoa production (Schroth et al., 2016).	Which interventions, under which conditions	Southern Ghana	Community, district	Medium	● Spatial analysis ● Participatory methods ● Cost-benefit analysis	● Limited information on mitigation co-benefits
6Agricultural system transitions: Shifts in the location of, or production from, livestock farming systems (Havlík et al., 2014; Weindl et al., 2015).	Which system transitions and where	Global	Global	Long	● Integrated assessment modelling	● Nature & amount of public & private investment needed

Temporal scale: short, 1–3 years; Medium, 3–10 years; Long, > 10 years.

horizon, within a specific growing season. The appropriate scales for the research will depend in part on the stage of development of the intervention, such as foresight, development, piloting and scaling up.

4.2.3. *Which research questions, and how will they be addressed*

The studies encompass different types of research and research questions. These include prioritising locations of technology applicability (study 1); technology design (studies 2 and 3), technology identification and testing (studies 3, 4 and 5); and foresight work (study 6). The research outputs of study 6 are as yet quite far removed from any policy-making arena, but in time the results could contribute to actionable interventions. The other studies revolve around more immediately actionable research outputs, such as lists of places to implement specific technologies, new varieties with specific traits for different locations, and bundles of interventions suited to different circumstances, for example.

4.2.4. *Estimate production, adaptation, mitigation research impacts*

The studies demonstrate some of the ways in which production, adaptation and mitigation impacts may be estimated. Most studies involved cost-benefit analyses, in some cases along with simulation modelling to take into account production and economic risk. For most of the studies, there are as yet few or no estimates of the mitigation impacts, although these could be developed. The exception is study 6, one of whose focuses is the mitigation impact of broad-scale livestock system transitions. Assessing the relationship between production, adaptation and mitigation impacts is an important element of CSA prioritisation. Many CSA interventions show synergies between them in different circumstances, but there are others that exhibit trade-offs (Rosenstock et al., 2016; Thornton et al., 2018b). At the same time, different stakeholders may view (and weight) the relative importance of the three pillars quite differently; smallholder farmers in lower-income countries may see mitigation as a lower priority compared with achieving productivity and adaptive capacity gains, for example.

4.2.5. *Estimate other environmental and social impacts*

In general, the case studies here do not address to any great extent other environmental and social impacts of the interventions outlined. Several of the studies identified information gaps as to the possible effects of adoption at scale on different groups of target beneficiaries and power relations at the community level, for example. Study 6 on agricultural system transformations utilised models that are able to estimate commodity price effects and impacts on poverty, for example, although these results are not reported in Havlík et al. (2014) or Weindl et al. (2015).

4.2.6. *What will be needed to go from research output to impact*

The studies address a variety of enablers and activities that would be needed in moving from research outputs to impact on the ground. For the breeding studies (numbers 2 and 3), for example, these include the need for capacity development of different actors in national extension systems and the provision of appropriate incentives to involve the private sector in strengthening national seed systems. For study 5, the enablers include capacity development and policies to encourage existing cocoa farmers to intensify production where this is feasible. The factors that can facilitate uptake of CSA interventions will generally depend upon the nature of the intervention and the impact pathway envisaged. Identifying these facilitating factors, as well as the relative weights to apply to the three pillars of CSA in relation to evaluating possible trade-offs between them, may often depend on stakeholder engagement and participatory methods.

The six studies and several other examples of interventions from the literature are summarised in Table 4, with respect to the type of intervention and the basic system entry point, the spatial and temporal scale of the activity, the feasibility of the research, estimated impacts on various metrics, and probability of success and the associated enablers

Table 4

Different types of intervention and relation to the prioritisation framework in Fig. 1. Estimates taken from the references cited or authors' assessment. Examples in light blue shading are from Table 3 and are referred to in Section 5.2.; Carter et al., 2014, Chowdary and Theodore, 2016, Grajales et al., 2015, Kaczan et al., 2013, Kumar et al., 2011, Kumar et al., 2016a, Kumar et al., 2016b, Makate et al., 2016, Meinzen-Dick et al., 2017, Ojango et al., 2015, Ombogoh et al., 2018, Pathak et al., 2009, Rao et al., 2016, Saxena, 2018, Seo, 2010, Singh et al., 2007, Swain, 2014, Tabo et al., 2011, Thierfelder et al., 2017, Venkateswarlu et al., 2012, Wajih, 2008

