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A guide towards climate change adaptation in the livestock sector: adaptation options and the role of robust decision-making tools for their economic appraisal

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Abstract Economic appraisal and technical effectiveness of adaptation options are key criteria for judging climate change adaptation investment decisions in all sectors. Yet relatively little methodological guidance exists for determining the most appropriate appraisal techniques for different adaptation options. This paper provides adaptation options and scopes relevant appraisal methods in agriculture focussing on livestock production specifically. We find that for many adaptation options for livestock agriculture, standard (expected) cost-benefit analysis is an appropriate tool. For adaptation options requiring long lead times or those with long lifetimes, techniques incorporating uncertainty ('robust' methods) are more suitable, including real options analysis, portfolio analysis and robust decision-making. From a comprehensive list of adaptation options in the livestock sector, we identify the most appropriate appraisal technique for each option and describe how the robust appraisal tools could be applied to heat stress, flood risk and water management.

Introduction

Agriculture is especially vulnerable to climate change due to its dependence on climate-sensitive natural resources (Howden et al. 2007). Climatic changes are already being experienced: across Europe, the average decadal temperature for 2002–2011 was 1.3 ± 0.11 °C above the 1850–1899 average and since the 1950s annual rainfall has increased over Northern Europe and decreased over Southern Europe, as well as an increase in extreme conditions. Temperatures are projected to rise by between 1 and 4 °C per century across Europe, and precipitation to increase in Northern Europe and decrease in Southern Europe (Kovats et al. 2014).

The projected changes, including the effects of climate variability and extremes, will have direct effects on livestock productivity, either on the animal directly (e.g. through heat stress) or indirectly through effects on crop production and the disease vectors to which the livestock are exposed. For example, increases in winter temperature will lengthen the thermal growing season in regions where temperature constrains crop growth during winter. But higher temperatures during the growing season may result in yield reduction as experienced during the heat waves of 2003 and 2010 when grain losses reached 20% in Europe (Kovats et al. 2014). The livestock sector contributes

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substantially to the European economy (€169.5bn in 2013), being 41% of total agricultural value (FEFAF 2013) and creating employment among the 10 million people working full-time and 25 million people working part-time in agriculture in Europe (European Commission 2013b). Further, demand for livestock products is likely to increase in the future, particularly in developing countries (Thornton 2010). Thus, given the economic importance of the livestock sector in Europe, minimising the impact of climatic changes on its output through effective and strategic implementation of adaptive practices will be critical. Adaptation options are wide-ranging, from incremental changes in management in current systems, to long-term structural and transformative changes in the farm as well as the sector as a whole, with a growing body of research identifying options and their effectiveness (e.g. Renaudeau et al. 2012; Hoving et al. 2014).

Decision-makers in agriculture, from farmers to policy-makers, require information on the anticipated costs and benefits of adaptation, in order to evaluate the most economically efficient adaptation options. Economic appraisal methods synthesise the effects of adaptation options on production, farm businesses and risks in order to fully evaluate adaptation options. Planning for adaptation requires some foresight that the climate will change in the future, or if changes are already being observed, that these changes will continue. The Ricardian approach (Mendelsohn and Nordaus 1994; Seo and Mendelsohn 2008) measures empirically the economic impact of climate change on land prices and controls for adaptation and has shown that farmers adapt to climate change to address changes in economic return caused by climate variables. While significant advances have been made in projecting future climate scenarios [e.g. CMIP5 scenarios (Taylor et al. 2012)], these projections, as well as their implications for agricultural systems, are associated with considerable uncertainty that can pose challenges for decision-making.

Uncertainty in climate projections stems from four main sources: (1) modelling uncertainty, which arises from our incomplete understanding of the climate system and the inability of climate models to represent the real system perfectly; (2) natural climate variability; (3) uncertainty in our future emissions; (4) uncertainty resulting from downscaling projections (Jenkins et al. 2010).

In this paper, we explore the applicability of different economic appraisal methodologies for livestock adaptation options, given the uncertainty surrounding climate impacts. We take recognised adaptation options available to the livestock sector and provide recommendations on which appraisal method is most appropriate given the characteristics of the options. To our knowledge, this classification of appraisal method to adaptation option has not previously been carried out and we believe it provides a useful

summary of ways to approach adaptation appraisal in the livestock sector. Three detailed examples of appraisal methods to illustrate their potential application are provided. The focus is on farm decision-making within European livestock, but the principles can be applied to a range of production systems.

Economic appraisal, risk and uncertainty

The uncertainties described above make the application of decision-making approaches, at least in their 'basic' formulation, challenging. Standard cost-benefit analysis (CBA) attempts to maximise the benefits for society based on potential Pareto efficiency.

