Regional Environmental Change (2020) 20: 18
https://doi.org/10.1007/s10113-020-01585-x

ORIGINAL ARTICLE

Analysing trade-offs in adaptation decision-making—agricultural management under climate change in Finland and Sweden

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Received: 6 May 2019 / Accepted: 16 January 2020 / Published online: 8 February 2020

Abstract

In light of the increased focus on climate change adaptation, there is a need to understand when and how adaptation decision-making generates trade-offs. This study presents a novel framework for adaptation trade-off assessments, which integrates (I) two trade-off mechanisms (direct and interactions) and (II) two types of trade-off characteristics (substantive and processual). Perspectives on adaptation trade-offs were collected from 37 Swedish and Finnish agricultural experts through semi-structured interviews supported by serious gaming and visualization. The data were thematically analysed based on the provided analytical framework. The results show that trade-offs in agricultural adaptation decision-making processes involve balancing a number of socio-ecological system aspects that are of different character and have different functions. The study identified 20 aspects generating trade-offs related to adaptation management in Swedish and Finnish agriculture, among which 'crop yield and profitability', 'farm economy', 'pest and weed robustness' and 'soil quality' were discussed as the most prominent by respondents. The framework enables an examination of complex trade-off structures that can have implications for adaptation management decisions. The results show that the identified aspects constitute different components and functions of trade-offs, including both processual and/or substantive ones. In conclusion, the 20 identified aspects and the framework together demonstrate the importance of the two types of adaptation trade-offs and the resulting complexity of climate change adaptation decision-making in Swedish and Finnish agriculture. Furthermore, the study asserts the potential of applying the framework for various strategic contexts—to recognize and cope with trade-offs in adaptation management.

Keywords Climate change adaptation · Agriculture · Finland · Framework · Sweden · Trade-offs

Communicated by Chandni Singh

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10113-020-01585-x) contains supplementary material, which is available to authorized users.

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Introduction

Climate change is projected to pose significant challenges to agricultural production on a global scale (IPCC 2014) and in Europe (Aaheim et al. 2012), which will require aligned adaptation management and pathways to sustainable development. While more adaptation is likely to be necessary in areas where impacts are high, changes in management strategies need to be made everywhere (Challinor et al. 2014). Adaptation in the agricultural sector is already taking place, with studies showing that adaptation measures have been identified and implemented in numerous regions (Anwar et al. 2013; Bizikova et al. 2014). Socio-economic factors such as investments in rural infrastructure, technical efficiency, equality, knowledge and social capital are factors that influence the capacity to adapt and have potential to improve adaptation practices—to make farmers, or the agricultural sector as a whole, less vulnerable to climate change (Below et al. 2012). However, there is an increasing recognition that adaptation management strategies in agriculture encompass a multitude of complex decisions of how to address pressures from e.g. policy and economic liberalization (Claessens et al. 2012; Feola et al. 2015), as well as the changing climatic and weather conditions. Thus, adaptation decisions often imply a situation in which a decision has to be made between addressing multiple pressures and objectives (Smit and Skinner 2002), implying that there are trade-offs between individual adaptation practices or with other social, economic or environmental strategies or goals (Denton et al. 2014; Wiréhn 2018). Trade-offs can be defined as balancing of factors that cannot be attained at the same time or in combination, involving, for example, pathways to achieve various social, economic and environmental goals of sustainable development (Denton et al. 2014).

The Intergovernmental Panel on Climate Change (IPCC) has declared that transformations towards sustainable development in a 1.5 °C warmer world involves fundamental societal and systemic changes, but in parallel acknowledges the complex trade-offs that are expected along the range of the different pathways. IPCC stresses not only that synergies and trade-offs between and across adaptation and mitigation measures as well as with sustainable development have to be carefully considered when planning climate actions but also that there is limited research that has systematically evaluated such synergies and trade-offs for specific contexts (Roy et al. 2018). This concerns a general knowledge gap (Roy et al. 2018) as well as a knowledge gap for the land-use sectors specifically, where the sectors' objectives to produce food, fibre, timber and fuel have to be aligned with the potential pathways for sustainable development (de Coninck et al. 2018, pp. 386–387).

Research on this topic has so far tended to focus on mitigation-related synergies and trade-offs with adaptation, or mitigation trade-offs with sustainable development pathways, whereas there is limited literature explicitly on adaptation-related synergies and trade-offs (c.f. Denton et al. 2014; Smith et al. 2014; Landauer et al. 2015). While addressing that mitigation-related trade-offs is an essential challenge that has to be considered in climate actions, recent studies imply that there is a large number of important trade-offs involved in adaptation decision-making from a broader socio-ecological perspective than in relation to mitigation solely (Chelleri et al. 2016; Neset et al. 2018; Roy et al. 2018 p. 457; Wiréhn 2018).

In agricultural management, such trade-offs could for example concern the choice to plant and harvest potatoes one month earlier in Finland due to the warmer conditions, however, that increases the risk of frost damage and may result in harvest loss or the decision to invest in frost protection (Pulatov et al. 2015). Another example is the rising need for new or improved drainage systems as a response to the increased precipitation in Finland and Sweden. Depending on context, implementation of these improvements can involve economic, environmental and social trade-offs in terms of investment costs, impact on nearby wetlands and shifting flooded areas to neighbour's fields, respectively (Neset et al. 2018).

There is a recognized need to seize adaptation synergies and minimize trade-offs in the implementation of sustainability policies and measures in order to create climate resilient pathways (Aggarwal et al. 2018; Roy et al. 2018). Adaptation measures that potentially involve maladaptation (Juhola et al. 2016; Magnan et al. 2016) inherently also involve a trade-off between the intended positive effect of the adaptation measure and the unintended negative outcome. The focus of the present study is to analyse adaptation induced trade-offs, like the previously mentioned examples, in *Swedish and Finnish agricultural production*. Emphasis is put on potential trade-offs that arise from taking adaptation decisions. Since only few studies concern adaptation trade-offs explicitly, there is little available theory and, to our knowledge, no specific framework that conceptualizes or supports the analysis of adaptation induced trade-offs. This study therefore adopts theoretical entry points from related research to cover various analytical perspectives on adaptation induced trade-offs. Specifically theories on relationships between ecosystem services (Bennett et al. 2009) and conceptualizations of trade-offs in sustainability assessments (Morrison-Saunders and Pope 2013) were used to design a new framework to apply in this analysis.

Hence, this study advances adaptation research by addressing the need for a systematic analysis of trade-offs in agricultural crop production from an adaptation perspective as well as the theoretical development through introducing a novel analytical framework to analyse and understand adaptation-induced trade-offs generally. The designed framework outlines adaptation induced trade-offs by combining an assessment of adaptation measures' potential effects on different aspects of the socio-ecological agricultural systems across spatial and temporal scales, with an assessment of the aspects' characteristics. The specific aim of the study is to present and test the framework and by means of it, identify and assess adaptation induced trade-offs in Swedish and Finnish agricultural management.

