The **CLIMSAVE** Project

Climate Change Integrated Assessment Methodology for Cross-Sectoral Adaptation and Vulnerability in Europe

Report describing the adaptive capacity methodology

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1. Introduction and definitions

The purpose of this paper is to set out the way in which the CLIMSAVE project, and in particular the Integrated Assessment (IA) Platform, can define, measure and utilise the concept of "adaptive capacity". This paper explains current thinking, but aspects of the methodology may change in response to experience in implementing these ideas within the IA Platform and/or following stakeholder feedback on the platform during the second round of workshops. In particular, the adaptive capacity method may need to co-evolve with the method for defining and measuring vulnerability, as explained further below.

1.1 The CLIMSAVE approach

The CLIMSAVE project is developing an IA Platform that will enable decision-makers and other interested stakeholders to access the latest scientific information on climate change impacts and opportunities for adaptation. The platform is being designed closely with stakeholders through a series of workshops in which new scenario storylines are being created. Thus the platform will allow stakeholders to run their own scenario simulations across multiple sectors to explore and test alternative adaptation options.

What are the adaptation options?

The IA Platform is based on a series of linked meta-models (see Deliverable 2.1 - Holman and Cojocaru, 2010 - and Deliverable 2.2 – Holman and Harrison, 2011 - for further details). The user can run these meta-models under a wide range of scenarios to assess impacts and vulnerability. In order to reduce vulnerability, the user can then implement a range of adaptation options. Adaptation options that can be represented in the platform are obviously limited to those that can be linked to a parameter/variable in one or more of the meta-models. These 'adaptation sliders' are shown in Table 1. These could be further broken down into specific actions, or examples of actions, that fall within each category, though it is not possible within the platform to give an exhaustive list. In addition to these adaptation options, there are several parameters that are scenario dependent (both climate scenarios and socio-economic scenarios): these can be changed by changing the scenario under consideration, but are not available as adaptation options.

CLIMSAVE covers six sectors (agriculture, forests, biodiversity, water, coasts and urban) and hence only adaptation options related to these sectors are covered. Further, not all options within these sectors relevant to the drivers of vulnerability (see Figure 1), can be handled by the meta-models such as generation and spreading of knowledge, development assistance, and compensation and insurance of catastrophic losses. Hence, our consideration of adaptation, and associated adaptive capacity, should not be seen as a complete characterisation for the sectors under consideration and this must be taken into account in interpreting and presenting results, and in the cost-effectiveness work.

Table 1: Broad adaptation options ("sliders") in the CLIMSAVE platform.

Household externalities preference (Green_red): Reflects people's relative desire to live in rural areas with access to green space or urban areas with access to social facilities.
Spatial planning (compact vs sprawled): Planning policy to control urban expansion, and so protect land availability for food and biodiversity.
Attractiveness of coast: Discouraging coastal development to reduce exposure to coastal flooding.
Flood protection upgrade: Improving the standard of flood defences.
Flood resilience measures: Changes to reduce the amount of damage caused by a flood.
Water technological change: Using technology to reduce industrial and domestic water demand.
Water structural change: Promoting behavioural change to use less water through, for example, education, training, water pricing.
Water demand prioritization: How water should be prioritised when demand is greater than availability (food, environment, domestic & industrial).
Irrigation water cost: Changing irrigation water price to change water use efficiency and demand.
Irrigation efficiency: Changing the amount of water used to produce a fixed amount of food.
Yield improvement: Change in yields, due to plant breeding and agronomy (leading to increases) or environmental priorities (leading to decreases).
Change in food imports: To encourage food self-sufficiency but reduce European land availability for biodiversity, or increase imports but make Europe more vulnerable to external crop failures.
Change in bioenergy production: Represents more land allocated to agricultural bioenergy and biomass crops (and so less for food and nature) or *vice versa.*
Change in dietary preference for beef/lamb and chicken/pork: Reducing meat consumption in response to anticipated food shortages.
Reducing diffuse source pollution from agriculture: Changing agricultural practices to reduce water pollution.
Set-aside: Represents the percentage of land removed from production for environmental benefits or to regulate production.
Forest management: Changing forest management practices - from intensive management for timber production with lower nature and recreation values, through to lower intensity management with good nature and recreation/cultural values and reasonable timber production.
Tree species: Planting trees species which are better suited to the changed climate.
Wetland creation: Represents managed re-alignment where flood defences are moved inland to make space for creating coastal wetlands.
Habitat creation options: Increasing the size of existing protected areas (PA), so as to improve the ability of species to cope with change; or increasing the number of PAs, so as to fill gaps in the PA network and to improve species' movements across the landscape.

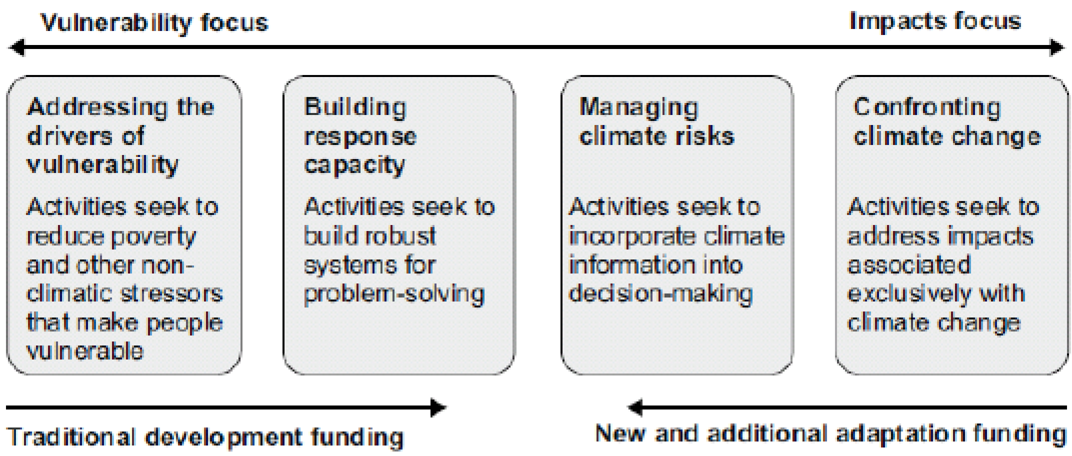

Figure 1: Adaptation from addressing vulnerability to facing impacts. Source: Klein and Persson (2008).

Treatment of time within CLIMSAVE

The CLIMSAVE IA Platform works on time-slices representing average conditions within the 2020s and 2050s. Previous discussions had examined the scope within CLIMSAVE for linking the 2020s and 2050s time slices via a dynamic component to adaptation, by distinguishing between early and late adaptation options, and keeping track of choices in the 2020s in terms of the adaptive capacity and adaptation options available in the 2050s. This would have given additional 'realism' in the presentation of time-relevant, sequential choices for platform users. However, this would have required introducing additional complexity to the platform in order to track these variables, and would have added constraints, or potential confusion, for users regarding the order of taking decisions and the possibility of changing 'early' decisions at a 'later' stage.

It was therefore decided to not distinguish between long and short term adaptation options. This means that the adaptation screen will allow users to investigate the amount of adaptation (and how it can be achieved through different combinations of options) to ameliorate negative impacts either in the 2020s or in the 2050s, but there will be no link in the platform between these slices (users could, however, make such a link in their thinking).

Time-dependence can still be considered in the cost-effectiveness work, where the batch runs of the platform can be designed such that 2020s decisions can carry forward to 2050s options. And there is an implicit time-requirement associated with many of the adaptation options (see Table 1), either because the option is expressed as a rate (for example, annual % improvement in some technology) or because it is 'obvious' that the option requires a long lead-time before taking full effect (for example, changes in planning policy).

1.2 Adaptive capacity

The definition of adaptive capacity is difficult and contested - Patt et al. (2009) describe adaptive capacity as “an intellectual quagmire”. We need to draw on the literature to develop a working definition that serves a useful purpose in CLIMSAVE.

IPCC (2007) defines adaptive capacity as the ability of a human-environment system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences. This broad definition covers both planned and autonomous adaptations, and instantaneous and reactive adaptations (Levina and Tirpak, 2006). In contrast to the IPCC definition, Van Ierland et al. (2006) state that adaptive capacity is mostly interpreted to reflect only adjustments to moderate potential damages, not to extreme scenarios. UN/ISDR (2004), on the other hand, focuses more on extremes by defining adaptive capacity as the combination of all the resources and capabilities available within a community, society or organization that can reduce the level of risk, or the effects of a disaster.