CBA assesses whether it is worthwhile implementing a project by comparing all its monetised costs and benefits expressed over a defined time span to obtain its net present value (NPV) (Eq. 1):

$$(\text{NPV}(i, N)) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} \tag{1}$$

where N is the total number of periods, i the discount rate, t is time and R_t is the net cash flow (benefits minus costs) at time t. Where decisions are being made over short time frames or where there is reasonable certainty about the climate impacts, and the effect of the adaptation can be quantified, estimating the benefits of adaptation is relatively straightforward. A positive NPV indicates the project should generally proceed. Providing reliable data on costs and benefits are available, CBA can be carried out with limited technical resources and is accessible to a non-technical audience. Other related methods to CBA are cost-effectiveness analysis (CEA) or multi-criteria analysis (MCA) (Boardman et al. 2014; Triantaphyllou 2000).

Uncertainty in CBA (or CEA and MCA) can be addressed in different ways. For example, an expected values framework attaches subjective probabilities (Hallegatte et al. 2012), to evaluate the expected benefits as the probability-weighted average of the benefits based on how likely different states of the world are. Equation 2 can be modified as follows such that each mutually exclusive NPV is associated with a specific probability $p(R_t)$:

$$E(\text{NPV}(i, N)) = \sum_{t=0}^{N} p(R_t) \frac{R_t}{(1+i)^t} \tag{2}$$

Probabilities can be based on past occurrences of events, expert knowledge or both. Subsequently projects matching the conditions of that future are designed and fine-tuned with sensitivity analysis. Additionally, scenarios of how the future might unfold (of equal likelihood) can be used (Boyd et al. 2006; García de Jalón et al. 2014); for CBA,

this is a variant to include more than the central estimate as in the expected value framework. Worst and best cases that might be of particular interest in the context of climate change can be easily turned into scenarios. The theory of expected utility (Von Neumann 1967) allows for the inclusion of risk preferences in addition to contingent outcomes. The utility functions will differ depending on whether the decision-maker is risk-neutral, risk-loving or risk-averse.

All of these approaches have associated difficulties. Using several climate change scenarios provides the end-user with a range of possible outcomes, but with no attached probabilities making it difficult to make an informed decision. Expected values and utility can be used in situations of quantifiable uncertainty (and well-known risk preferences for expected utility). But for climate change we do not have a strong methodology to assess these subjective probabilities. They cannot be fully based on the past, because climate change is a new process for which we have no historical equivalent. Models share common flaws in their assumptions and their dispersion in results cannot be used to assess the real uncertainty (Hallegatte et al. 2012). The term deep uncertainty or severe uncertainty is used in such contexts and is characterised as a condition where decision-makers do not know or cannot agree upon a model that adequately describes cause and effect or its key parameters.

Uncertainty regarding future climate changes together with the imperative to make adaptation decisions in anticipation of these future climates can leave decision-makers struggling to understand what the appropriate course of action might be, particularly with adaptation actions that require significant investment. Fortunately, many of the adaptations available to the agricultural sector do not involve long time horizons. Economic approaches based on expected values such as CBA and expected utility are generally suited for decision-making where probabilities can be attached to outcomes or changes are only implemented after the change has occurred. In the context of climate change, this will be particularly the case for short-term decision-making. Expected utility approaches are particularly useful to consider risk attitudes, specifically risk aversion, under increased weather variability which we expect to see more under climate change (IPCC 2012). But in some cases longer time horizons cannot be avoided— either through the adaptation requiring a longer time to be fully effective (long lead time) or because once it has been adopted, it is difficult to reverse (long lifetime). In such contexts, CBA does not cope well and could lead to an inappropriate investment if the adaptation was unsuited for the actual climate outturn.

In both the academic and policy literature, alternative decision-making methods to appraise adaptation options are therefore being explored (Dessai and Hulme 2007; Dessai and van de Sluijs 2007; European Commission 2013a; Fankhauser et al. 1999; Hallegatte and Corfee-Morlot 2011; Lempert and Schlesinger 2000; Ranger et al. 2010; UNFCCC 2009; Watkiss et al. 2014). The focus is on so-called robust approaches. While all approaches that consider risk and uncertainty tackle the challenge of choosing actions in a future that cannot be predicted, robust approaches aim to better incorporate uncertainty by selecting projects that meet their purpose across a variety of plausible futures (Hallegatte et al. 2012). Here we identify three robust decision-making methods that would be applicable to appraisal in the agricultural sector.

Portfolio analysis (PA) combines several adaptation options in a portfolio to reduce risk by diversification (Markowitz 1952). Real options analysis (ROA) develops strategies that allow for learning and can be adjusted (e.g. upscaled or extended) when additional climate information becomes available. It originates from option trading in financial economics (Black and Scholes 1972; Cox et al. 2002; Dixit and Pindyck 1994; Merton 1973). Finally, robust decision-making (RDM) identifies how different strategies trade-off in order to identify options which might not be optimal under a specific climate outcome but less vulnerable under many climate outcomes (Lempert and Schlesinger 2000).