While climate impact and adaptation studies indicate that agriculture in northern European regions needs to adapt to changing climatic conditions (Olesen et al. 2011; Eckersten et al. 2012; Iglesias et al. 2012), only a few studies specifically address the adaptation needs, capacities, barriers or consequences specific to Nordic agriculture (e.g. Lehtonen 2015; Himanen et al. 2016). Agricultural studies in relation to climate change in Finland and Sweden have rarely had adaptation as a central focus (Wiréhn 2018) even though adaptation can be considered a necessity in future Nordic agriculture. In particular, adaptation is needed in terms of reducing vulnerability to more extreme weather and warmer and wetter winters in the Nordic countries, as well as to enable gains from the climatic opportunities of higher temperatures and an extended growing season (e.g. Bindi and Olesen 2011; Peltonen-Sainio et al. 2018). For a comprehensive overview of climate change related challenges, opportunities and associated adaptation requirements in the Nordic region, see Wiréhn (2018).

The designed framework that was applied in this study to examine trade-off structures can also have implications for adaptation decision-making more broadly. Agricultural experts' views on adaptation, and in particular the related trade-offs, were collected and analysed through a methodological approach that integrates visualization, serious gaming and semi-structured interviews. A serious game was played as part of the interviews in order to support the dialogues on adaptation needs and choices through both studying and communicating potential unintended negative effects of climate change adaptation in agriculture. For this study, qualitative data from 20 combined interview-gaming sessions in pairs (with three exceptions involving single players) were collected and analysed. The results show that trade-offs in agricultural adaptation decision-making processes involve the balancing of a number of socio-ecological aspects that are of different characters and have different functions. While adaptation has various potential effects on a number of aspects, the same or other aspects may also constitute preconditions, functioning as barriers or drivers for adaptation decision-making.

Method

Analytical framework

In this study, we present and apply a novel framework that identifies linkages between adaptation measures and socio-ecological aspects and further classifies the 'aspects' into different types based on the characteristics of the generated trade-off. The agricultural system and its relation to society and the biophysical environment is an example of a 'socio-ecological system'—a system with societal and ecological subsystems in mutual interaction (Gallopín 2006). The term 'aspects' is here defined as factors, elements or dimensions at any scale of the socio-ecological system that either are being effected by adaptation measures or constitute preconditions affecting the adaptation decision. This framework is tested against our empirical data and allows us to identify and structurally analyse trade-offs related to agricultural adaptation management.

We start with the notion that farmers and agricultural practitioners observe multiple options and choices that are available to them over different time periods and that they are also affected by multiple external pressures (Feola et al. 2015). Decisions related to adaptation take place in an inherently complex decision-making context that will inevitably imply certain trade-offs (Glasson et al. 2012). In order to identify how these trade-offs are perceived, it is necessary to understand how adaptation decisions interplay with different socio-ecological aspects of agricultural management.

For this, we adopt an analytical framework developed by Bennett et al. (2009) and use it to study adaptation decision-making in an agricultural context. The framework of Bennett et al. (2009) is grounded in the theory of relationships between ecosystem services and suggests that these relationships are caused by two kinds of mechanisms: (i) the effects of external drivers on ecosystem services and (ii) interactions between ecosystem services. Similarly, this study is concerned with relationships that generate trade-offs, but instead of relationships between ecosystem services the focus is on relationships between socio-ecological aspects induced by adaptation decision-making. We propose that the framework by Bennett et al. (2009) can be reconfigured to the field of climate change adaptation to conceptualize how adaptation decisions affect the farmer and farm management more broadly (Fig. 1). When applied to assess adaptation decision-making within the agricultural context, the framework allows us to structurally identify aspects and interactions that generate trade-offs. Two mechanisms are outlined to describe adaptation related trade-offs:

1. Direct effects of adaptation measures on socio-ecological aspects (*positive and/or negative*)
2. Interaction between socio-ecological aspects (*positive and/or negative effects*)

While a climate change adaptation measure has one or several purposes of being implemented, the same measure could involve additional positive and/or negative effects on the socio-ecological system. For example, adaptation to increased precipitation through implementation of a drainage system may involve direct positive effects in terms of decreasing the risk of flooding and increasing crop yield, while it might also involve investment costs, directly affecting the farm economy negatively. However, a less vulnerable production system may result in higher crop yields and positively affect the farm economy, exemplifying the second interaction mechanism. Hence, in this example, the two mechanisms generate trade-offs between crop yield and farm economy.

In addition to these two mechanisms, Morrison-Saunders and Pope (2013) distinguish between process and substantive trade-offs. We use this distinction to further analyse and characterize the potential effects of adaptation decisions on socio-ecological aspects as well as various socio-ecological aspects' effect on adaptation decisions. On the one hand, processual trade-offs reflect the realities of decision-making, where choices have to be made based on the resources available at the time (Morrison-Saunders and Pope 2013). This could concern the information base for decision-making, e.g. 'between