Willows and Cornell (2003) note that adaptive capacity can be considered as an inherent property of the system (allowing for spontaneous or autonomous response), but alternatively can be seen as dependent upon policy, planning and design decisions carried out in response to, or in anticipation of, changes in climatic conditions. Metzger and Schröter (2006), however, define adaptive capacity as reflecting the potential to implement planned adaptation measures: deliberate human attempts to adapt to, or cope with, change and not autonomous adaptation. Adger et al. (2004) note that the distinction between planned and autonomous can become blurred: “if we include in our definition of adaptive capacity all the factors that facilitate and inhibit adaptation, adaptive capacity at any given point in time represents the degree to which a system will “automatically” adapt” – in other words, what we consider to be autonomous depends on how we define the system.

These definitions allow adaptation to occur at any time. Brooks (2003), however, argues for a definition of adaptive capacity that focuses on diminishing *future* vulnerability, not current vulnerability. Similarly, Gallopin (2006) stresses that capacity of response is clearly an attribute of the system that exists prior to a perturbation. The ability to deal with perturbations when they arise, or with the after-effects of a shock, can be better described as coping capacity. Birkmann (2006) defines coping capacity as a combination of all strengths and resources available within a community or organisation that can reduce the level of risk or the effects of a disaster.

Under the above definitions, adaptive capacity relates to the *potential* to adapt to climate change. Adaptive capacity can be transformed into adaptation, which can lead to enhanced coping capacity. A system often requires time to realize its adaptive capacity as adaptation. Smit and Pilifosova (2001) argue that enhancement of adaptive capacity represents a practical means of coping with changes and uncertainties in climate, including variability and extremes: enhancement of adaptive capacity reduces vulnerabilities and promotes sustainable development.

In most of the literature, there is no clear distinction between adaptive capacity and coping capacity (Adger et al. 2004). However, for the purposes of CLIMSAVE this distinction is useful, and it is clearer to define *adaptation* as the means of enhancing coping capacity and reducing vulnerability to future climates; *adaptive capacity* as the ability to carry out such adaptation, and *coping capacity* as the ability to deal with climate changes (including variability and extremes) as they happen. Adger et al. (2004) note that, although coping and adaptation are not synonymous, there is a feedback loop between coping and adaptation, whereby lessons learned from a hazard event may result in better adaptation to increase future coping capacity. As the IA Platform works with time-slices representing 'average' conditions within a decade, such dynamic interactions cannot be incorporated, rather we can consider adaptation as relating to actions taken in advance of a platform simulation / time-slice. Along with the climate and socio-economic scenarios, the adaptation actions determine the average conditions faced during the time slice, and the amount of coping capacity that is available to deal with them within the time slice.

Thus we have a rather clear distinction between:

- adaptation options, that are chosen by platform users, occur in advance, influence platform inputs, and change average conditions during a time-slice; and
- coping actions, that are not yet explicitly represented in the platform, but conceptually are the ways that populations facing the average conditions generated by the platform could react to climate change (including variability and extremes) within a time slice.

This has clear implications for what we are trying to measure. Adaptive capacity relates to the potential ability of societies to adapt, and is a function of the adaptation options and the extent to which their requirements can be met by the resources available. Coping capacity is defined by the residual resources and options, resulting from the combination of scenarios and adaptation options taken. These capacities are not directly represented in the meta-modelling part of the IA Platform and a new methodology is required to incorporate them into the Platform.

The distinction between autonomous and planned adaptation within CLIMSAVE is less clear. While the decisions taken by platform users can all represent planned adaptations, some could occur in autonomous forms (for example, a change in dietary preference could be the result of a deliberate policy, or it might just happen for reasons not associated with climate change or adaptation to it). The platform users explore the consequences of changing certain variables, in the context of adaptation to climate change, but there is nothing to say that all the interesting features must be planned, and they are exploring scenarios as well as adaptations. Also, the platform itself includes some autonomous adaptation that is built into the underlying meta-models (e.g. farmers choice of crops). Thus measurements of modelled adaptation using the CLIMSAVE platform will include a mix of autonomous and planned adaptations.

Coping ranges and vulnerability

Given the above definitions of adaptation and coping capacity, (future) vulnerability is a function of exposure, sensitivity and coping capacity. Adger et al. (2004) distinguish between biophysical and social vulnerability. The direct effect of adaptation is to reduce social vulnerability. Whether or not this translates into a reduction in biophysical vulnerability or risk will depend on the evolution of hazard. In CLIMSAVE, this is represented by adaptation influencing sensitivity and exposure through changes in land use, technology and population characteristics. If we wish also to take account of the coping capacity, this must be modelled separately.

Carter et al. (2007) notes the use of the coping range as a way of linking the understanding of current adaptation to climate with adaptation needs under climate change. It can be used as a qualitative metaphor (e.g. for stakeholder discussions) and can also be developed into a quantitative model (Jones and Boer, 2005). Figure 2 illustrates the key concepts:

- some (arbitrary) indicator varying with climate;
- the coping range of acceptable outcomes – generally, the best ones near the middle, with the edges of the coping range populated by undesirable, but acceptable, outcomes;
- beyond this, regions of intolerable outcomes, flagged as vulnerable;
- climate change is pushing outcomes more into the upper 'vulnerable' range (upper figure);
- adaptation can extend the coping range to reduce vulnerability (lower figure). This can be understood as changing the exposure, sensitivity and/or coping capacity of a population, in the context of the climate-driven indicator.

Coping ranges are usually defined specifically for an activity, group, and/or sector (Carter et al. 2007) although society wide coping ranges have been proposed (Yohe and Tol, 2002). Risk can be defined by the frequency with which the coping range is exceeded under given conditions. Historical frequency of exceedance can serve as a baseline from which to measure changing risks using a range of climate scenarios; for measuring adaptation, the change in expected exceedance following action can be used.

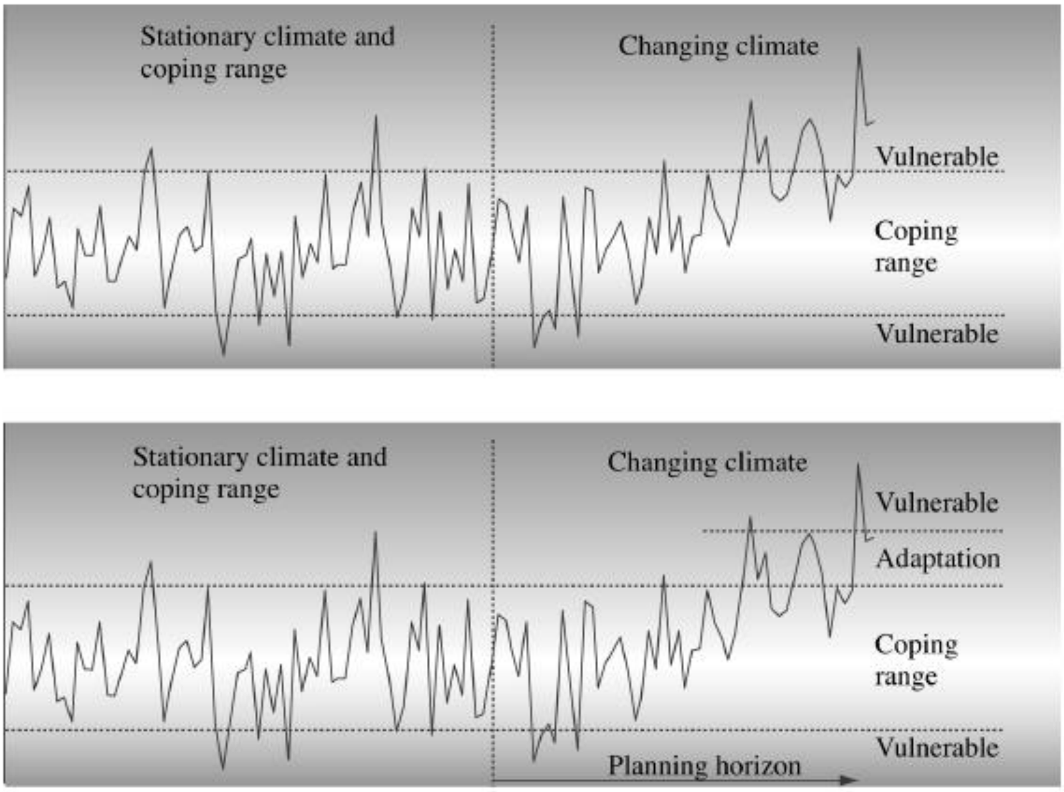

Figure 2: Illustration of the coping range and vulnerability without adaptation (upper graph) and with adaptation (lower graph). Source: Jones and Mearns (2005).