These techniques are particularly suited for adaptation options with long lead and/or lifetimes as they integrate uncertainty in the decision-making process. For a more detailed overview of robust approaches, see Dittrich et al. (2016) and Watkiss et al. (2014). In this paper, we focus on the identification of adaptation options and application of appropriate appraisal methods to the livestock sector. Possible adaptations are grouped by their lead and lifetime characteristics, in order to clarify the methodological approaches most appropriate for each option. The adaptation options considered were previously identified for European livestock agriculture in Wreford and Dittrich (2015) and are based on impact categories identified from the literature (Iglesias et al. 2012). Most of the decision-making for the adaptations covered in this paper would be autonomous adaptations made by private individuals (in these context livestock farmers). However, some of the options that require robust appraisal techniques may fall under the realm of planned public decision-making, such as large-scale water storage facilities or flood defence schemes.

Short-lifetime adaptations

Many of these adaptation options in the agricultural sector involve managerial changes, such as adjustments to the timing of operations, the movement of stock in response to

immediate conditions, the management of feeding and grazing and disease and pest control. They also include soil and water management and conservation. The options are also often flexible and/or reversible, with few longer-term implications, such as changes to the grazing regime or the installation of small-scale water storage facilities. A comprehensive range of adaptation options are identified in Table 1 and their types of costs and benefits summarised so that the appropriate appraisal option can be recommended. Options with short lifetimes such as these managerial changes and options associated with small investments and when changes are reversible are generally suitable for appraisal by either (expected) formal or informal CBA.[1] Because there is less long-term planning and economic evaluation required for these options, we spend the remainder of this article examining the appraisal methods appropriate for the long-lifetime or long-lead time adaptations.

Long-lifetime adaptation: robust appraisal methods

Other types of adaptations will require either a longer lead time in their planning, or will have long lifetimes, where the implications of decisions made now will be long-lived, and where uncertainty regarding the future climate can create a barrier to decision-making. These types of adaptations will often come under the realm of public decision-making and will require more robust appraisal approaches for efficient decision-making. In Table 1, we identify which of the three robust approaches discussed previously would be most suitable for a range of potential adaptation options in the livestock sector. We also include measures that would be made in response to increased weather variability, which may not necessarily have long lead times but address a range of future climates and hence require an appraisal method which takes the increased range of outcomes into account. The types of adaptations where portfolio analysis is most appropriate typically involve diversification of species (animal or crop). Adaptations that involve a large initial capital investment in the construction of a building or infrastructure are more suited for real options analysis, while RDM is ideal when a range of differentiated strategies for adaptation is available.

In Sects. 2.2.1 to 2.2.3, we take one adaptation example for each of the robust appraisal methods and describe in detail how the appraisal methods would be applied in practice.

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[1] Many of these options would be appraised informally by the individual farmer without a quantitative appraisal; however, we can still expect the farmers to weigh up the (expected) costs and benefits of any action they take.

Adapting to heat stress: application of portfolio theory

All animals have a range of ambient environmental temperatures known as the thermal neutral zone and exceeding this range negatively affects livestock performance. Heat stress starts at the upper critical temperature of this zone. The animal cannot dissipate an adequate quantity of the heat to maintain the body's thermal balance (Moran et al. 2009). Heat stress causes productivity losses or even mortality and thus incurs economic costs to the industry. St-Pierre et al. (2003) estimated that total losses across animal classes averaged \$2.4 billion in the USA annually if there is no heat abatement.

Higher-yielding animals produce more body heat due to their greater metabolic activity (Settar et al. 1999; West et al. 2003), indicating a trade-off between productivity and heat tolerance (Hoffmann 2010). There is a general trend towards more productive animals to maximise profits, and we may thus expect heat stress to become more of a problem in future due to both climate change and trends in breeding. While this trade-off between productivity and heat tolerance can apply to a range of livestock species, we focus here on dairy cattle due to data availability.

We suggest the application of PA to appraise adaptations to combat heat stress in livestock. In the context of climate change adaptation, PA has been applied to choosing wetland habitats in different locations (Ando and Mallory 2012), and to the regeneration of forests with different tree seeds (Crowe and Parker 2008). Our approach to address heat stress in livestock is to diversify the breeds in a particular herd to reduce the risk of heat stress while trading off some productivity. Having a number of high-productivity animals in the herd with low heat tolerance levels and a number of lower-productivity animals with high heat tolerance will achieve this objective. It should be noted that this is not an adaptation to long-term temperature changes (as the productive lifetime of a dairy cow usually does not exceed 5 years); rather, it is an adaptation to increased variability in climate due to climate change.