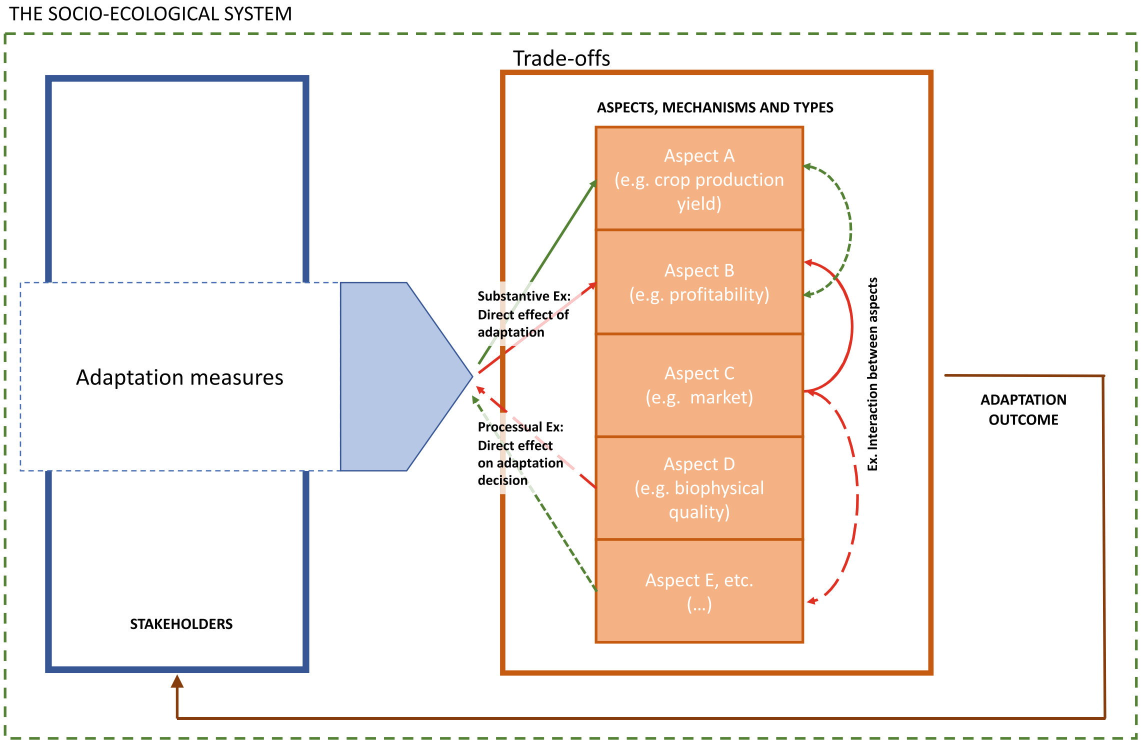

Fig. 1 Analytical framework for adaptation induced trade-offs. Dotted and solid arrows represent processual and substantive trade-off types respectively, whereas red and green colours of arrows represent negative and positive effects or interactions

simplification and the complexity of reality; between the urgency of the decision and the need for further information; between facts and values; between forecasts and evaluation; and between certainty and uncertainty' (Morrison-Saunders and Pope 2013, p. 55). More specifically, trade-offs can occur in the allocation of resources between activities, knowledge or interest in engaging in one activity over another. Substantive trade-offs, on the other hand, can be defined as involving the positive and negative outcomes when weighing different outcomes against each other. This type of trade-off can be identified as a trade-off between environmental benefits versus economic ones, where an action is chosen to favour one or the other. Substantive trade-offs can involve substitutions over time or place (Morrison-Saunders and Pope 2013), e.g. that short-term gains can be considered favourable over long-term decisions.

Given the above, the presented analytical framework for adaptation trade-offs (Fig. 1) is based on the notion that adaptation decisions are likely to affect one or several socio-ecological aspects, but that decisions are also likely to be affected by the same or other socio-ecological aspects. Dotted arrows from the aspects to the adaptation measure under consideration, or to other aspects, signify processual trade-offs in adaptation decision-making. Aspects that generate processual trade-offs consequently work either as barriers (red) or drivers (green) for adaptation management. The adaptation decision-making process makes allowances for substantive trade-offs when choosing between taking a certain action for its positive effects while accepting other negative outcomes, including both direct effects and interactions between aspects. The generation of substantive trade-offs is signified by different potential outcomes of an adaptation decision—indicating a trade-off between the specific aspects involved. In addition to trade-offs between aspects, there may be different temporal or spatial scales of the aspects involved (Chelleri et al. 2015). While temporal or spatial dimensions are not prominent in the proposed framework, it acknowledges the inclusion of adaptation measures' relations to socio-ecological aspects of all temporal and spatial scales and to balance them against each other. The processes generating substantive trade-offs are represented by solid arrows, where positive effects are green and negative effects are red (Fig. 1). Although the analysis focuses on adaptation-related trade-offs, positive synergies are not excluded from the study's scope, as the analytical framework of the study is designed to capture mechanisms for both synergies and trade-offs.

Data collection and analysis

The applied data collection method integrates visualization, serious gaming and semi-structured interviews. Qualitative data was collected from 20 combined interview-gaming sessions, 10 in Sweden and 10 in Finland. Agricultural experts in two agricultural regions of Sweden and Finland with knowledge in crop production were targeted and recruited via e-mail for the combined interview-gaming sessions. The experts included extension officers, county officials, students and teachers of agricultural science, agricultural advisors and representatives of national agencies and farmers' unions (see Online Resource 1, for a complete list of interviewees' professions). Except for three occasions, the sessions were held in pairs in order to capture discussions and perspectives that were triggered before, during and after the gaming. Thus, 37 experts participated and were interviewed for this study. The interviews lasted approximately 1 h each and for about half of that time the participants engaged with a serious game to support the dialogue on adaptation needs and decisions. The 'Maladaptation Game' was developed with the specific aim of studying and communicating potential unintended negative effects of climate change adaptation in agriculture. It is designed as an online game that sets the player to make choices between different adaptation measures and their potential negative consequences in four climate-related challenges (Neset et al. fc). The climate change challenges and adaptation measures included in the game are based on a literature review (Wiréhn 2018) and stakeholder interviews in two Nordic agricultural regions (Neset et al. 2018). For a complete list of the adaptation measures included in the game, see Online Resource 2.

As the interviewees played the game together in pairs, they were encouraged to discuss their adaptation choices while playing, whereas follow-up questions were posed in case their reasoning was unclear. In the game, participants needed to agree upon the adaptation choices made, which triggered discussions on diverging views and perspectives. While the game provided specific adaptation measures and potential negative outcomes that influenced the initial discussions, the game setting also led to discussions in which respondents contested the options given in the game and proposed alternative measures and outcomes. As such, the game setting not only might have influenced topics that were discussed but also stimulated discussions that went well beyond the topics raised in the game (Asplund et al. 2019; Neset et al. fc). Questions related to the research field of climate adaptation in Swedish/Finnish agriculture were posed, both before and after the game. Except for follow-up questions connected to a specific statement, all questions were asked to both interviewees simultaneously in order to create discussions and reflections between the two interviewees. The interviews were held in Swedish and Finnish. An English version of the interview guide is available in Online Resource 3.

Transcriptions of the recorded gaming sessions were analysed by means of thematic analysis (Vaismoradi et al. 2013) to identify socio-ecological aspects and mechanisms that constitute different types of trade-off in line with the presented framework (Fig. 1). Relevant text sections referring to trade-offs were coded in the material (using NVivo and Atlas.ti software for the Swedish and Finnish coding, respectively). The coded material was subsequently screened for the trade-off mechanisms related to certain adaptation measures (negative effect of adaptation on an aspect, positive effect of adaptation on an aspect in addition to the intended one, negative influence or interaction between two aspects, positive influence or interaction between two aspects). Based on this material, socio-ecological aspects and their linkages with each other or with the adaptation measure of concern were inductively identified and defined to generate processual and/or substantive trade-offs.

Results

The following three subsections present the results of this study on three levels. Firstly, the 'Socio-ecological aspects of trade-offs' section presents the socio-ecological aspects that were identified to generate trade-offs based on the agricultural experts' discussions on adaptation management. The second section, 'Trade-off categories', demonstrates different levels of complexity in how the respondents discussed trade-offs for specific adaptation measures, outlined in six categories. Lastly, the 'Trade-off assessments' section includes trade-off assessments of two challenging, but significant adaptation measures, based on the interview material.