This can lead to consideration of the amount of adaptation needed in order to avoid vulnerability (Figure 3). The term 'capacity' in this figure is best interpreted within CLIMSAVE as coping capacity (as defined above) and adaptation relates to options that either enhance this capacity to deal with climate change, or reduce the sensitivity/exposure of the population. There may be an 'adaptation deficit' in that the system is not able to cope even with current climate variability – for example, it may be vulnerable to current levels of flood risks – and an additional need for further adaptation to cope with increasing risks in future. Whether or not such adaptation is feasible depends on the *adaptive capacity* of the system. Lim et al. (2004) note that it is further possible to differentiate between adaptive *potential*, a theoretical upper boundary of responses based on global expertise and anticipated developments within the planning horizon of the assessment, and adaptive capacity that is constrained by existing information, technology and resources of the system under consideration.

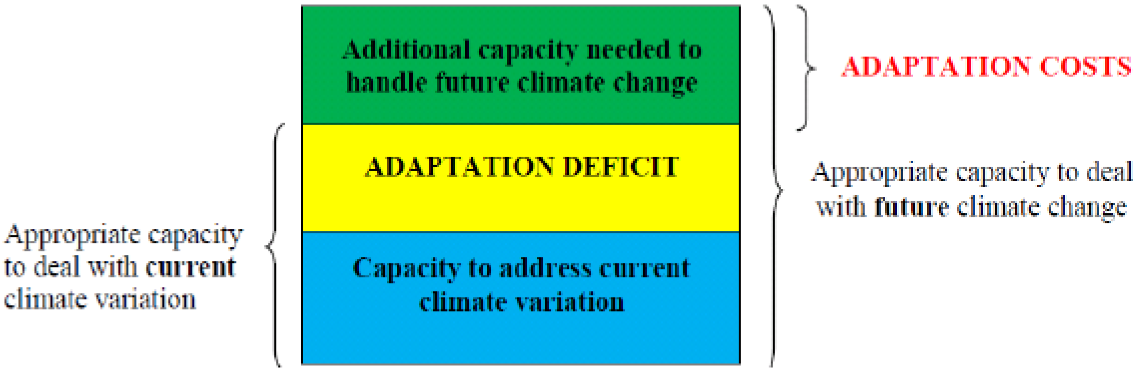

Figure 3: Illustration of the capacity required to deal with current and future climate variations. Source: GermanWatch and WWF (2010), from World Bank (2009).

The concept of adaptive potential could be relevant and useful within CLIMSAVE. Linked to this, we might also be interested in current vulnerability, i.e. before implementation of adaptation options: what is our capacity to adapt in such a way as to create a situation we can cope with. However, adaptive potential and current vulnerability depend on working out 'the best we can do'. This could be assessed in two ways:

- Through a batch run of the platform, calculating the outcomes with all possible combinations of adaptation options, revealing where it is/is not possible to avoid unacceptable outcomes, though this begs the question of how we should determine what 'unacceptable' outcomes are, and how we should deal with trade-offs in choosing adaptation options, costs and residual vulnerability or damage. Such questions are being addressed in CLIMSAVE via the vulnerability methodology.
- As a result of platform user decisions: that is, the final selected set of adaptation options is assumed to be the best combination, given the preferences of the user. Of course this is subjective and would result in different measurements of vulnerability and potential depending on the user, and the real interest may lie in an analysis of why different users reach different decisions.

1.3 Determinants of adaptive capacity

Adaptive capacity has diverse elements encompassing several capacities: to modify exposure to risks associated with climate change, to absorb and recover from climate impacts; and to exploit new opportunities that arise in the process of adaptation. But this means there is a potentially very wide range of contributing factors, covering social, technological, and biophysical factors (e.g. Chambers, 1989; Bohle et al., 1994), and it would be difficult or impossible to measure all of these, or to understand exactly how they combine and interact to determine the capacity to adapt. There is no 'general theory of adaptation' to explain adaptive capacity as simple functions of social and economic characteristics.

There is, however, broad agreement that the principal determinant of the capacity to adapt to climate change, at whatever scale, is likely to be access to resources. Resources can be defined broadly to include intangible features such as social networks and the ability to coordinate actions effectively, especially at the societal scale where institutions for resource management and distribution, and their effectiveness, efficiency and legitimacy are key. Whatever the scale, access is determined by entitlements, which are often the product of external political factors. Adger et al. (2004) list the following determinants of adaptation:

- availability of resources necessary for implementation of adaptation strategies;
- ability to deploy resources in an appropriate manner;
- external constraints on, or obstacles to, the implementation of adaptation strategies;
- recognition of the need for adaptation;
- belief that adaptation is possible and desirable; and
- willingness to undertake adaptation and accept the costs.

Similarly, the IPCC (2001) identifies eight broad classes of determinants of adaptive capacity (Table 2). These determinants vary in detail and relative importance across systems, sectors, regions, and so on (Yohe and Tol, 2001).

Some authors (e.g. Hug and Reid, 2009; Burton et al., 2009) make a distinction between *generic* adaptive capacity and *specific* adaptive capacity. Generic adaptive capacity refers to the inherent or existing capacity of a whole social-economic-environmental system to adapt to climate impacts. Generic capacity is described as a function of: wealth; population characteristics such as demographic structure, education and health; organizational arrangements and institutions and access to technology; and equity. Specific adaptive capacity refers to the capacity of a particular community to cope based on an understanding of the anticipated impacts of human-induced climate change.

Some determinants of adaptive capacity are mainly local while others reflect more general socio-economic and political systems. Smit and Wandel (2006) note that at the local level the ability to undertake adaptations can be influenced by such factors as managerial ability, access to financial, technological and information resources, infrastructure, the institutional environment within which adaptations occur, political influence, kinship networks, and so on. Hertin et al. (2003) consider some of the properties of businesses and management systems that may increase the ability of organisations to adapt to climate change. These include flexible management processes that are able to integrate climate considerations into existing processes, technical capacity in climate change, risk assessment and risk management, and good relationships with key other decision-makers driving the adaptation issues. Different determinants and relationships apply at different levels: adaptive capacity is context-specific, and may be considered at different scales (individuals, organisations, sectors, regions, nations).

Table 2: Determinants of adaptive capacity

Determinant	**CLIMSAVE representation**
The range of available technological options for adaptation.	Fixed range of variables that can be modified in the platform (see Table 1). Numerous specific adaptation options for achieving the changes in these variables have been identified. The cost-effectiveness analysis will consider the costs and benefits of each specific adaptation option under each heading.
The availability of resources and their distribution across the population.	Several land-use resources and several aspects of natural capital are directly represented spatially. Distribution is partly represented in some areas (e.g. water allocation across sectors). Many resources and infrastructures are not modelled in the IA Platform.
The structure of critical institutions, the derivative allocation of decision-making authority, and the decision criteria that would be employed.	Not represented in the platform. To some extent they are implicit in the socio-economic scenarios.
The stock of human capital, including education and personal security.	Population is included. Certain aspects of skills (technologies, efficiencies) and tastes/preferences are represented as adaptation options. Other aspects to be partly incorporated by defining scenario-dependent human capital.
The stock of social capital, including the definition of property rights.	To be incorporated by defining scenario-dependent social capital.
The system's access to risk-spreading processes (e.g. insurance).	Not directly included in the IA Platform. Consider as included within social capital.
The ability of decision-makers to manage information, the processes by which they determine, which information is credible and the credibility of the decision-makers themselves.	Not directly included in the IA Platform. Consider as included within social and/or human capital.
The public's perceived attribution of the source of stress and the significance of exposure to its local manifestations.	Not included in the IA Platform. Consider as included within social capital.

The above suggests that adaptive capacity and coping capacity are rather complex constructs. Yohe and Tol (2001) conclude that many of the determinant variables cannot be quantified and many of the component functions can only be qualitatively described. In CLIMSAVE, the capacities cannot be measured simply as a function of platform inputs or outputs, and will be scenario and context dependent. In Table 2, the column 'CLIMSAVE representation' shows that most of the determinants are not directly reflected in the CLIMSAVE platform, but can potentially be included in a measure of capacity or of capital, to be defined in relation to the socio-economic scenarios. Smit et al. (2001) note that, while scenarios often give economic resources and the level of technology, other determinants for adaptive capacity are often not defined. To address this deficiency, the future evolution of five different types of capitals (natural, manufactured, human, social and financial - see below) within the

CLIMSAVE socio-economic scenarios was discussed at the first set of stakeholder workshops and categorised into five qualitative classes (see Gramberger et al., 2011 – Deliverable 1.2).