Type of CSA intervention 1 Entry point	2 Spatial & temporal scale		3 Research feasibility	4 CSA metrics			5 Other metrics		6 Outputs to impact	
	Space	Time		Productivity (P)	Adaptation (A)	Mitigation (M)	Environ-mental (E)	Social (S)	Likely impact	Enablers
Climate smart technologies										
Farm ponds: Constructed on-farm rainwater harvesting structures (RWHS) to capture runoff for reuse for irrigation, stock water, etc. (Kumar et al., 2016a).	Plot, farm	Short	M	+	+	+/-	+	+/-	M	Capacity to determine appropriate size and location of the structures, efficient water use methods for high value crops, RWHS implemented as context specific integrated packages
Supplemental irrigation: addition of small amounts of water to rainfed crops to improve and/or stabilize yields (Oweis and Hachum, 2012).	Plot, farm	Short	H	+	+	u	+	+/-	M	Sustainable source of water, energy access (for a pressurized irrigation system), suitable crop/cultivar
Conservation agriculture: retention of crop residues, minimum tillage and rotations including legumes (Kumar et al., 2011; Thierfelder et al., 2017).	Farm, community	Long	L	+/-	+/-	+	+	+/-	H	Local capacity building, cost effective access to appropriate machines and implements
Crop diversification: Using multiple crop types and varieties to increase dietary diversity and resilience (Makate et al., 2016).	Farm, community	Long	L	+/-	+	+/-	+	-	M	Access to inputs (e.g. seed) and market for diversified outputs
Agroforestry: Combination of perennial tree species with cropping (Kaczan et al., 2013).	Farm, community	Long	L	+/-	+	+	+	+/-	M	Assured markets via long-term contracts with industry (for commercial perennial tree crops)
Climate-smart breeding: development of new or replacement varieties adapted to future climates (Atlin et al., 2017).	Farm, community	Medium	H	+	+	+/-	+	+/-	H	Effective seed and extension systems
Crop/animal improvement: Breeding for new and improved crops/animals (Beebe et al., 2013; Ojango et al., 2015).	National	Long	H	+	+	+/-	+/-	+/-	H	Effective research and extension systems, private sector involvement
Drought-tolerant crops: development of new crop varieties that are high-yielding under current drought conditions (Andrade et al., 2017).	Farm, community	Medium	H	+	+	+/-	+	+/-	H	Effective systems capable of providing adequate planting material, and effective extension and education systems
Micro-dosing: Application of small amounts of inorganic fertilizer with / without organic inputs like farm yard manure or compost (Tabo et al., 2011).	Farm	Short	H	+	+	+/-	+	+/-	H	Effective farmer education and extensions systems, effective private sector linkages
In-situ moisture conservation: broad-bed & furrow systems, contour bunds, drainage and intercropping systems (Pathak et al., 2009).	Farm, community	Short	H	+	+	+/-	+	+/-	H	Farm mechanization options available, farm credit
Integrated farming systems: farming systems with integrated enterprises including livestock, perennials (Seo, 2010; Kumar et al., 2016b).	Farm, community	Long	M	+	+	+	+	u	H	Effecting farmer education and extension systems, farm credit
Bundles of CSA options: managing climate risk in highly variable environments (Kumar et al., 2018)	District	Medium	M	+	+	+/-	+/-	+/-	H	Integration of many different stakeholders' perspectives
Climate information services										
Agro-meteorological information: short-term to seasonal climate forecasts released through radio, climate information centers, contingency plans (Singh et al., 2007).	Community, district	Short	M	+	+	+/-	+/-	+/-	H	Effective farmer and extension education systems, weather information well matched to farmers' needs
Crop insurance: covering yield loss due to weather related calamity (Carter et al., 2014).	Region, state	Medium	H	+/-	+	u	+/-	+/-	M	Reliable and quick estimation of crop losses
CSA packages for cocoa production: Farmer innovation for adapting to new climate risks in cocoa production (Schroth et al., 2016).	Community, district	Medium	H	+	+	+/-	+/-	+/-	M	Options matched to the production risk by ecological zone, appropriate training materials, broad stakeholder engagement
Local level development plans										
Village water budgeting plans: collective action to help govern the use of scarce ground water resources (Meinzen-Dick et al., 2017).	Farm, community	Short	L	+	+	u	+	+	H	Community participation, collaboration based on capacity and trust
Crop planning and monitoring; collective action to manage community resources (Grajales et al., 2015; Ombogoh et al., 2018).	Sub-district, district	Short	M	+	+	u	+/-	+	H	Communal capacity development, access to financial resources and resource maps, mechanisms to spread risk
Local knowledge and institutions										
Village seed banks: establishment and maintenance of village seed banks to deal with seasonal and extreme events (Wajih, 2008).	Village	Medium	L	+/-	+	u	+/-	+/-	L	Effective farmer and extension agent education activities