Socio-ecological aspects of trade-offs

Based on the thematic analysis of the transcribed discussions, a number of socio-ecological aspects were identified to generate adaptation induced trade-offs in Swedish and Finnish agricultural management. The trade-off discussions involved potential positive and negative effects on these aspects, interactions between them and preconditions for adaptation decisions. Dependent on the character of the trade-off and the functions of the aspects involved, these aspects could be described to generate either processual or substantive trade-offs in accordance with the analytical framework. Some of the aspects are closely associated with each other but still included as separate aspects due to the different focus in the discussions. For example, 'farm economy' and 'time' are associated with each other, but the 'time' aspect was discussed as a processual aspect concerning time as a limited resource and the associated investment in time, not the direct economic costs. Table 1 outlines and briefly describes the span of socio-ecological aspects discussed by the participants and identified based on thematic analysis.

The four key aspects discussed were 'crop yield and crop profitability' (substantive), 'robustness to pests and weeds' (substantive), 'farm economy' (substantive, processual) and 'soil quality' (substantive, processual). The respondents reflected upon these aspects in relation to most of the adaptation measures discussed during the gaming sessions, which

Table 1 Identified socio-ecological aspects of trade-offs and corresponding descriptions of how participants discussed these as processual and/or substantive, including examples from the empirical data

Aspect	Processual	Substantive
Farm economy	A precondition for adaptation measures. This aspect was also discussed in relation to temporal scale, i.e. a long-term vs. short-term economic perspective.	Direct economic costs involved in adaptation investments as well as interactions with other aspects, especially with crop yield and market.
Crop yield and profitability		Outcomes of measures directly affecting crop production, yield and crop production profitability. This aspect also interacts with other aspects, both positively and negatively.
Robustness to pests and weeds		Outcomes of adaptation measures directly affecting the risk of, or robustness against, pests and weeds. This aspect was also discussed in relation to other aspects, e.g. policy, and their influence on vulnerability to pests and weeds.
Common pool for sustainability		Outcomes of adaptation measures on the environment, humans or socio-ecological systems in general. This aspect was also discussed in relation to the influences of other aspects.
Climate		Outcomes of adaptation measures affecting the climate in terms of increasing emissions of greenhouse gases or increasing mitigation of greenhouse gas emissions. This aspect was mainly discussed as being directly affected by adaptation measures, but a number of interactions with other aspects (e.g. chemical demand, soil nutrients, policy) are mentioned.
Soil quality	A precondition for adaptation measures. The type and quality of the soil was discussed as determining which adaptation measures are relevant and/or feasible.	Outcomes of adaptation measures generally affecting soil quality, fertility and structure. This was discussed both as direct effects of the adaptation measure (e.g. measures affecting soil compaction) and as being influenced by or influencing other aspects.
Soil nutrients		Outcomes of adaptation measures or interactions with other aspects, such as knowledge and soil quality, that affect the nutrient-holding capacity, nutrient uptake by crops or leaching, which subsequently increases or decreases soil nutrient content and further affects others aspects (climate, water quality, crop yield, chemical demand).
Market	A precondition that could affect the outcome of the adaptation measure and the decision whether or not to implement the adaptation measure. Thus, this aspect was discussed, not as being affected by a measure or another aspect, but as affecting the adaptation decision or as influencing other aspects (farm economy, farm management, policy, food security, soil quality).	
Water quality and supply	A precondition that affects the decision to implement an adaptation measure, weighing the water need against water supply.	Adaptation measures directly impacting upon the water quality and supply and further influencing other aspects.
Knowledge and communication	Refers to the lack of scientific or common knowledge and/or accessibility and distribution of knowledge, as well as farmers' or policymakers' lack of knowledge about practical adaptations and their effects.	
Robust production	This aspect is related to long-term strategies, self-subsistence and sustainable production for securing the livelihood/production in the long term.	Outcomes of measures that effect robustness or stability of the crop production; mainly positive effects were discussed. It was discussed in various ways in relation to sustainable development matters.
Chemical demand		This aspect concerns outcomes of adaptation measures that affect the need and/or use of *chemical* fertilizers or pesticides, directly, or indirectly as a result of another aspect (climate, policy).
Farm management	The management system, determining whether or not an adaptation measure is feasible.	Outcomes of adaptation measures on the farmer's whole management system. The scale of farming was also discussed

Table 1 (continued)

Aspect	Processual	Substantive
		as being affected by adaptation measures (economic investments to scale up, increasing the potential profitability)
Policy	Environmental and water directives were discussed as a preconditional aspect, mostly as a barrier, affecting the adaptation decisions, e.g. regarding the use of chemical pesticides or the implementation of water management systems.	
Land ownership	A precondition for the decision to implement an adaptation measure, specifically in relation to water management and long-term soil quality enhancing measures, which in turn may affect other aspects (e.g. farm economy).	
Scale of farming	This aspect includes the spatial scale/distribution of farm resources and the size of the farm enterprise and was discussed as a precondition affecting the adaptation decision or as a condition influencing other aspects (e.g. water supply).	
Interest and tradition	This aspect was discussed in terms of how interests, traditions, habits, norms and cultures affect adaptation decisions, both as a limiting factor for change—related to the knowledge aspect in the sense that farmers might stick to management methods they or their neighbours are familiar with—and as a driver for change—even if farmers know that an adaptation measure might affect another aspect negatively (e.g. farm economy) the interest in changing to e.g. new crop types or conservation farming steers the decision.	
Time	This aspect was discussed as a precondition—a limited resource affecting the adaptation decision; adaptation often involves investments in time, in addition to potential economic investment.	
Biodiversity		This aspect was discussed as direct positive or negative outcomes of adaptation measures, especially in relation to surface and subsurface drainage systems, respectively.
Food security		This aspect concerns the direct effect of production on food security—addressing human need and the greater value of adapting agriculture in order to produce food.

makes them particularly relevant to adaptation decision-making in order to recognize and cope with potential trade-offs. The linkages between these aspects and the adaptation measures involved exemplify the complexity of the trade-offs.