The lists given by Adger et al. (2004) and by IPCC (2001) include not only resources and access to them, but also features relating to the recognition of the problem and the willingness to address it. Adaptive capacity in the IPCC assessments is determined by the 'characteristics of communities, countries, and regions that influence *their propensity or ability* to adapt' (IPCC 2001, p. 18, our emphasis). In CLIMSAVE, we could define adaptive capacity in various ways. It could be simply the availability of resources: for example, Adger and Vincent (2005) argue that adaptive capacity "is a vector of resources and assets that represent the asset base from which adaptation actions and investments can be made." Or it could cover the ability to marshal these resources too, as in Lim et al. (2004) who state that "the adaptive capacity inherent in a system represents the set of resources available for adaptation, as well as the ability or capacity of that system to use these resources effectively in the pursuit of adaptation." Or, it could cover all the points: resources, ability to use them, and features associated with recognition of the problem and willingness to act, as in the IPCC definition.

The appropriate choice of which features to include in an index of adaptive capacity may depend on the purpose for which the index is intended. If the idea is to explain why some societies adapt, and others do not, then a fully inclusive approach to defining the capacity is more useful. However, that is not what CLIMSAVE aims to do. Rather, we seek to help decision-makers (platform users) to explore possible adaptation options and their consequences. Hence, an index that includes recognition of the problem and willingness to adapt and bear costs is not necessary; these might be better considered internal to the decision-makers / decision processes. The challenge for CLIMSAVE is to find a way of representing the capacities that helps, but does not second-guess the thinking, and decisions, of platform users.

Brooks and Adger (2005) further note several possible constraints on adaptation, including factors such as ideological or self-interested refusal to accept the existence of a problem, or responsibility for adapting to it. Adaptation options may be culturally, socially or ecologically unacceptable, or prohibitively expensive. They suggest that identifying the "weakest link" of the system in terms of its capacity is an important step.

For CLIMSAVE, it is conceptually clearer to consider these constraints as part and parcel of adaptive capacity than to attempt to account for constraints separately. But the idea of the weakest link is useful, and underlines the fact that adaptive capacity is not a simple sum of component parts: there can be bottlenecks or limiting factors that prevent other capacities from being brought into play. In so far as the stakeholder use of the platform is concerned, we do not need to focus on this: it is up to the platform users to determine what they find both feasible and acceptable. However, our definitions of adaptive capacity – used to signal to users when it seems that capacity may be insufficient for an option – should in principle reflect these issues, for example by rejecting trade-offs between components of adaptive capacity.

Relating adaptive capacity to wealth

The above discussion focuses attention on the relationship between adaptive capacity and resources available to society. This can also be set in the context of relating adaptive capacity to wealth and to its component capital stocks (already noted in Table 2 above). UNECE (2009) notes that "welfare is very closely related to what we think of as wealth, as wealth represents the totality of resources upon which we are able to draw to support ourselves over time. From this it is clear that welfare is a forward looking concept in which what counts is not how well off we are at a point in time, but our prospects for being well off in the future."

Adaptive capacity is closely related to wealth, in its broadest sense, and wealth is closely related to well-being. Vulnerability, in turn, can be thought of as the prospect of suffering a decline in well-being due to impacts that available wealth do not allow us to avoid. So the objectives of measuring vulnerability and adaptive capacity can be set within the wider context of measuring wealth and well-being, and insights from these fields will help in developing measures for CLIMSAVE. This approach will also help to tie the work into the cost-effectiveness analysis within the project, where the cost concept is defined in economic rather than financial terms.

Stiglitz/Sen/Fitoussi (2009) distinguish between assessment of current well-being and assessment of sustainability. Current well-being is related to both economic resources, such as income, and non-economic aspects of peoples' lives (what they do and what they could do, how they feel, and the natural environment they live in). Whether these levels of well-being can be sustained over time depends on whether stocks of capital that matter for our lives (natural, physical, human, social) are passed onto future generations.

So it is possible to think of the flow of benefits to human societies – "consumption", in a wide sense – as deriving from the use of a number of capital stocks, together forming the "wealth" of the society. Development can then be viewed as a process of building and managing a portfolio of capital assets. The key challenges are:

- balancing consumption and wealth: deciding how much to save versus how much to consume; and
- balancing the composition of the asset portfolio: how much to invest in different types of capital, including the institutions and governance that constitute social capital.

There is some variation in the specific stocks identified in the literature, but the five types of capital defined by Porritt (2006) are commonly encountered. They are:

Manufactured (or produced or physical) capital consists of material goods -- tools, machines, buildings and other forms of infrastructure – that contribute to the production process but do not become embodied in its output.

Natural capital is any stock of energy and matter that yields valuable goods and services. This includes resources, some of which are renewable (e.g. timber, grain) and others that are not (fossil fuels, minerals). Natural capital also includes sinks that absorb, neutralize or recycle waste.

Human capital goes beyond simple conceptions of the labour force and includes health, knowledge, skills and motivation.

Social capital consists of the structures, institutions, networks and relationships that enable individuals to maintain and develop their human capital in partnership with others, and to be more productive when working together than in isolation. It includes families, communities, businesses, trade unions, voluntary organizations, legal/political systems and educational and health institutions.

Financial capital represents a claim on other forms of capital: it has no intrinsic value, but represents the ability to secure rights to traded forms of natural, human, social or manufactured capital. Recognising financial capital allows us to consider relationships with the world beyond the boundaries of a specific analysis (for example, when we focus on Europe, we recognise that the financial capital held by Europeans allows other capitals to be bought in from the rest of the world) and also to take account of distributional features within the area of analysis (for example, recognising that certain countries or regions face heavy financial debts and must surrender significant parts of the services of their other capital stocks in order to finance these debts).

UNECE (2009) notes that, to reach its full potential, the capital approach requires measurement of all capital stocks using a common unit. However, developing a single measure for each capital type is very difficult. The only obvious choice of unit – money – is problematic:

- It is hard to determine all of the ways in which capital contributes to well-being, and ways that cannot be identified obviously cannot be valued.
- Valuation remains difficult even where effects can be identified, due to market failures and to limitations of valuation methods.
- There are ethical concerns regarding the use of monetary valuation, in particular as regards treatment of equity and distributional issues (though methodological adjustments are possible to deal in part with these concerns).
- Capitals are not perfectly substitutable: if some services flowing from a capital stock have no substitutes, the stock can be defined as ‘critical’ (i.e. essential) capital. Critical natural capital is the most often discussed. If critical capital stocks exist, it is not possible to use a single monetary aggregate to sum across all capital types to reach totals (see Figure 4), though marginal valuation may still be possible provided critical stocks are intact.

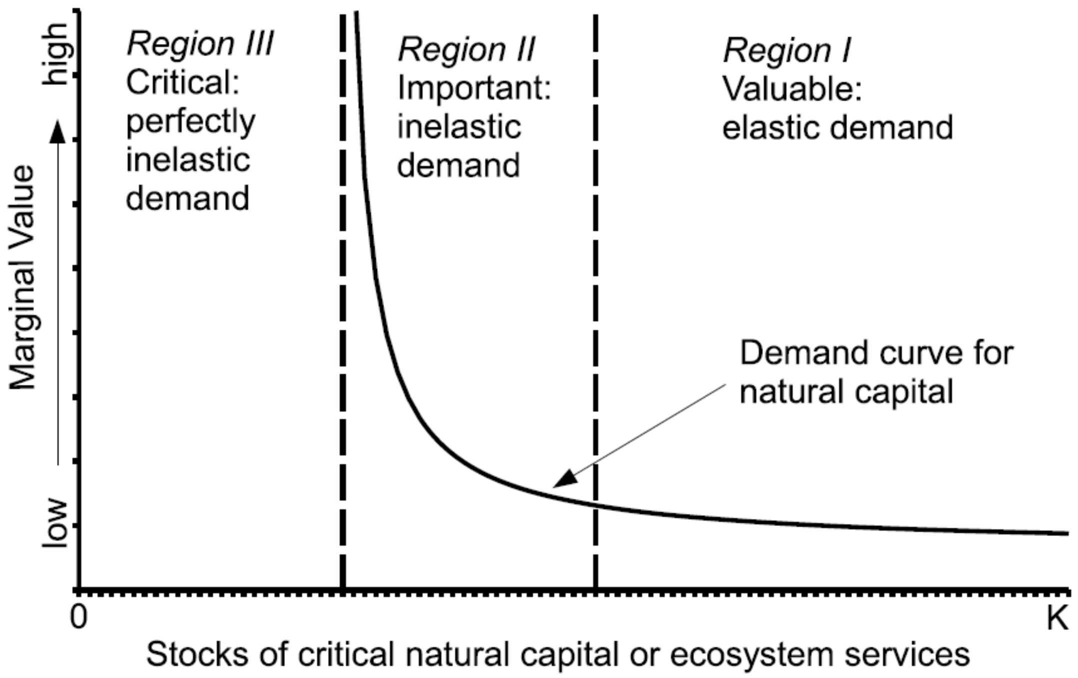

Figure 4: The demand curve for natural capital (Farley, 2008).