The adaptation choice (breed composition) is determined by maximising benefits (measured through a productivity metric such as milk yield) given the decision-maker's risk affinity. Alternatively, given a defined benefit of the adaptation options, risk is minimised across all adaptation options. Equation 3 specifies an example minimisation problem of the latter type taken from Ando and Mallory (2012).

$$\text{Min } w^T \sum w, \text{ subject to } \sum_i w_i = 1, \ w_i > 0$$
$$\text{for all } i, \text{ and } E[R]w = \mu \tag{3}$$

Table 1 Adaptation options and the identification of their relevant costs and benefits as well as of a suited appraisal method

Type of appraisal	Types of adaptations	Further explanation
CBA	Move herds to more suitable conditions from waterlogged fields, extreme dry situations and extreme heat or cold	Benefits include maintained productivity; costs include management and labour (if no shelter exists, long-term adaptation will be to construct more housing; see options for robust appraisal)
	Change breeding and shearing patterns. For animals kept outside, e.g. sheep, the time of lambing and shearing can be adapted to the seasonal weather conditions	Benefits include maintained productivity (e.g. through avoidance of heat/cold stress); costs include labour
	Adjust stocking density to avoid poaching and overgrazing; to cope with a reduction in available food; to minimise disease outbreaks; to cope with heat stress in intensive conditions (e.g. transport)	Benefits include pasture preservation; avoided costs of disease outbreaks; maintained productivity (per animal); costs include reduced total production
	Ensure access to water to aid thermoregulation	Benefits include maintained productivity; costs include management/labour costs
	Adjust timing of animal transport to avoid heat/cold exposure	Benefits include maintained productivity and avoided mortality; costs include management/labour costs
	Adjust diet to ensure sufficient dealing with hot weather. Ensure energy requirements are being met if the heat reduces total feed intake; supplements can also assist	Benefits include maintained productivity/reduced mortality; costs include cost of feed/supplements, labour
	Vaccination for climate-related diseases	Benefits include maintained productivity/reduced mortality; costs include labour; purchase of vaccines
	Conserving surplus production of feed supply. Seasonal variations in roughage feed supply are buffered by conservation methods	Benefits include continued production; costs include foregone income from sale of surplus feed
	Supplemental feeding in situations of a loss in forage quality and quantity	Benefits include maintained productivity/reduced mortality; costs include purchase of supplemental feed
	Restoring degraded land to increase agricultural output or counteract decreases in output in other areas	Benefits include increased output; costs include initial investment and ongoing maintenance, loss of output where this involves leaving the land fallow
	Apply crop/fallow rotation	Benefits include increased soil fertility and yield due to N fixing in soils in the medium/long term and also improved water holding capacity, thus reducing drought and pest outbreaks. Costs include management changes
	Optimal use of fertilisers and manure	Benefits include improved productivity and potential increased resilience to climate change; costs may include increased fertiliser costs (potentially also indirect costs of increased GHG emissions)
CBA	Set clear water use priorities. Ensuring the most important water demands are covered such as drinking water for animals and basic irrigation for crops	Benefits include avoided costs of purchasing water; or implications of stock and crop dehydration. Costs include foregone profit from lower prioritised uses
	Increase water use efficiency	Benefits include avoided costs of purchasing water; or implications of stock and crop dehydration. Costs include foregone profit from lower prioritised uses
	Reduced/zero tillage in order not to disrupt the soil	Benefits include higher yields due to improved soil fertility and water retention. Costs include the loss of crop residues for animal feed
	Improve field drainage water absorption capacity to minimise waterlogging	Benefits include avoided soil compaction and stock health costs; negative crop impacts. Costs include machinery and maintenance
	Small-scale reservoirs on farmland to collect rainwater and technical improvements in irrigation equipment	Benefits include production continuity; costs include installation, maintenance and potential foregone profit from land taken out of production
	Reduce run-off through contoured hedgerows and buffers	Benefits include avoided erosion and the costs of planting of and more difficult field access due to hedgerows/buffers
	Use of precision agriculture techniques	Benefits include improved efficiency; costs can include machinery and equipment
	Insurance	Benefits include avoided expected financial loss; costs include premiums
	Water management practices. Terraces, mulching, ditches and grass strips can be used to conserve soil water. Timing of water use such as irrigation at night, water efficiency and conservation strategies through separating dirty/clean water can be adjusted	Benefits include avoided costs of purchasing water; or implications of stock and crop dehydration. Costs include machinery, maintenance and labour
	Incorporation of crop residues	Benefits include soil fertility and water retention through building organic matter. Difficult to quantify due to the long-term nature of changing soil C. Costs include the loss of crop residues for animal feed; labour and machinery