Discussions on how *crop production, yield and crop production profitability* can be affected by certain adaptation measures often addressed the perspective of positive effects, i.e. how to increase crop yield, or to make use of the potential positive effects of climate change. Discussions regarding the negative effects were related to the risk of decreased yield if no adaptation measures are taken and to the processual aspects of trade-offs, such as *robustness to pests and weeds*. Moreover, it was often discussed that crop production profitability is not only determined by the management but significantly also by the demand and, thus, is related in particular to *farm economy* and *market* aspects. Discussions around farm economy often considered measures such as investments with direct effects on farm economy and management from both long-term and short-term perspectives. Crop rotation, for example, has positive effects for *crop production*, *robustness to pest and weed infestations* and *soil quality* in the long term but involves short-term economic losses during years when new crops are introduced and when there are less productive crops in circulation. Nevertheless, most respondents agreed that farmers must take a long-term perspective on management and economic strategy that also considers the contextual preconditions. The *soil quality* aspect was specifically emphasized as an important precondition, i.e. a processual aspect where the type and quality of the soil determines the feasibility and relevance of an adaptation measure. Frequently, respondents returned to the question of when it becomes profitable to implement a measure or not.

Trade-off categories

The analysed discussions demonstrated different levels of complexity in the respondents' views on specific adaptation trade-offs and the related management decisions. This section presents six categories of trade-offs based on the level of interaction between aspects, as well as the number of aspects being affected by, or affecting, adaptation decisions. Categories 0–5 are represented in Fig. 2, with trade-off examples for each of the categories. The examples are single cases of trade-offs as discussed by respondents and do not represent the whole material or the scientific or grey literature. While examples of respondents' views are presented for each of the categories, the results show that trade-offs in categories 1 or 3 are mostly referred to when discussing trade-offs in relation to a single adaptation measure.

Trade-offs related to a single aspect (category 0) were barely mentioned in the discussions because trade-offs and synergies inherently involve balancing more than one aspect. However, the processes per se could involve trade-offs. An example raised by one respondent concerns adjusting the sowing date as an adaptation measure to decrease the risk of pest infestations. On the one hand, sowing could be postponed during spring to get a rapid emergence so that the crops are less sensitive to pests; on the other hand, insect pressure is higher later in spring, resulting in a higher exposure to insects. Thus, this measure involves a trade-off between two processes that are both related to the aspect of pest robustness. Another category 0 trade-off involves using marginal land for crop production, which was included in the game as an adaptation measure to address food security on a global scale due to climate change. Some respondents considered that the implementation of such a measure would be a farm economy trade-off only, for example stating that:

> It's all about the cost, if it's profitable to cultivate the land or not.

The following trade-off categories are all related to more than one aspect, either directly (trade-off mechanism 1) or through interaction with aspects (mechanism 2). One trade-off that was discussed addresses the measure of increasing the production of winter crops to adapt to new climate conditions and taking advantage of potential yield increase and, thus, having a

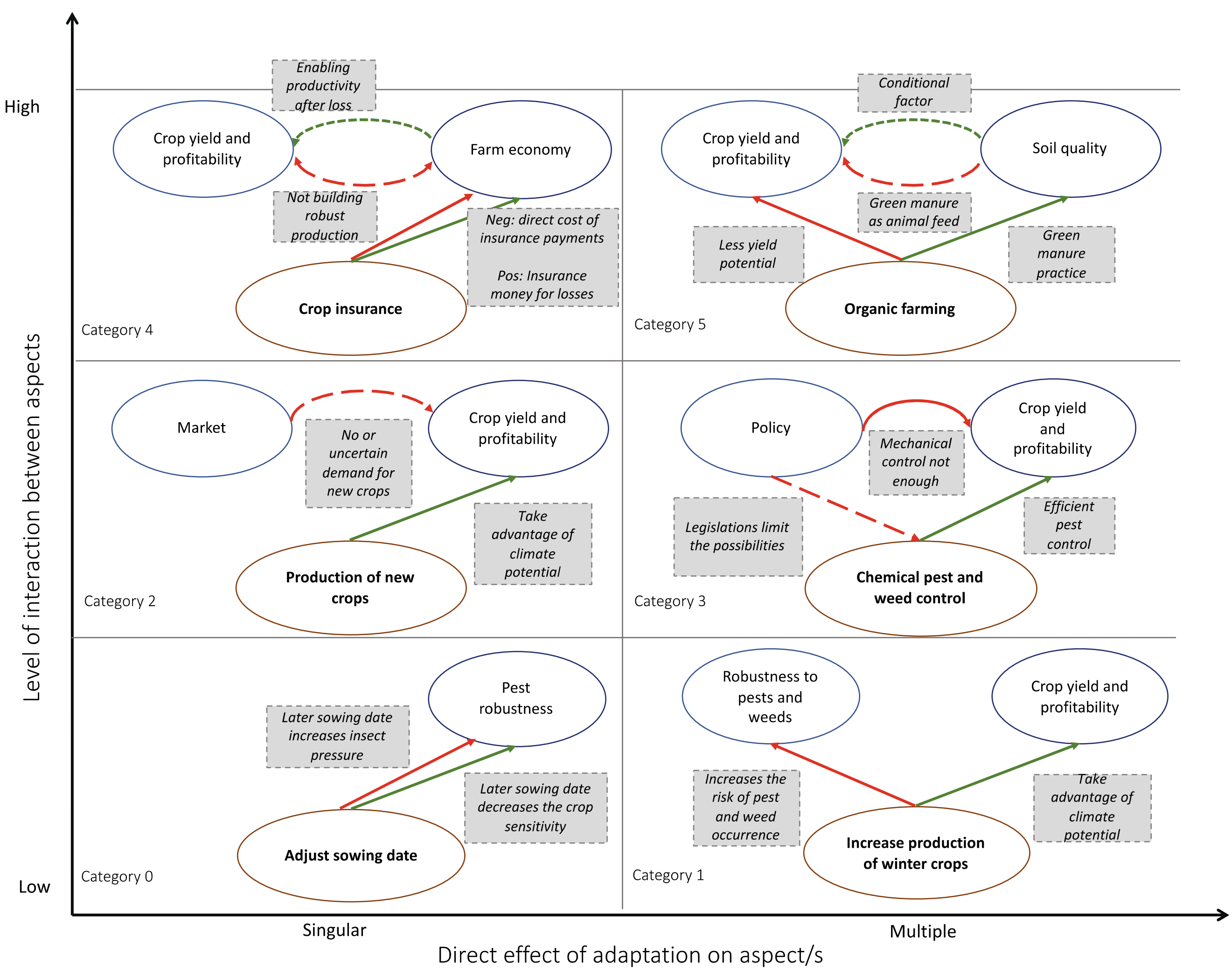

Fig. 2 Examples of adaptation trade-off as discussed in individual cases, categorized according to the adaptation framework (Fig. 1). Dotted and solid arrows represent processual and substantive trade-off types respectively, whereas red and green colours of arrows represent negative and positive effects or interactions

positive effect on crop yield and profitability. However, too much production of winter crops increases the risk of pest and weed infestations, specifically winter weeds. This can be categorized as a category 1 trade-off with two direct effects.