(*continued on next page*)

Table 4 (*continued*)

Type of CSA intervention 1 Entry point	2 Spatial & temporal scale		3 Research feasibility	4 CSA metrics			5 Other metrics		6 Outputs to impact	
	Space	Time		Productivity (P)	Adaptation (A)	Mitigation (M)	Environ-mental (E)	Social (S)	Likely impact	Enablers
Custom Hiring Centre–mechanization: Equipment available for hire to mechanize farm operations (Venkateswarlu et al., 2012)	Village	Short		+	+	u	+/-	+	M	Multiple models: community based, collective business and individual entrepreneurship needed
Farmer producer organizations / village climate risk management committees: Collective action to create and manage climate adaptation and commercialization opportunities (Venkateswarlu et al., 2012)	Community	Medium	M	+	+/-	u	+	+	M	Hand holding and credit support in the initial phases
State / national policy interventions										
Soil Health Cards: provision of soil testing to all farmers for use in fertilizer recommendations (Chowdary and Theodore, 2016).	National	Short	H	+/-	+/-	+	+	+/-	L	Effective extension systems, use of digital tools such as mobile apps to enhance sustainability of use
National Crop Insurance Schemes: covering yield loss due to weather related calamity (Swain, 2014).	Region, state	Medium	H	+/-	+	u	+/-	+	M	Reliable and quick estimation of crop losses and aligning policies to promote climate smart practices
Demand creation & value addition: Enhancing value of climate resilient grains and legumes using novel products (Rao et al., 2016; Saxena, 2018).	Region, state	Medium	H	+/-	+	u	+	+	M	Policy to promote their integration into public distribution system, public awareness building and education
Agricultural system transitions: Shifts in the location of or production from farming systems (Havlik et al., 2014; Weindl et al., 2015).	Global	Long	M	+	+	+/-	+/-	+/-	L	Region-specific understanding of impacts, costs and benefits of transitions for different stakeholders
National adaptation and mitigation planning**:** development and implementation of NDCs, NAPs and NAMAs (Richards et al., 2015).	National	Long	M	+	+	+	+	+/-	M	Finance, policy alignment and convergence

Time: short, 1–3 years; Medium, 3–10 years; Long, > 10 years.
Research feasibility: technical feasibility, cost of technology, inclusivity (smallholder, gender) and synergy with local or national plans and development programs.
Likely impact: the likely impact of the intervention in adapting to climate variability and change, both short-term events (such as individual drought) as well as long-term (a changed climate). L = Low, M = Medium, H = High.
+ positive impact, − negative impact, −/+ context-specific impact; u largely unknown impact.

that are envisaged to contribute to this success. The impacts in Table 4 are presented as summary indicators only; a specific priority setting exercise would involve more disaggregated information than is shown.

The different types of intervention shown in Table 4 are not comprehensive. Nevertheless, many of the activities shown tend to be clustered in time and space, particularly in the short- to medium-term and at relatively local scales (plot, farm and village).Many of the interventions have actions that are designed to address immediate needs, and few are implicitly coupled with larger-scale, longer-term strategies. Table 4, along with the six case studies in Table 3, also highlight the numerous gaps in information concerning particularly the mitigation and social impacts of different interventions. The framework proposed above should help the analyst to think about a more complete approach to addressing the challenges surrounding both local, short-term implementation of research outputs as well as longer-term research processes. Both situations will greatly benefit from the development of well-thought-out impact pathways and assumptions that can be monitored in scaling out high-potential climate-smart interventions in space and time.

The metrics shown in Table 4 can be estimated based on the time, tools, skills and data available.As shown in Table 1, the various methods each have advantages and disadvantages, particularly relating to time, complexity and data needs. Most evaluations will make use of mixed methods or combinations of different tools, and likewise data may be both quantitative where they exist and qualitative where they do not.The framework described is amenable to being implemented as an on-line tool, with links to several databases and to the CSA compendium (Rosenstock et al., 2016) and CSA country profiles (https://ccafs.cgiar.org/publications/csa-country-profiles), for example.

4.3. Challenges in using the framework

In common with priority setting in general, several challenges remain in implementing all the elements of the framework described above. One challenge lies in evaluating the appropriateness of different CSA practices and technologies in different situations, given the importance of local context. It may not be straightforward to decide on the minimum scale of analysis that will allow reasonable estimates of adoption to be derived. For example, relatively simple spatial analysis based on broad agro-ecological and market-related factors may be adequate for estimating potential adoption rates of new crop varieties. Estimating adoption rates of interventions that heavily modify the enterprises in a farming system, such as the addition of new crops or new livestock species, on the other hand, may require much more detail if meaningful estimates of adoption potential (and thus potential impact) are to be derived. All cases of CSA prioritisation should have some estimate of impacts on the three pillars, to allow synergies and trade-offs between them to be evaluated.