Table 1 continued

Type of appraisal	Types of adaptations	Further explanation
	Additional weed/pest control	Benefits include avoided weed and pest outbreaks; costs include weed and pest control products; labour; indirect costs of increased nutrient leakage, pesticide resistance
	Shelter belts	Benefits include shade and protection from wind, potentially increased yield and decreased erosion. Costs include more difficult access to fields, labour, equipment, maintenance and potentially foregone profit from land taken out of production
	Advisory service for farmers	Benefits include increased adoption of these measures and thus avoided losses and maintained production of the sector. Costs include the administrative costs of establishing advisory services (although existing services may be able to incorporate adaptation advice), labour
Portfolio analysis	Changing high-yield/high-productive breeds for lower-yielding/less productive more heat-tolerant breeds of cows/sheet	Heat tolerance/productivity can be traded off through a 'basket' of breeds
	Cover crops to improve soil structure and to reduce erosion due to wind and rainfall	Cover crops can be sown on some fields and not on others depending on the cost for cover crops and time available to sow, i.e. a basket of cover crops. This is not a long-term adaptation option but can help to improve soil structure in a given climate more efficiently
	Grass and legumes can be combined in a way to trade-off productivity and heat tolerance	Grass–legume swards have important yield advantages compared to monocultures. Legume species have higher temperature optima than grasses. Other potential benefits: On soil structure due to deep rooting systems and for carbon sequestration (the latter is partially dependent on the change in reseeding that may be required). Improvement of productivity on crops/grasslands through more efficient fertiliser use due to reduced requirement for N by the legumes
	Replace/combine high-productivity crop varieties with more pest-resistant varieties	
	On a regional/national level: portfolio of pastures and crops according to land capability	
Real options analysis	Hard flood risk defences to protect livestock and agricultural land	The defences can be scaled up over time in the least costly way if the potential full design is considered now
	Natural flood risk management (NFM) measures to protect livestock and agricultural land	The defences can be scaled up over time in the least costly way if the potential full design is considered now
	Housing to protect animals from heat	The possibility of later adding cooling pads, fans systems, water sprays/misters to buildings and/or outdoor areas (e.g. collecting yards)
	Large-scale irrigation for improved water supply/farm scale reservoirs	Can be scaled up over time in the least costly way if the potential full design is considered now
Robust decision-making	Holistic water basin management in a region to identify the least vulnerable strategies to meet the water demand	Water flow related to climate change scenarios as well as benefits/costs of the options under climate change

where w_i are the weights of the portfolio of breeds, T is the transpose operator, Σ is the covariance matrix of R, $E[R]$ is the expected return (milk yield or price per litre milk) of each breeds and μ is the target expected return. A higher return is associated with a higher risk. A portfolio is best balanced if the co-variances of the assets are negative, off setting the risk under different scenarios. In other words, low return on one asset will be partly offset by higher returns from other assets during the same period. This applies directly in the livestock case. The higher the productivity of an animal, the lower the heat tolerance, and vice versa. The challenge is to relate the climate change scenarios directly to heat stress and thus to return. Using UKCIP02 data (probabilistic climate data for the UK), Moran et al. (2009) calculated the maximum temperature humidity index (THI) [i.e. the relationship between temperature, humidity and heat stress (Wiersma 1990)] under different climate change scenarios using maximum monthly temperatures. Each class of animal was assigned a THI threshold based on empirical studies above which that class of animal begins to suffer from heat stress. Subsequently, the data can be related to milk loss in kilograms per day, and based on the number of days where the threshold is exceeded, milk loss per year can be calculated. The return (milk yield) for each breed can then be calculated under each climate change scenario. Average expected returns then need to be calculated across all

chosen climate change scenarios by attaching probabilities to the scenarios. This is also a possible short-coming of the method as it is not clear that probabilities can be attached with confidence to climate change outcomes (Hallegatte et al. 2012). PA makes the implicit assumption that climate change uncertainty can be quantified through expected values. Further data that are required include the co-variances between the returns of the different breeds. Given these data, the problem can be solved either as a minimisation or a maximisation problem with a constraint. For Eq. 3, risk is minimised (based on the co-variances of the assets) for a given return. A so-called efficiency frontier can be derived as shown in Fig. 1 if the minimisation problem is solved for a range of target returns. The efficiency frontier identifies different portfolios for the number of dairy cows that should be purchased proportionally as part of the herd (i.e. the portfolio weights). PA assumes that the decision-maker is risk-averse and the choice of a specific portfolio on the efficiency frontier depends on his/her risk tastes (i.e. their type of utility function). Thus, for example, under increased weather variability, a more risk-averse farmer may opt for a portfolio with an overall lower expected return but relatively low risk, i.e. a point in the left bottom corner on the efficiency frontier in Fig. 1.

Adapting to flood risk: applying real options analysis

The frequency and intensity of extreme events is likely to increase as a result of climate change (Schär et al. 2004; Stott et al. 2016). Flooding can pose a threat to livestock in two ways: first, directly by threatening the safety of animals, in both housed or fields, and second, indirectly by damaging forage in the form of pastures and crops used to feed livestock, and damages to farm buildings, machinery and other assets. As a consequence, additional forage may need to be bought in by the farmer and assets repaired at potentially high cost. In automated systems, waste

management systems can be damaged leading to increased exposure to pathogens and risk of disease or threaten water quality (Schmidt 2000). In monetary terms, storms and floods are already the most frequent and costly weather-related disasters in Europe and accounted for 77% of the economic losses caused by extreme weather events between 1980 and 2006 (CEA 2007).