Production of 'new' crop types is a commonly suggested adaptation measure for northern agriculture. Several respondents discussed this measure in relation to market dependency. They argued that it is not realistic to start producing a new crop simply because it is more climate resilient and can have a positive effect on crop yield and profitability since farmers need to know that there is demand and a market for the new product. This generates a processual trade-off in which the market affects the profitability of crop production, and hence, the market per se, or uncertainty about the market, could be a barrier to adaptation implementation. In this example, the market is discussed as affecting the crop yield profitability and thus the decision of whether or not to implement new crops, representing a trade-off category 2.

Category 3 consists of trade-offs related to more than one aspect and a one-way interaction between aspects. A category 3 example that was discussed involves the use of chemical pesticides to secure crop yields, addressing the increased risk of pests that is projected to be a result of climate change. Chemical pesticides were considered a necessary measure because mechanical control of pests was regarded as insufficient, based on the current level of knowledge and experience. This trade-off was discussed in particular in relation to the aspect of policy. As policies and legislation determine which chemical compounds are permitted for application, a decreased variety of chemical compounds directly affects the adaptation decision. In turn, restrictions on permitted chemical compounds were argued to increase vulnerability to pests, affecting crop yield.

The fourth category involves a high level of interaction between aspects, but only discussed as having a direct effect on one aspect. The use of insurance to adapt to climate stress is an example of a category 4 trade-off. Getting insurance involves direct costs for the farmer, directly affecting the farm economy negatively. However, if farmers receive insurance payments (which was considered a rare outcome by the respondents), this could imply a direct positive effect on the farm economy and, hence, enable productivity after potential yield loss. It was nevertheless emphasized that adapting to climate stress and managing the impacts through insurance would not build climate-robust crop production systems, and hence, it was not regarded as a long-term sustainable adaptation measure.

The last category describes trade-offs between several aspects and a high level of interaction between them. Organic farming was discussed as having direct positive effects on soil quality (through green manure practices), while acknowledging a potentially negative effect on productivity (from not using the full yield potential of fields). This processual trade-off was discussed as resulting from whether or not the green manure crop should be used as animal fodder. In single discussions around the measures as presented in this section, category 5 trade-offs were not often raised. However, when assessing the material of this study as a whole, the complexity in the trade-offs increases, as illustrated in the following section ('Trade-off assessments').

Trade-off assessments

Although trade-offs belonging to categories 1 and 3 dominated the individual discussions on adaptation trade-offs, the entire material demonstrates that adaptation measures in fact involve trade-offs associated with complex levels of interaction between a multiple number of socio-ecological aspects. Increased irrigation and drainage, crop rotation, the production of new crops and mechanical pest and weed control were the adaptation measures discussed as concerning the greatest number of aspects. This section presents trade-off analysis results and mappings of two particularly challenging, yet important adaptation measures based on all the aspects and interactions raised by the respondents in the interview discussions. This demonstrates how the developed analytical framework can support assessments of complex trade-off structures to obtain an overview of the aspects and interactions involved in adaptation management. The adaptation measures examined here concern 'improved or increased drainage' and 'mechanical pest and weed control'. These two adaptation measures were two of the most complex measures in terms of the respondents' perceptions of the number of aspects involved and the associated linkages—including interactions between aspects as well as linkages between the respective adaptation measure and the aspects.

Increased or improved drainage systems (Fig. 3) were generally discussed as a positive adaptation measure from the *crop yield* perspective. Several of the respondents pointed out the synergies between soil nutrient uptake and the intended positive effect of being less vulnerable to excess water on fields and argued that well-drained soil results in increased root volume and improved root systems and that stronger crops take up and hold *soil nutrients* to a greater extent. Respondents thus suggested that crops cultivated in well-drained soils make better use of fertilizers. While the risk of nutrient leakage downstream from the drainage system was acknowledged, one respondent pointed out that drained soils would decrease the risk of nitrification and thus reduce greenhouse gas emissions and subsequent effects on *climate*.

> (…) it is of course possible that nitrogen and phosphorus leach into the ditches, so to speak. It sure does. But swamped land may not leach in that direction, but in another direction … it's gasified instead, the nitrogen. So, the nitrogen disappears, namely, nitrification is happening. Thus, poorly drained soil leaches as well. (…) But it's just that the nitrogen goes in the other direction (…)

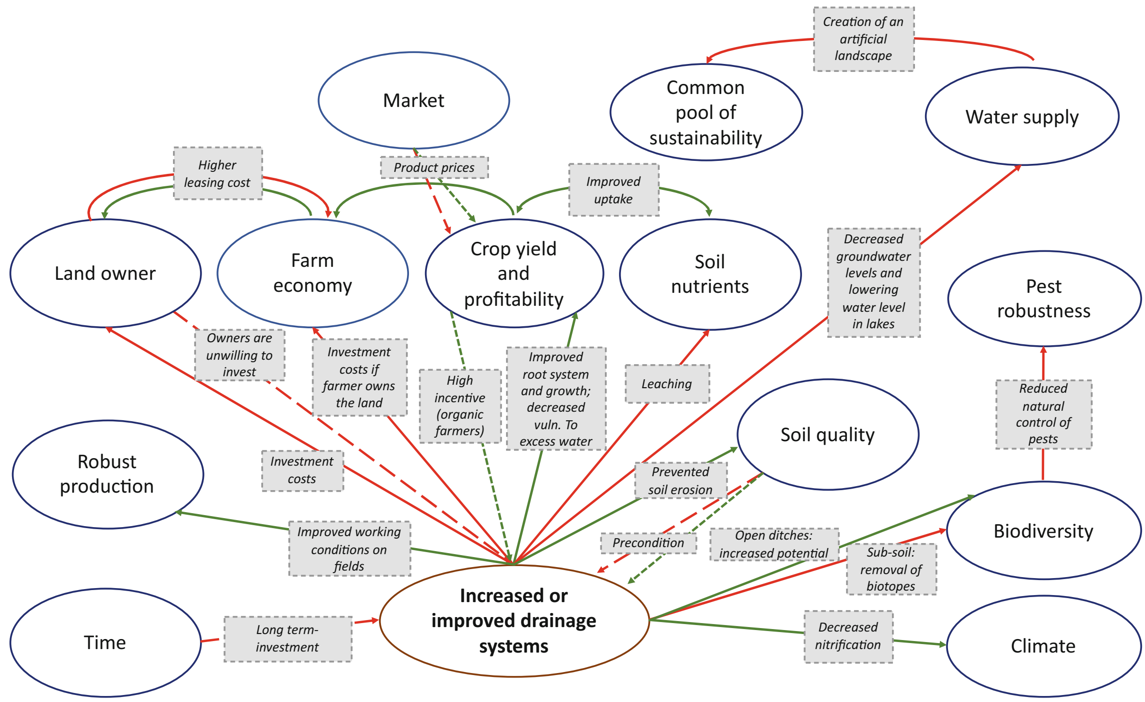

Fig. 3 Trade-offs and the associated aspects and interactions discussed in relation to the implementation of new or improved drainage systems. Dotted and solid arrows represent processual and substantive trade-off types respectively, whereas red and green colours of arrows represent negative and positive effects or interactions

Farm economy and *land ownership* were two further aspects that were emphasized in relation to drainage systems. Several respondents agreed that it would be a costly investment for the farmer. It is also common for farmers to lease their land, and this may complicate the realization of new or improved drainage systems even more, as the decision about whether or not to invest is in the hands of the land owner.