So, arguably, not all capital stocks can or should be measured in monetary terms. Additional indicators of critical capital stocks measured in physical units can be used (although some of the above concerns will also apply to non-monetary measurements). Yet many stocks and/or the goods and services they provide are bought and sold in markets and there is good reason to argue that the market value assigned to these assets (or goods and services) is a reasonable approximation of their contribution to well-being. This is most likely to hold for financial and produced capital, and can also apply to those elements of natural capital and related products that are commonly traded in the market, including timber, fish, minerals and energy. It applies as well to the output of human capital (labour) insofar as it is used in the market. However, corrections can be needed, for example, to deal with the distorting effects of government subsidies, externalities, or other market failures. The necessary adjustments may be large, where these market failures are important – for example, the climate change damage caused by burning fossil fuels.

It must be stressed, however, that considering wealth, broadly defined, as the relevant top-level indicator does *not* imply a focus on GDP, even if monetary measures are used. Indeed, UNECE (2009) points out that "Only a few common policy-based indicators cannot be reconciled with the capital approach. Among these, GDP per capita is the most important. It is simply not possible to justify selection of any indicator based on GDP as a sustainable development indicator from the capital perspective".

Furthermore, though economic wealth is an important measure of sustainable development from the capital perspective, it must be supplemented to form a practical and complete indicator set. Additional indicators are needed to reflect the well-being effects of capital that cannot or should not be captured in a market-based monetary measure, taking into account limited substitutability among different forms of capital, the existence of critical forms of capital and the fact that well-being is derived from more than market consumption. Indicators must also take into account flows as well as stocks, because flows determine changes in stocks from one period to the next.

1.4 The role of adaptive capacity in CLIMSAVE

A measure of adaptive and/or coping capacity is not directly necessary for the IA Platform to operate. So we need to ask why we want to measure or model these capacities. There are three main possible uses:

1. Adaptive capacity as a constraint on possible adaptation options within the platform. This derives from two ideas:
    a. each option has certain requirements (costs, skills, technologies) that may not be available in all scenarios; and,
    b. these requirements are cumulative and so choice of some adaptation options may 'use up' the capacity needed to take further adaptation options.
2. Coping capacity as an additional feature complementing the modelled outcome (i.e. the situation arising after implementation of the adaptation options represented in the platform) and facilitating the conversion of the modelled physical impacts to measures of their significance for humans (vulnerabilities). This derives from the ideas that:
    a. the platform models average conditions over a time slice (decade) and does not represent extreme events and their impacts directly; and,
    b. the severity of impacts expected over a time slice will not only depend on a population's exposure and sensitivity to a given impact, but also on the residual capacity to adapt to the new conditions, or cope with extreme events.
3. Adaptive capacity as a modelled result of the platform: the observed ability to reduce vulnerability in the future to avoid vulnerability via appropriate choices of adaptation options.

The first and second are rather different concepts, though related. The crucial distinction is a temporal one: in (1) above we are dealing with the capacity *now and in the short term future* to implement actions that modify expected *mid to long term future* outcomes: it is the capacity *prior to* the adaptation options represented in the platform. In (2), we focus on the *future* capacity to carry on adapting and/or coping with the conditions *that result from* the options (and scenarios) modelled in the platform. This distinction is blurred in the real world (where adaptation may be seen as an ongoing process rather than a set of discrete actions prior to impacts) but is a useful distinction for CLIMSAVE because of the sequential aspect of the modelling: scenarios plus adaptation options followed by time-slice simulation followed by future results. The coping capacity will form an important input to the vulnerability hotspot methodology, allowing us to bridge the gap between the average conditions modelled in the platform, and the residual impacts on human populations taking account of their coping abilities.

The third is quite different. Here, we are interested in whether or not it is possible to avoid vulnerable outcomes, within the platform, and this could be determined via a batch run of all the possible combinations of options, coupled with a definition of what outcomes are unacceptable. In doing this, we may wish to take into account both of the other capacity concepts – that is, constrain adaptation options according to adaptive capacity (1), and determine vulnerabilities by combining modelled physical impacts with modelled coping capacity (2). This could be interesting for an academic analysis of a scenario, but could not be implemented in the version of the IA Platform designed for stakeholders due to long runtime issues. The role of this platform is to allow users to rapidly explore alternative options and "what if" situations rather than being a predictive or prescriptive tool.

This third concept is not quite the same as the 'unrealistic adaptation' discussed by Füssel and Klein (2006), that relies on a degree of clairvoyance in picking the best possible combination of adaptation options (see Figure 5). In CLIMSAVE, we have a degree of autonomous adaptation built into the meta-models, because decisions such as crop choice are modelled and climate-dependent. In addition, the platform users are faced with a number of planned adaptation options. The extent to which these are 'feasible' or 'unrealistic', in Füssel and Klein's terms, is scenario-dependent. Allowing the platform users to explore the consequences of different combinations of options is not quite the same as endowing them with clairvoyance regarding actual outcomes. Rather, this is a matter for the uncertainty analysis within CLIMSAVE.

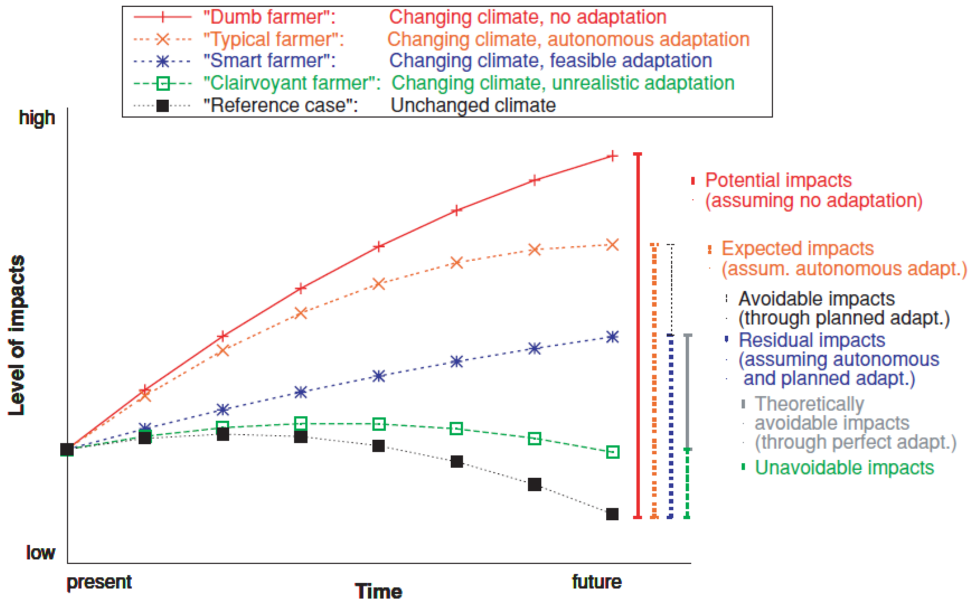

Figure 5: Different grades of agricultural intelligence. Source: Füssel and Klein (2006).

Adger et al. (2004) note that "The capacity to adapt, that most fundamental aspect of human behaviour is, by its opportunistic nature, so situation-specific and dynamic that predictive understanding may be extremely difficult to achieve. It may well prove impossible to model the adaptive process from "first principles" with the science of adaptation limited to description and eschewing prediction, an interesting philosophical dilemma."

We must be wary, therefore, of setting the bar too high, and should bear in mind that the rationales for measuring adaptive and coping capacity in CLIMSAVE are firstly to help platform users to remember the existence of such constraints when exploring the adaptation options, and secondly to enrich the interpretation of the exploratory scenarios for future time slices by introducing the idea of the capacity to cope with climate change. Precise measurement is not possible at present, and a qualitative approach is likely to be most appropriate. This will feed through to the methodology for identifying vulnerability hotspots which will combine quantitative and qualitative indicators to qualitatively assess overall vulnerability.

Jumping ahead to the conclusions of this paper, the definition of adaptive capacity as a constraint on options will remain loose in the platform. Platform users' choices will not actually be constrained by the availability of adaptive capacity: strictly limiting the options on the basis of modelled capacities would be too restrictive, leaving too few options open to the users. Instead, users will be warned that their decisions might be unrealistic in the light of available capitals in the scenario. Another rationale is that the CLIMSAVE platform only represents six sectors, and one 'adaptation option' would be to enhance the capitals available to these sectors by drawing on other sectors. Although this is in principle reflected in the definitions of capitals via socio-economic and climate scenarios, the limits are fuzzy, and there would be little justification in setting hard-and-fast boundaries within the platform.