Building flood risk mitigation measures can help to alleviate this problem. The measures can be both standard 'hard' engineering solutions such as flood walls but also natural flood management (NFM) measures such as afforestation along streams, rivers and field edges to slow down peak flow, restoration of flood plains and retention ponds for water. Hard engineering solutions and to an extent soft NFM measures involve long-lived decisions with high sunk costs that are likely to be sensitive to climate change uncertainties.

If the frequency of floods changes substantially, i.e. a flood that occurs in the current climate on average every 50 years may occur in the future on average every 35 years, flood mitigation measures can prevent severe damage and associated costs. Uncertainty about the future means farmers may be unsure whether to invest in building flood risk mitigation measures, and risk over-adapting if extreme events do not change sufficiently in frequency to justify the action. In this situation, a ROA may enable a more informed decision.

ROA handles deep uncertainty by allowing for learning about climate change over time. The intuitive argument is to postpone costly (partly irreversible) measures until more scientific evidence on the impacts of climate change is gathered. Uncertainty is assumed to resolve with the passage of time due to increasing knowledge on climate change impacts (Hallegatte 2009; Watkiss et al. 2014). In the context of flood adaptation measures, this means starting out with a relatively small flood adaptation measure and scaling it up over time if necessary. However, there is a trade-off as additional investment comes with fixed cost; therefore, continuous investment is not the most economically efficient solution either (Van Dantzig 1956).

Applications of ROA to climate change include investment in coastal protection (Linquiti and Vonortas 2012; Scandizzo 2011; Woodward et al. 2014). Gersonius et al. (2013) determined the adjustable design of an urban drainage system in West Garforth, England, that minimises the lifetime cost of the system and Dittrich et al. (Dittrich 2016) examined the application of ROA to afforestation as a flood management measure.

For a ROA model that can either minimise costs (as an extension of cost-effectiveness analysis) or maximise benefits (as an extension of cost-benefit analysis), the following steps need to be carried out. Note that the specific
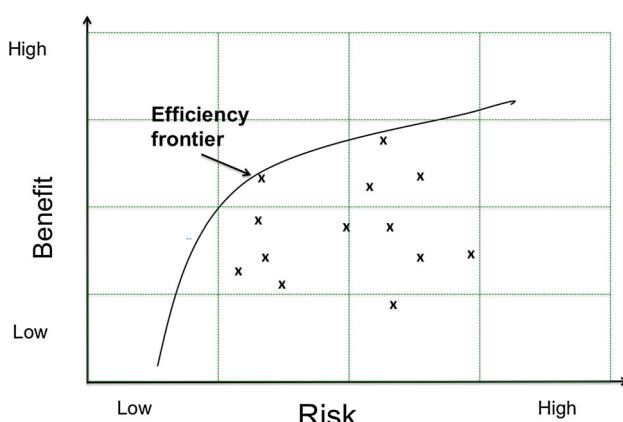

Fig. 1 Graphical representation of different feasible portfolios

solution will vary depending on the problem at hand. ROA also assumes risk neutrality such as CBA and CEA but extends both by adding the option of learning instead of having to make a now or never decision.

In a first step, climate scenarios for the area in question are required, specifically rainfall data. The UK Met office (Murphy et al. 2009), for example, provides a dataset with historical rainfall data across the UK which is perturbed for a range of climate change scenarios. These data need to be further processed as transition probabilities need to be assigned to different plausible climate change paths. Obtaining such transition probabilities for different time paths can prove challenging such as for PA as this requires attaching probabilities to climate change scenarios and subsequently probabilities on how to move from one climate change path to another. In some studies (Gersonius et al. 2013; Linquiti and Vonortas 2012), the probabilities have been be obtained with the same formula as in the financial option model which is based on the assumption that the logarithm of the underlying uncertain parameter, here rainfall, follows a stochastic process called geometric Brownian motion (GBM) (see Cox et al. (2002) for an overview). Moving window processes have also been applied (van Der Pol et al. 2015). In a next step, the climate data need to be linked to a hydrological model. The exact hydrological data needed will depend on the specific question and the level of hydrological detail that is required. For a cost-effectiveness application, a constraint such as a specific flood protection standard may be defined. For a cost-benefit analysis, a damage module needs to be included. At a minimum, the model needs to measure discharge without the flood mitigation measure and with different implementations of the mitigation measure under different peak flows. The aim is to relate different levels of peak flow to different levels of discharge subject to different levels of implementation of the flood mitigation measure. In a subsequent step, the economic optimisation model is added. Costs comprise the design, land, construction and maintenance costs of which some are incurred in the present time period, and others are delayed or avoided altogether. Maintenance costs depend on the specific flood mitigation measure. Benefits are avoided damages. Finally, the decision on when to exercise the option to scale up the flood mitigation measure must be made. The decision criteria can be tailored to the requirements of the problem, for example, once certain damage has been exceeded with a certain probability, or once a predefined standard (e.g. avoid 1 in 10 flood) cannot be guaranteed anymore.