Although many respondents pointed out the benefits of drainage systems in relation to crop yield and soil nutrient uptake, one respondent emphasized that current agricultural practices—with their continued tendency to drain land for crop cultivation—construct an artificial landscape with a decreased *groundwater supply*, which also inhibits the ecological sustainability of lakes and wetlands. Moreover, subsoil tiles will decrease the presence of small water streams and dams, negatively affecting the existing biotopes and *biodiversity*, subsequently decreasing the *robustness to pests* and increasing the need for *chemical* pesticides. Improved drainage systems through open drainage, on the other hand, have a positive influence on biodiversity, in terms of, for example, habitats for birds of prey and pollinators. Several respondents justified the use of open drainage in favour of subsoil tile drainage because of the biodiversity aspect.

Because increased risk of pest and weed outbreaks is an expected consequence of climate change, pest and weed control is of paramount importance. Adaptation through the mechanical control of pests and weeds was one adaptation measure that was discussed in relation to most aspects by the respondents (Fig. 4). This measure was discussed in relation to its association with organic farming and the related positive effects on *sustainable development*, with its limited use of pesticides on agricultural fields. Nevertheless, the challenges related to this adaptation measure were the topics deliberated upon the most by respondents. To start with, mechanical control would challenge, or even conflict with, a 'no-tillage' field practice, which one respondent reflected by posing the question: 'should we go for more no-tillage farming, or in the other direction (i.e. mechanical control)?' Simultaneously, agricultural *policies* and trends influence these management decisions, as no-tillage is generally communicated as having several environmental and production benefits, including climate change mitigating effects. One of the key aspects discussed was that mechanical pest and weed control is anticipated to be more time-consuming and to involve increased numbers of routes across the fields, thus increasing the *farmer's costs* in terms of time and energy consumption and affecting the *climate* negatively due to increased greenhouse gas emissions from diesel combustion. Moreover, one respondent specified that the management per se involves greenhouse gas emissions.

> So, processing (...) it releases, you get emissions there. And it's probably not possible to get away from that.

While climate change is anticipated to increase the occurrence of weed and pest infestations, several respondents regarded this as a barrier to implementing increased mechanical control. Such future conditions would increase the

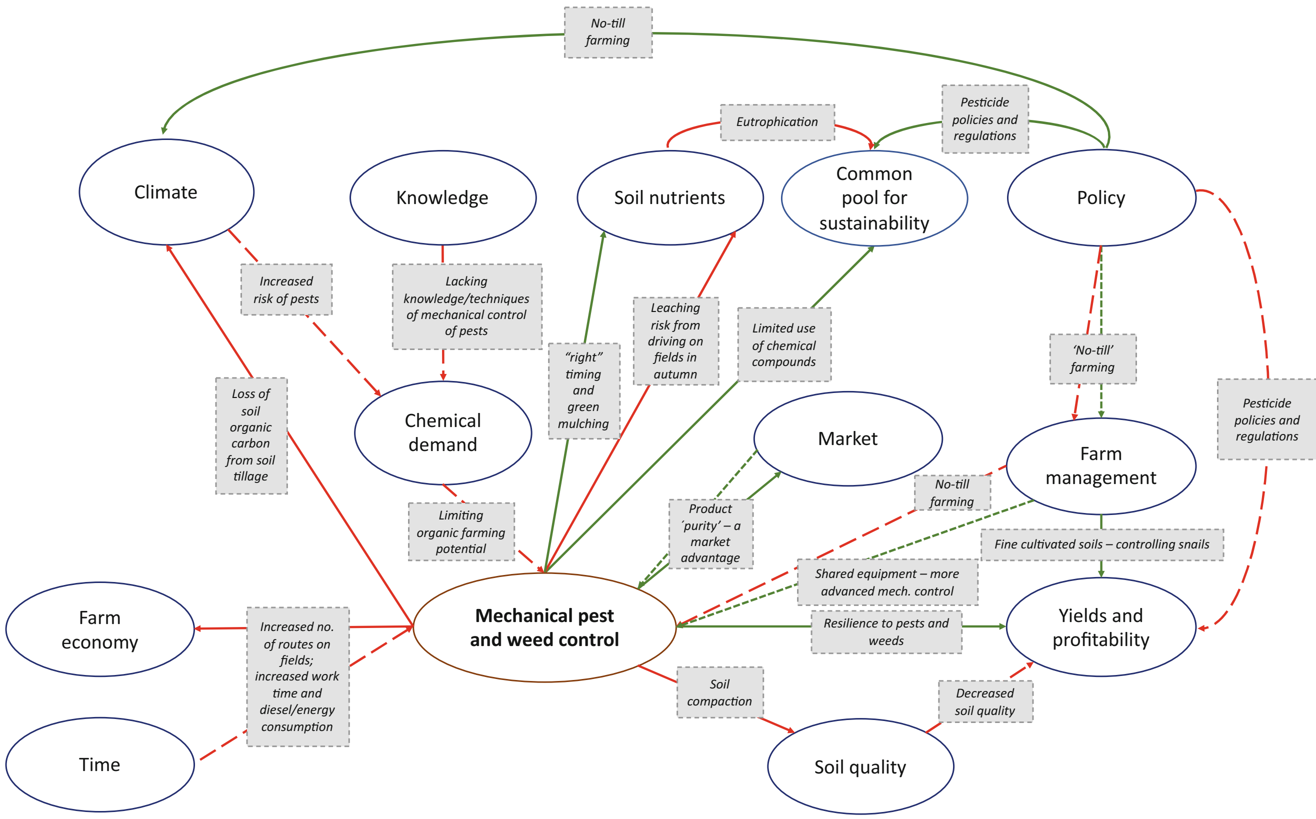

Fig. 4 Trade-offs and the associated aspects and interactions discussed in relation to the implementation of mechanical pest and weed control. Dotted and solid arrows represent processual and substantive trade-off types respectively, whereas red and green colours of arrows represent negative and positive effects or interactions

demand for pesticides and thereby decrease the possibilities for mechanical pest and weed control, thus inhibiting organic farming. It was also mentioned that limited *knowledge* and a lack of techniques for mechanical control, especially pest control, contributes to the increased demand for pesticides. One respondent summarized this issue by saying:

> It will probably be more difficult to be an organic farmer if there are more pests… I would say, it would rule out that possibility.