Coping capacity, the capacity to cope or adapt spontaneously to conditions within a future time slice, is not represented by the meta-models in the IA Platform and therefore needs to be incorporated separately. The platform models the land use and various outputs associated with average conditions in the future time slices, but does not directly reveal the ability of future populations to deal with these conditions, their variability and associated extreme events. It is not possible to develop a complete model of coping capacity and how adaptation influences the severity of impacts and the vulnerability of future populations to particular risks. However, we can develop indices of this capacity that can be of use in interpreting the outputs of the platform. This must be understood in the context of the creation and interpretation of exploratory scenarios – we are not formally modelling how populations cope with changed conditions, and the aim is to enhance the storylines, rather than to predict outcomes.

For reasons of clarity, in particular to distinguish between them, we will refer to the first form as *adaptive capacity* (the ability to take actions now that result in adaptation to possible future climates by improving coping capacity, reducing exposure and/or reducing sensitivity) and the second form as *coping capacity* (the ability in the future to adapt to / cope with the climate, exposure and sensitivity actually experienced).

1.5 Summary and workplan

Within CLIMSAVE, we should consider as (potential) *adaptation* only those options that are available to platform users, or autonomously built into the meta-models and scenarios. We need to consider, separately, the ability to adapt spontaneously or cope with future situations that arise as a result of these adaptation options. In both cases, we have to take account of resources available to human populations, and break this problem down by considering resources/wealth as composed of five capital stocks.

The first part of the adaptive capacity work involves determining how the adaptive capacity under each scenario may restrict the feasible range of adaptation choices from among the full set represented in the platform.

The second part relates to *coping* within future time-slices, and is not directly predicted by the platform. The adaptation options in the platform reduce vulnerability by decreasing sensitivity, and/or decreasing exposure, and/or increasing coping capacity. We need to derive an expression of coping capacity that is based on the scenarios and the capitals, after accounting for the adaptation options selected by a platform user.

A possible third part lies in the recognition that actual adaptation may be less than adaptive capacity. The adaptive capacity is the maximum amount of adaptation possible, for any given combined socio-economic and climate scenario. This can be calculated by testing all the different possible combinations of adaptation options, taking into account capital constraints and the impacts on coping capacity. This is not directly part of the adaptive capacity work in the context of developing the IA Platform (it will use the Platform but will not be used within it) and will be further developed in the context of later CLIMSAVE work streams on cross-sectoral comparison and cost-effectiveness.

The first part of the work depends only on an understanding of what the adaptation options are (within CLIMSAVE) and developing a model of how they are constrained within any given socio-economic scenario (or potentially, any given combination of socio-economic and climate scenarios). It does not directly depend on the definition of vulnerability.

Measuring coping capacity in the second part of the work presents a more significant challenge. The ability to cope with climate change and reduce vulnerability is closely related to the definition of vulnerability. The implementation of the methods set out in this paper will take place alongside the development of the methodology for identifying vulnerability hotspots, and adjustments may be required in an iterative process of indicator development.

2. Developing indicators of adaptive capacity

Indicators of adaptive and/or coping capacity must be based on characteristics of societies and environments. These can be measured directly, modelled via the IA Platform or projected as part of scenarios. As discussed above, capacity is closely related to access to resources and the structure of societies, including human capabilities and technologies. There are many similarities with concepts of wealth (broadly defined) and sustainability: we have defined adaptation as 'drawing on resources in order to avoid vulnerability', and this is almost the same as 'drawing on wealth to ensure sustainability'. So indicators of wealth and sustainable development can be used to inform development of indicators for adaptive/coping capacity.

Early in the CLIMSAVE work on this topic, we decided to focus efforts on describing adaptive and coping capacity in terms of the capital stocks available to human populations (Omann et al., 2010). This has the advantage of linking our adaptive capacity framework to an existing conceptual framework with substantial research and data available. The separate identification of natural capital as one of the capital types fits well with the CLIMSAVE IA Platform that models land use and several features of ecosystem services related to natural capital, offering scope to link our measurement of that capital type directly to platform outputs.

For natural capital, Weber (2010) notes two different approaches to expressing the value of the natural world.

- **Bottom-up** approaches focus on valuation of individual ecosystem services via micro-economic valuation studies and CBA. While useful at the local scale, there are theoretical and statistical difficulties for aggregation, and using this approach to make overall value assessments can be sensitive to assumptions regarding discount rates and opportunity costs.
- **Top-down** studies focus on the sustainable macro-economic benefits of ecosystems as the income made possible by ecosystem services, as analysed via input-output analysis. This also has the advantage of following the distribution of ecosystem service rents through the whole production chain. However, the fundamentally linear and additive nature of input-output models may not be able to reflect the full complexity of ecosystem-economy links.

In CLIMSAVE, we could adopt either approach. The spatial nature of the IA Platform lends itself well to bottom-up assessments, based on characteristics of individual grid cells, presented at that level or aggregated to NUTS 3, NUTS 2 or national levels. However, the adaptation options are set across the whole map (i.e., Europe or Scotland, depending on the case) and the socio-economic scenarios are similarly determined at the aggregate level. We will likely need a combined approach, whereby scenario features, adaptation options and the broad components of adaptive capacity are determined at aggregated levels, then the implications are investigated at a finer resolution.

The other forms of capital (human, social, manufactured, financial) are either partly modelled, or not modelled at all, within the platform. To develop an adaptive capacity model, these forms must either be built into the socio-economic scenarios, or be modelled separately drawing on those scenarios (for example by correlation with GDP, which is included in scenarios). They could be represented directly (via variables headed 'human capital' and so on), or they could be constructed based on other variables that are either component parts of the capital stock, or reliable indicators of the stock. The remainder of this section explores the options.

2.1 Indicators of sustainable development

Sustainable development can be defined as non-declining *per capita* wealth over time (United Nations et al., 2003). Or, more subtly, if sustainable development is increasing well-being over a very long time (UNECE 2009), then while stable or growing total wealth per capita is no guarantee of sustainable development, the opposite is a guarantee of its absence: with declining per capita capital stocks, well-being must eventually deteriorate and sustainable development will not be possible (Hamilton and Ruta, 2006).

The best known, and most widely used, indicator of economic progress is (growth in) gross domestic product (GDP). This is a broad measure of the value of production occurring within a nation's borders. However, as noted above, GDP is inadequate as an indicator of development, welfare or wealth. For example, GDP treats both the production of goods and services and the value of asset sales as part of the product of the nation. Thus, a country can enjoy high GDP by depleting stocks of forests and fossil fuels, for example, but this would not be sustainable, unless the proceeds ('rents') were reinvested in other forms of capital.

GDP remains an important and widely recognised indicator, and measurements are available at national and regional (NUTS2, NUTS3) scales. For these reasons it is included in the socio-economic scenarios and as an input to the meta-models. But there are several methods and initiatives for improved measurements of economic activity and GDP itself is not adequate for assessing the results of adaptation nor the capacity to undertake it. Key developments of relevance to Europe include (Weber 2011):

- Beyond GDP Conference (2007), EC Communication (2009) and Parliament Resolution (2011);
- Potsdam initiative and the resulting TEEB studies;
- The Stiglitz/Sen/Fitoussi report (2009) on the measurement of economic performance and social progress;
- Simplified Ecosystem Capital Accounts fast track project in Europe (2009-2012): the EEA (for ecosystems) and Eurostat (for economic sectors);
- SEEA revision for 2012/13: to include a special volume on ecosystem accounts and valuation.

The Beyond GDP initiative is about "developing indicators that are as clear and appealing as GDP, but more inclusive of environmental and social aspects of progress." Improved indicators are needed to address global challenges such as climate change, poverty, and resource depletion. In August 2009, the European Commission released its Communication "GDP and beyond: Measuring progress in a changing world" (COM(2009) 433 final). The Communication outlines an EU roadmap with five key actions to improve indicators of progress:

1. Complementing GDP with environmental and social indicators.
2. Near real-time information for decision-making.
3. More accurate reporting on distribution and inequalities.
4. Developing a European Sustainable Development Scoreboard, including thresholds for environmental sustainability.
5. Extending National Accounts to environmental and social issues.

Work under the first item is to include: a comprehensive environmental index based on the major strands of environmental policy: climate change and energy use; nature and biodiversity; air pollution and health impacts; water use and pollution; waste generation and use of resources. In addition to this comprehensive index on harm to, or pressure on, the environment, there is potential to develop a comprehensive indicator of environmental quality, e.g., showing numbers of European citizens living in a healthy environment. Work is also planned on indicators that capture the environmental impact outside the territory of the EU and on improved measures of the Ecological Footprint. Indicators of quality of life and well-being are being researched.