Equation 4 presents an example of a cost-effectiveness problem set up as a Bellman equation which is solved recursively (van Der Pol et al. 2015).

$$J_t(\varphi, x) = \min z \frac{\left(\frac{I(z) + O(x+z)}{(1+\delta)^t} + E\{J_{t+1}((\varphi_{t+1}|\varphi), x+z)\} \right)}{\text{s.t. } R(f, x+z) \geq \alpha}$$
(4)

where J_t is the value function, x the stock variable of the system element, z the additional investment at each time step and φ describes distribution of the uncertain parameter today and in the next time period. The cost function depends on the investment cost I, the maintenance cost O and the discount rate δ. Finally, this is subject to a reliability constraint R which depends on $x + z$ and f the distribution of specific rainfall events, and α the predefined reliability standard.

ROA does not result in a single highest ranked option as an output. It provides flexible strategies along the different climate paths that can be adjusted over time and an explicit valuation of created and destroyed capabilities. The present value of the total costs of the RO mitigation measure must be less than or equal to the present value of the total costs of the non-flexible mitigation measure (NRO) (if they are not then there is no benefit to the adjustable mitigation measure and a large flood mitigation measure should be installed from the outset).

To provide quantitative results, good data are necessary: methods such as genetic algorithms or dynamic programming that usually require expert knowledge can provide solutions to the objective function. However, ROA can also be applied qualitatively by drawing up a decision tree that outlines different adaptation paths to provide conceptual guidance on the adaptation strategy.

Water management: application of robust decision-making

In some cases, farm-level adaptation in the livestock sector requires integration with a wider set of policies. This may be the case in a region suffering from water scarcity where a holistic water management approach is needed. Water may be needed for irrigation of fields, drinking water for animals, as well as for household use. Meeting the demands of all stakeholders under such conditions can be extremely challenging even without the changes in future water availability resulting from climate change. An adaptation appraisal method that works well in such situations is RDM. The concept of RDM is not new (Matalas and Fiering 1977) and has been used in different variations, but it is most prominently linked to the RAND Corporation (Lempert et al. 2003). It was originally designed for decision-making in poorly characterised uncertainty with a subsequent application to climate change adaptation (Lempert et al. 2006).

RDM can help to structure a complex decision-making process with a large set of options. It helps to understand the

potential consequences of strategies over many scenarios. Lempert and Groves (2010) applied RDM to determine water management strategies in the western USA in the context of climate change. The study tested the current water management plan which aims to ensure sufficient and affordable water supply considering that precipitation and temperature patterns might change significantly in the long term. Besides a wide range of climate change scenarios, further uncertainties considered included future socioeconomic conditions and the agency's ability to implement the plan. Further applications include a set of coastal risk reduction and restoration projects in Louisiana, USA, given a budget constraint (Groves and Sharon 2013). In an application to flood risk management in Ho Chi Minh City's Nhieu Loc–Thi Nghe canal catchment, Lempert et al. (2013) evaluated that the current infrastructure plan may not be the most robust strategy in many plausible futures emphasising the importance of adaptively using retreat measures.

RDM determines less vulnerable strategies by identifying measures that have little sensitivity to different climate change scenarios by trading off some optimality (Lempert and Collins 2007). Figure 2 illustrates the decision-making process of RDM.

In general, RDM models will strongly depend on the adaptation problem analysed. If needed, the analysis can be simplified according to the decision-makers' needs by reducing the range of climate scenarios and other uncertainties considered as well as the number of strategies.

In a first step, the aim of the decision-making process and a number of potential strategies need to be defined. Ideally, the potential strategies must be sufficiently differentiated to allow for a meaningful comparison of trade-offs. For water demand, this may be a certain supply to all parties involved over a specific time period and how this

might be accomplished, for example, through irrigation measures, water conservation devices, reduction in water leaks, local water consumption audits. The second step includes identifying uncertain parameters and their plausible ranges including climate change impacts, future water demand and others. This is a crucial task, as it will define the vulnerability of different strategies. Values may be obtained from the literature, expert opinion elicitation or stakeholder consultation. The choice and range of these parameters is determined by the decision-maker, introducing unavoidable subjectivity. RDM applied fully quantitatively is very data and resource intensive, but to avoid overly complex outcomes it may be advisable to limit the number of uncertainties. For the uncertainty concerning climate change, simulation models are used to create large ensembles (thousands or millions of runs) of multiple plausible future scenarios from the parameters without assuming a likelihood of the different scenarios. A simplified version will use fewer model runs, however, at the cost of potentially ignoring the least vulnerable option.