Another effect that participants reflected upon was the risk of increased nutrient leaching due to driving on the fields during autumn. This would affect the soil nutrient content and potentially affect surrounding environments and *sustainable development*. On the other hand, mechanical control is a measure that is inherently intended to limit the use of chemical pesticides and hence limit their negative effects on sustainable development. Lastly, while pest and weed control is intended to include measures that increase the robustness of crop production, some respondents pointed out that the environmental policies and legislation that permit fewer varieties of pesticides will, together with the increased risk of pests, instead increase the vulnerability of crop production.

Discussion and conclusion

The general call for climate change adaptation, and particularly for agricultural adaptation management, makes it pertinent to understand the complexity of adaptation decision-making—in order to manage adaptation in a sustainable manner (e.g. Aggarwal et al. 2018). This study's scientific contribution lies in addressing the current lack of studies focusing on adaptation trade-offs as well as to support theoretical development in the field. Research on trade-offs has frequently focused on climate change mitigation (e.g. Landauer et al. 2015), socio-ecological goals (e.g. Denton et al. 2014) or ecosystem services (e.g. Bennett et al. 2009; Cord et al. 2017). While adaptation might be included as a factor in the previous examples, the present study specifically focuses on trade-offs in socio-ecological systems induced by climate change adaptation and proposes and tests an analytical framework to analyse such trade-offs. By means of this framework, the study concludes that adaptation trade-offs in Swedish and Finnish agriculture involve balancing a number of socio-ecological aspects that can be of different character and serve different roles within the trade-off structure. In agricultural decision-making, the identification of different types of aspects related to a single adaptation measure can inform the understanding of different stakeholder groups and facilitate informed dialogues and cross-sectoral understanding.

Based on agricultural experts' perspectives we identified 20 socio-ecological aspects related to adaptation induced trade-offs in agricultural management (Table 1). The results suggest that 'crop yield and profitability', 'farm economy', 'robustness to pests and weeds' and 'soil quality' are the most prominent aspects in adaptation management in Swedish and Finnish agriculture. Although the socio-ecological aspects identified in this study are specific for Swedish and Finnish contexts, the general findings are supported by results for agricultural production in Bolivia, emphasizing the need for assessments of adaptation actions' complex enchained effects on the socio-ecological system and the question of what should be regarded as positive, for what, and for whom (Chelleri et al. 2016).

In line with previous studies (Morrison-Saunders and Pope 2013), the analysis indicated that an exclusive assessment of the balancing of different potential outcomes of adaptation measures would be limiting, since respondents discussed 'trade-offs' as also involving barriers and drivers for adaptation, which jointly affect decision-making. The developed analytical framework addresses this by integrating (I) two mechanisms that can create trade-offs (direct and interactions) with (II) two types of trade-off characteristics (substantive and processual), based on the theoretical approaches proposed in Bennett et al. (2009) and Morrison-Saunders and Pope (2013), respectively. As such, the framework presented here has been shown to enable a thorough assessment of complex adaptation trade-off structures, where the inductive identification of socio-ecological aspects generating the trade-offs was followed by an assessment of trade-off mechanisms and types.

We argue that this framework can facilitate comprehensive systematic analyses of components involved in trade-offs, as well as their characteristics and linkages. Once a set of aspects has been identified, the framework can be used for assessments and comparisons of trade-offs for various adaptation practices. In this study, we apply the framework to analyse experts' perspectives on trade-offs; however, we suggest that it could also be applied, for example, to meta-analyses and literature reviews (e.g. Kongsager 2018; Wiréhn 2018).

In line with Bennett et al. (2009), we demonstrate that the framework supports the assessment and comparison of the complexity of different trade-offs, in terms of the number of aspects and linkages involved in the trade-off (Fig. 2). Furthermore, the mapping of aspects and linkages, as illustrated in Figs. 3 and 4, provided the basis for a comprehensive assessment to support adaptation management. While we have assessed individual adaptation measures in this study, the framework could be applied to assess more than one adaptation measure affecting various aspects and/or being influenced by these aspects. This would, however, increase the complexity of the structure even further and would be most applicable if fewer aspects were targeted. A methodological challenge of trade-off assessments under the suggested analytical framework is the identification of a representative set of aspects that are neither too detailed nor overlap too much. A factor that was not accounted for in this study is the importance of different aspects, which could be included in future applications of this framework, by weighting or ranking trade-off types and mechanisms.

The 20 socio-ecological aspects that were identified in this study were exclusively based on perspectives of agricultural experts in two regions of Sweden and Finland respectively and did not include additional aspects or linkages from scientific or grey literature. Nevertheless, the aspects discussed in relation to most adaptation measures indicate their importance in agricultural adaptation decision-making. 'Increased or improved drainage systems' and 'mechanical pest and weed control' were the measures discussed in relation to the greatest number of aspects, exemplifying the complex trade-off structures that affect these adaptation decision-making processes. According to our analysis, some of the identified aspects generate both processual and substantive trade-offs while some were assessed as merely generating either processual trade-offs, such as 'policy' and 'knowledge and communication', or substantive trade-offs, such as 'crop yield' and 'biodiversity'. However, taken together, these different types of aspects constitute different parts of the trade-off structure and are hence equally important to include in an adaptation trade-off assessment.

In conclusion, this study provides a novel analytical framework for assessing, comparing and mapping the trade-offs associated with adaptation decision-making at the practical level of adaptation management. This study furthermore contributes to increased understanding of the complex nature of climate change adaptation decision-making and the associated trade-offs among various socio-ecological aspects in Swedish and Finnish agriculture. This study shows that adaptation decision-making in Swedish and Finish agriculture involves a combination of processual and substantive trade-offs and that 'crop yield and profitability', 'farm economy', 'pest and weed robustness' and 'soil quality' are discussed as the most prominent aspects to generate trade-offs. Hence, there is a need for climate adaptation management in Swedish and Finnish agriculture to consider these aspects in relation to each other and to cope with the involved trade-offs in a sustainable manner.

We argue that the provided analytical framework supports adaptation induced trade-off assessments and furthermore conscious adaptation management and policy decisions, which create opportunities for sustainable development pathways. Finally, we suggest that the presented analytical framework is applicable to various adaptation decision-making contexts, for different sectors and regions, to support adaptation strategy development and implementation while recognizing and coping with associated trade-offs.

Acknowledgements We would like to thank the interviewees for their participation and for contributing their perspectives to this study.

Funding information Open access funding provided by Linköping University. This study was funded by the Swedish Research Council FORMAS (under Grant No. 2013-1557).

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