In the summer of 2011, MEPs approved legislation on environmental economic accounts, requiring Member States to report to Eurostat on air emissions, material flows and environmental taxes. Further requirements to report e.g. on the use of water and forest resources may be added in the future, following a review. MEPs also adopted a non-binding resolution on "Beyond GDP", supporting the Commission's work towards supplementing economic measures with social and environmental indicators and calling for concrete and consistent proposals for indicators that can be monitored by Eurostat.

So this is work in progress, and there may be scope for work in CLIMSAVE to adapt to imminent developments at the European scale. In the meantime, we can draw on existing work. Table 3 shows the most common sustainable development indicators, as found in research for UNECE (2009). The focus of countries in establishing sustainable development indicator sets to date has been generally on meeting the information needs of a national sustainable development strategy, and not based on an explicitly defined conceptual framework, leading to somewhat random assemblages of indicators.

Table 3: Most common sustainable development indicators in policy-based sets (source: adapted from UNECE, 2009). Indicators in bold are included within the CLIMSAVE IA Platform. Indicators in *bold italics* may be measurable within the platform or are reflected in inputs to the platform.

Rank	Broad indicators	Number of indicator sets where found
1	***Greenhouse gas emissions***	***22***
2	Education attainment	19
3	**GDP *per capita***	**18**
4	Collection and disposal of waste	18
5	***Biodiversity***	***18***
6	Official development assistance	17
7	Unemployment rate	16
8	Life expectancy (or Healthy Life Years)	15
9	***Share of energy from renewable sources***	***15***
10	Risk of poverty	14
11	Air pollution	14
12	Energy use and intensity	14
13	***Water quality***	***14***
14	General government net debt	13
15	Research & Development expenditure	13
16	***Organic farming***	***13***
17	**Area of protected land**	**13**
18	Mortality due to selected key illnesses	12
19	Energy consumption	12
20	Employment rate	12
21	Emission of ozone precursors	11
22	Fishing stock within safe biological limits	11
23	**Use of fertilisers and pesticides**	**10**
24	Freight transport by mode	10
25	Passenger transport by mode	10
26	**Intensity of water use**	**10**
27	**Forest area and its utilisation**	**10**

UNECE (2009) proposes several extensions to total wealth indicators, including:

- Separate monetary indicators of financial capital, produced capital, human capital, natural capital and social capital, measured in real per capita terms to address the concern about the non-substitutability of capital stocks at the margin.
- Determination of "critical" capital, insofar as is possible.
- Accounting for non-marketed contributions to well-being.

UNECE goes on to develop a 'small set' of 28 indicators (fewer than in most policy-based sets), argued to represent a "theoretically robust, substantially complete and policy-relevant approach to measuring sustainable development" (Table 4).

Table 4: A proposed small set of sustainable development indicators (source UNECE 2009). Indicators in bold are outputs of the IA Platform and those in *bold italics* could be inferred from CLIMSAVE outputs.

Indicator domain	Stock indicators	Flow indicators
Foundational well-being	Health-adjusted life expectancy	Index of changes in age-specific mortality and morbidity (place holder)
	Percentage of population with post-secondary education	Enrolment in post-secondary education
	Temperature deviations from normal	Greenhouse gas emissions
	Ground-level ozone and fine particulate concentrations	Smog-forming pollutant emissions
	Quality-adjusted **water availability**	***Nutrient loadings to water bodies***
	Fragmentation of natural habitats	***Conversion of natural habitats to other uses***
Economic well-being	Real *per capita* net foreign financial asset holdings	Real *per capita* investment in foreign financial assets
	Real *per capita* produced capital	Real *per capita* net investment in produced capital
	Real *per capita* human capital	Real *per capita* net investment in human capital
	Real *per capita* natural capital	Real *per capita* net depletion of natural capital
	Reserves of energy resources	Depletion of energy resources
	Reserves of mineral resources	Depletion of mineral resources
	Timber resource stocks	***Depletion of timber resources***
	Marine resource stocks	Depletion of marine resources

__Relevance to CLIMSAVE__

The UNECE indicators cannot all be used directly within the CLIMSAVE platform. In Table 3 we have highlighted in **bold** broad indicators for which measures can be found in the CLIMSAVE platform. Those in ***bold italics*** may be measurable or are reflected in inputs to the platform (e.g. GDP per capita, which is a feature of the socio-economic scenarios, not a platform output). In Table 4, those highlighted in **bold** are CLIMSAVE outputs. Those in ***bold italics*** could be inferred from CLIMSAVE, though as a static model it is not well suited to measurement of flow indicators.

Although several indicators in this set are potentially useful, the majority are not covered in CLIMSAVE as the platform does not seek to model sustainability as such. Rather, the IA Platform focuses on adaptation to climate change within the context of six land use sectors. Missing sustainability indicators could be provided via the scenarios, but it may be more useful to find indicators which focus more narrowly on the sustainability of land use or ecosystem services.

The UNECE set does, however, include indicators for the different capital stocks. The methods of their calculation are not all fully determined, in particular for social capital. Nevertheless, this part of the UNECE proposals could be useful as a basis for developing capital measures as part of the adaptive/coping capacity methodology. This is addressed in section 2.2.

2.2 Bottom-up indicators of individual capital stocks

One obvious way in which we could advance the model of adaptive/coping capacity is to build up from separate bottom-up assessments of individual capital stocks. Relating these to adaptive capacity or to wealth is then challenging, but for broad comparative indicators of capacity this approach may be adequate. Besides, a top-down approach leaves a significant challenge in relating feasible adaptation measures to their capital requirements, and some forms of bottom-up measurement may be better in this respect.

Natural capital

Natural capital is any stock or flow of energy and matter that yields valuable goods and services. This includes resources, some of which are renewable (e.g. timber, grain) and others that are not (the most well-known these days being fossil fuels). Natural capital also includes sinks that absorb, neutralize or recycle waste.

UNECE (2009) states that for natural capital, there are several flow indicators that are important. For non-critical forms of natural capital – that is, those that can be meaningfully aggregated together and measured in monetary terms – the fundamental indicator is the aggregate value of net depletion. Physical stock indicators include timber resources, marine resources, energy and minerals.

Separate physical flow indicators are included for each critical form of natural capital identified:

- A reasonably stable and predictable climate: Temperature deviations from normal, Greenhouse gas emissions;
- Air that is safe to breathe: Ground-level ozone and fine particulate concentrations, Smog-forming pollutant emissions;
- High-quality water in sufficient quantities: Quality-adjusted water availability, Nutrient loadings to water bodies;
- Intact natural landscapes suitable for supporting a diversity of plant and animal life: Fragmentation of natural habitats, Conversion of natural habitats to other uses.

In CLIMSAVE the last two of these can be measured. But as discussed in Section 2.6 there are new developments in spatial mapping of natural capital and ecosystem services that we can adapt.

Manufactured capital

Manufactured capital (also termed physical capital or produced capital) consists of material goods -- tools, machines, buildings and other forms of infrastructure – that contribute to the production process but do not become embodied in its output.

For manufactured capital, the fundamental flow indicator is real per capita net investment. This is the value of new investment in manufactured capital during a period net of the depreciation of the existing manufactured capital stock, per capita. The stock variable is real per capita manufactured capital (UNECE 2009).

Financial capital

Financial capital reflects the productive power of the other forms of capital and enables them to be owned and traded. However, unlike other types, it has no intrinsic value – its value is purely representative of natural, human, social or manufactured capital.

Its role within measures of wealth or of adaptive capacity is to reflect the ability to draw in these real resources from other areas – or, conversely, the obligation (debt) to supply other areas with real resources from within the area. So for financial capital, at a national level, the fundamental flow variable is net investment in foreign financial assets, and the stock is real per capita net foreign financial asset holdings (UNECE 2009). Regional, local or sectoral equivalents could be described, at least in principle.

Human capital

Human capital includes health, knowledge, skills and motivation, as well as an individual's emotional and spiritual capacities.

Markandya and Pedroso-Galinato (2005) note that human capital can be measured in direct or indirect ways: direct measurement of human capital relates educational attainment with labour productivity; while indirect measurement can occur through the 'intangible capital residual' obtained as the difference between a country's total wealth and the sum of produced and natural assets. Part of the intangible capital residual captures human capital in the form of raw labour and stock of skills. Other parts include social capital (see below).

UNECE (2009) includes monetary and non-monetary measures of human capital. The fundamental flow indicator for human capital is net investment: the value of the increase in human capital during a period (education, training, health improvements) less its depreciation (obsolescence of skills, retirement, unemployment, morbidity, mortality). The stock variable is the real per capita human capital, although the methods of its valuation (based on Jorgenson and Fraumeni, 1987; Jorgenson and Fraumeni, 1992; Wei, 2004) are noted to "remain experimental and may not yet meet the standards of official statistics."