A second challenge concerns the level of accuracy in the tools and analyses used that is needed to trigger investment and other decisions at various scales (i.e., how much information, and of what quality, is "adequate"). Watkiss (2015) identified several recent shifts in adaptation planning and other decision-making spheres, including greater emphasis on capacity building, "low-regret" options (alternatives that can be implemented with some confidence regardless of the uncertainty concerning future conditions), and addressing market, governance and policy failures. These more "problem-orientated" approaches can help to address this challenge to some extent, given that investment and policy decisions will be made anyway, with or without relevant and available evidence. On the other hand, there are inherent risks in priority setting activity, including possible deficiencies and incompatibilities in the methodological tool-kit used, which could lead to maladaptation (Lonsdale et al., 2015).Where possible, identifying climate-resilient development around no- or low-regret alternatives may be able to address this issue, at least partially (Ignaciuk, 2015). The costs of even mild maladaptation may be dwarfed by the costs of not doing any adaptation (including not attempting any systematic prioritisation effort) at all.

A third challenge, which also besets all priority setting work, is that of data. The situation, however, is much improved compared with even

10 years ago: there are many large, publicly-available data sets that are available for a wide variety of variables of direct relevance to CSA. Many of these make use of innovative approaches based on remote sensing, citizen science and crowdsourcing, and big data mining approaches. Even so, there are still some fundamental gaps, particularly around smallholder agriculture that make the evaluation of trade-offs a persistent challenge. This is particularly the case with CSA; several of the studies in Table 3 show that CSA is sometimes about bundles of interventions rather than just one technology, and this adds to the trade-off and data challenges.

5. Conclusions

In this paper we have presented a framework for priority setting of CSA research interventions in space and time. We have reviewed the major tools and methods that are available for priority setting, all of which may be relevant in different situations when using the framework. The studies presented have highlighted some of the challenges surrounding CSA priority setting. We highlight several conclusions from this work.

First, the importance of evaluation and analysis at multiple scales is critical: viable CSA interventions need to provide benefits at different spatial and temporal scales, for producers as well as consumers, at time horizons that fit in with producers' and consumers' needs. Priority setting that explicitly addresses both longer-term uncertainty as well as shorter-term climatic variability is still comparatively rare, as is multi-scale analysis that can address the potential impacts on different stakeholder groups. For priority setting to be most effective, information is needed that addresses the costs and benefits of actions at the different spatial and temporal scales that are relevant to all decision makers. While in some cases there may be synergies between both scales and CSA pillars, in others there will be trade-offs, and these need to be appropriately quantified.

Second, priority setting of CSA research might best be seen as an iterative process rather than a one-off activity. Evaluation in any situation will be undertaken with respect to the time, skills and financial resources available. But for CSA evaluation, learning cycles may be particularly important, for helping to ensure that options are not dismissed too early in the prioritisation process, and for avoiding lock-in to a limited set of strategies or technologies that may turn out to be sub-optimal or maladaptive over longer time scales. This is particularly relevant during implementation cycles, when the assumptions underlying a project's theory of change can be tested and either validated or discarded. This is not to promote endless cycles of priority setting utilising increasingly nuanced or sophisticated data and tools, but more to highlight the importance of monitoring progress against envisaged outputs and outcomes so that mid-course corrections can be made when needed.

Third, no one method is likely to be adequate in most situations; a mixture of methods, integrated in different ways, will usually be needed to deal with the special nature of CSA, where it is often packages of interventions that are being evaluated. This relates not only to technology options but increasingly to the whole innovation process and what the factors may be that can enable it. The current toolkit appears to be weak in relation to the evaluation of social and institutional metrics, and improved methods for evaluating these are needed that can also be integrated appropriately with other economic and biophysical metrics.

Agricultural research for development needs to step up to help meet the Sustainable Development Goals associated with food production, human nutrition, climate change and environmental protection in a world with 9.7 billion people by 2050.A key part of addressing this challenge will revolve around effective priority setting that can provide information to help guide best-bet technology, policy and investment action that leads to desired, long-term development outcomes while meeting local, immediate needs for food security.A mix of strategies and activities across space and time scales can help address these immediate needs as well as build enabling conditions that can help farmers, policy makers and other stakeholders respond to new challenges.

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