In a third step, costs and benefits of different measures are assessed. This includes hydrological modelling for the area of interest in order to predict changes in flows under different climate change scenarios as well as demand models for agricultural and potentially household water demand. Subsequently, the different strategies are tested against a robustness criterion, which may be that the strategy performs well compared with alternative strategies in many different future scenarios or a certain cost-benefit measure (Lempert 2014). In an iterative process, the candidate strategies can be adjusted and fed repeatedly through the ensembles. Accordingly, RDM does not predict uncertainty and then rank alternative strategies, but characterises uncertainty in the context of a specific decision: the most important combinations of uncertainties to the choice among alternative options are determined in different plausible futures. As a result of the analysis, trade-off curves compare alternative strategies rather than providing any conclusive and unique ordering of options. Generally, a strategy that performs well over a range of plausible futures might be chosen over a strategy that performs optimally under expected conditions.
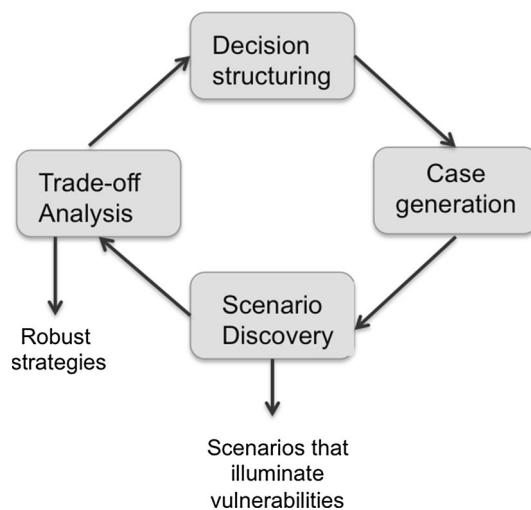
Discussion and conclusion

We assert in this paper that the lead time (and linked to this reversibility) and lifetime of an adaptation action determine the appropriate method of economic appraisal for decision-making. Adaptations that can take effect relatively instantaneously can wait until the climate is observed to have changed, and can be reversed if they are no longer appropriate (although farmers will likely be observing

Fig. 2 Decision-making steps: robust decision-making (Lempert et al. 2013)

trends and planning ahead before they take action). These types of adaptations can be appraised through (expected) formal or informal CBA.

It should also be noted that despite the short lead and lifetime of many options, farmers will not know the consequences of their actions with certainty in particular where there is increased weather variability under climate change. In such contexts, the use of expected utility theory with the inclusion of risk coefficients and PA can prove useful as a way to guide decision-making.

The choice of which robust decision-making method to apply for options with a longer lead/lifetime will very much depend on the characteristic of the adaptation problem, its adaptation options, as well as the objectives of the decision-maker. ROA can assist in identifying the value of flexible adaptation strategies where the adaptation options can be scaled up/extended. RDM is suited to determining the less vulnerable strategies for a complex adaptation problem, and finally PA can be used to identify the most efficient combination of options that work well across scenarios. We provided one potential application for each robust method; however, some of the adaptation options we describe (and which are given in Table 1) could also be appraised with another method. For example, RDM would also be suited to analyse the costs and benefits of a large-scale flood defence measure if it affects multiple stakeholders and suffers from poorly characterised uncertainty. Similarly, a standard expected utility approach could also be used when assessing the construction of defensive infrastructures; however, the information yielded from this versus a ROA approach may not be as useful as it would assume a now or never decision about the investment rather than allowing for adjustments over time. Yet if it were not feasible to design the flood defence measure in a flexible way (and the uncertainty is well characterised), an expected utility may be sufficient. Indeed, in many cases, the decision which approach to use will be determined by trade-offs between the approaches.

Proper application of these techniques may, however, be very data intensive and requires specialist skills that may not be available to all decision-makers. Over time decision-makers will become more familiar with the principles, the methods may become more mainstream, and concurrently academics should work towards making the full analysis more accessible. This includes user-friendly specific software or spreadsheets where practitioners could enter their specific data and requirements and the programme would provide the output. Examples of simplified applications include the TE2100 project (Reeder and Ranger 2010) for ROA and Frontier Economics (2013) evaluated natural flood risk measures in North Yorkshire, UK, using simplified RDM by reducing the number of climate change scenarios included. Matrosov et al. (2013) used RDM to select portfolios of water supply and demand strategies in the Thames water system, UK, simplifying the methodology by considering a smaller number of options but considering a detailed assessment of the different uncertainties (climate change through hydrological flows as well as demand and energy prices). Over time as decision-makers become more familiar with the principles, the methods may become more mainstream, and concurrently academics should work towards making the full analysis more accessible as well—such as user-friendly specific software or spreadsheets where practitioners could enter their specific data and requirements and the programme would provide the output.

It should be noted that the adaptations here are incremental rather than transformative, intended to avoid disruptions of the current systems (Kates et al. 2012). In some locations, this will not be sufficient due to high risk and vulnerability. Such transformation requires not only feasible adaptation options but also appropriate social and institutional contexts (Kates et al. 2012). In the European livestock sector, we may speculate that such options include changing the type of agricultural activity (e.g. from crops to livestock) or even abandoning agriculture as an income source in certain areas on the supply side (Howden et al. 2007). On the demand side, this may include attempts to reduce meat consumption (which also benefits mitigation) (Ripple et al. 2014). The latter point shows that climate change will not necessarily be the main driver of decision-making, other factors such as market risk and policy changes will prove influential.

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