The two core dimensions with non-monetary indicators are educational achievement and health status. The stock indicators are 'percentage of the population with post-secondary education' and 'health-adjusted life expectancy'; the associated flow indicator for education is the rate of enrolment in post-secondary institutions, while a place-holder is used for the health flow variable.

Alternatively, human capital can be measured in a bottom-up fashion via various indicators. Table 5 describes human capital indicators, which have been compiled from different sources and have been applied in various fields (natural sciences, management, population statistics). Indicators can be broadly categorized into demographic components (which also apply to social capital), employment situation, formal and informal education, information and knowledge, attitudes, governance, and health.

Social capital

Social capital consists of the structures, institutions, networks and relationships that enable individuals to maintain and develop their human capital in partnership with others, and to be more productive when working together than in isolation. It includes families, communities, businesses, trade unions, voluntary organizations, legal/political systems and educational and health institutions.

In top-down assessment of wealth and capital, social capital is also included in 'intangible capital residual'. But identifying flow indicators for the stock is difficult. UNECE (2009) uses place-holders rather than specific social capital indicators, stating "further research will be necessary before social indicators consistent with the capital approach and relevant to sustainable development policy across a large number of countries can be proposed."

Social capital indicators need to encompass all relevant scales (micro, meso, macro), as well as the processes underlying its establishment (bridging and bonding). Demographic factors are further included in Table 6 as a basis for assessing social capital.

Table 5: Human capital and its indicators (Source: own compilation).

Indicator categories	**Possible indicators of human capital**					
Demographic	Demographic structure *(population size/density, age, male/female, dependency ratio, etc.)*	Grade of urbanization	Class structure *(annual household income, education level, housing situation etc.)*	Level of development *(education level, link to manufactured capital)*	Seasonal/ permanent residents	Dependency ratio (relation working, non-working population)
Employment	Unemployment rate	Gender balance	Level of qualification	Income/ income structure		
Education	Educational commitment *(total education spending, per education type, private/public)*	Education quality *(literacy rate)*	Training/ lifelong learning *(hours of training per year)*	Years of education *(minimum required, total)*		
Information and knowledge	Access to information *(internet access, libraries, etc.)*	Skills/ life experience *(average total years of work/ education)*	Skills specific to local environment	Computer skills *(no of individuals never used a computer)*		
Attitudes	New ideas-design, innovation	Willingness to undertake adaptation	Understanding of anticipated impacts	Ability to appropriately deploy resources	Cultural norms, values, risk perceptions	
Governance	Exchange of innovations in adaptation with other populations	Managerial ability	Prevailing policy and institutional framework, participation	Diversification of human capital	Regional cooperation, National adaptation strategy *(existence of a NAS)*	
Health	Health spending/ governance (*public health expenditure as % of GDP)*	Nutrition (*calorie supply per capita)*	Life expectancy *(at year of birth)*	Sanitation	Health care personnel per inhabitants	Healthy Life Years, Disability Free Life Expectancy

Table 6: Social capital and its indicators (Source: own compilation).

	Micro-Indicators ***(individual level, close relationships with strong emotional ties)***	**Meso-Indicators** ***(characteristics of neighbourhoods, or communities that may affect social capital within those areas)***	**Macro-Indicators** ***(level of major communities and values: political, ideological, social, cultural and spiritual context)***
Demographic factors	Age, sex, health, family characteristics (e.g. marriage), resources (education, employment), attitudes and values, characteristics of living area.		
Bonding	Number of close friends and confidants	Number of acquaintances and friends	Frequency of attendance of likeminded communities (politics, religion, etc.)
	Structure of the close relations (where are the close confidants [family, friends, work, etc.], time spent with them, etc.)	Structure of the acquaintance-relations (where are they [family, neighbours, clubs, church, workplace, civic associations, virtual communities, etc.], time spent with them, etc.)	Type of likeminded communities and common beliefs which give a sense of community and a feeling of belonging (e.g. politics, ideologies, work, art, music, spirituality, etc.)
	Trust in close confidants	Trust in neighbours, workplaces, etc.	Evolution of common norms, rules (formal)
		Community engagement (group involvement, informal socializing, social trust, giving and volunteering, participation in activities, civic engagement, membership in voluntary associations)	Transparency
		Willingness to cooperate with other communities, etc.	
Bridging	Structure of the close relations (where are the close confidants [family, friends, work, etc.], time spent with them, etc.)	Willingness to cooperate with other communities, etc.	
		Information (news of internet, daily newspaper reading, TV watching, internet-based “virtual communities”)	
		Community engagement (group involvement, informal socializing, social trust, giving and volunteering, participation in activities, civic engagement, membership in voluntary associations)	

Relevance to CLIMSAVE

The review above suggests that a bottom-up assessment of capital types may be feasible. For human, social and natural capital we lack clearly defined measurements in a single unit (monetary or otherwise) but there are several indicators that could be used as proxies for the capital stocks.

Selection could be guided by the wish to have capital indicators for which data are available at reasonably fine spatial resolutions (ideally NUTS 3). We may also be interested in the ability to correlate the measures with features that are included in the socio-economic scenarios (for example GDP and population) though there is also the option of including capital stocks directly as features of the scenarios. For natural capital, we could aim instead to use indicators that are directly modelled within the platform.

There remains a substantial challenge in relating the capital measures to adaptive capacity (the ability to carry out the adaptation options) and coping capacity (ability to cope with future climate change).

2.3 ATEAM framework

For the ATEAM project, Schröter et al. (2004) examined different ways of assessing adaptive capacity. Initial attempts took the form of discussions with stakeholders relating to thresholds of adaptive capacity. However, this did not yield results that could be integrated with the ATEAM quantitative maps of potential impacts. This led the research team to develop an index of adaptive capacity that would be dynamic, quantitative and spatially explicit: present-day and future estimates of adaptive capacity based on, and consistent with, the scenarios produced by the IPCC in its Special Report on Emissions Scenarios (SRES; Nakicenovic and Swart, 2000). The adaptive capacity model and its results had to be both scientifically valid and comprehensible to stakeholders. The resulting index of adaptive capacity "is an index of the macro-scale outer boundaries of the capacity of a region to cope with changes" that does not include individual abilities to adapt.

- The first step was to choose determinants of adaptive capacity and to select indicators for these determinants.
- Developing scenarios of adaptive capacity required future projections of the data. These were available in the SRES scenarios for population and GDP; other data were collected for 1960-2000 at the NUTS2 level.
- Functional relationships between the indicators and population and GDP data were developed, and indicator scenarios were then extrapolated using the historical functional relationships between the respective indicator and population and GDP.
- A conceptual framework was developed to aggregate indicators to a generic index of adaptive capacity in three steps using a fuzzy logic approach. For future scenarios of the index of adaptive capacity, the projected indicator data were aggregated per scenario and time slice.

The selection of determinants of adaptive capacity was guided by a set of questions (Table 7) and a final compromise struck taking into account complexity and availability of data.

Particular indicator values were classified as low, medium or high, and used to define membership functions for each indicator. Inference rules were then developed for stepwise aggregation of indicators (if literacy rate is high and enrolment ratio is medium, then knowledge is high; and so on). Fuzzy set theory then produces a value between 0 and 1 for the overall adaptive capacity index. The aggregation was performed in three steps: from the list of indicators to the six determinants, which are then aggregated into the three components, which are then aggregated into an adaptive capacity index (see Figure 6).

Table 7: Questions used in the ATEAM approach. Source: Schröter et al. (2004).

Guiding question	Related components of adaptive capacity	Related determinants of adaptive capacity
Is awareness building encouraged in society?	Awareness	Equality
Is society aware of the issue and does it perceive it as a problem?	Awareness	Knowledge
Is society equipped to address the problem?	Ability	Technology, Infrastructure
Is society constrained to take action?	Action	Flexibility, Economic power

Using this methodology, maps of the generic adaptive capacity index for the four SRES scenarios and four time slices for each of the scenarios were produced, leading to maps of adaptive capacity. Further research suggestions include sensitivity analysis of the membership functions in the fuzzy model and of the indicators, increasing the number of independent variables for the indicator scenario development or using more variables for the regression analysis (multivariate analysis), and developing adaptive capacity indices that are specific for particular sectors or climatic events, and exploring the possibility of 'validation' of this adaptive capacity approach using historical data of past hazards in regional comparison.

All usual and well-documented problems with using indices apply to this way of assessing adaptive capacity as well. Schröter et al. (2004) report their "impression from the last stakeholder workshop…that stakeholders show little interest and trust in this indicator. As individuals they are concerned with their individual adaptive capacity, which is not captured by the index. They were however willing to see this as a first attempt to capture the regional context in which they make decisions."

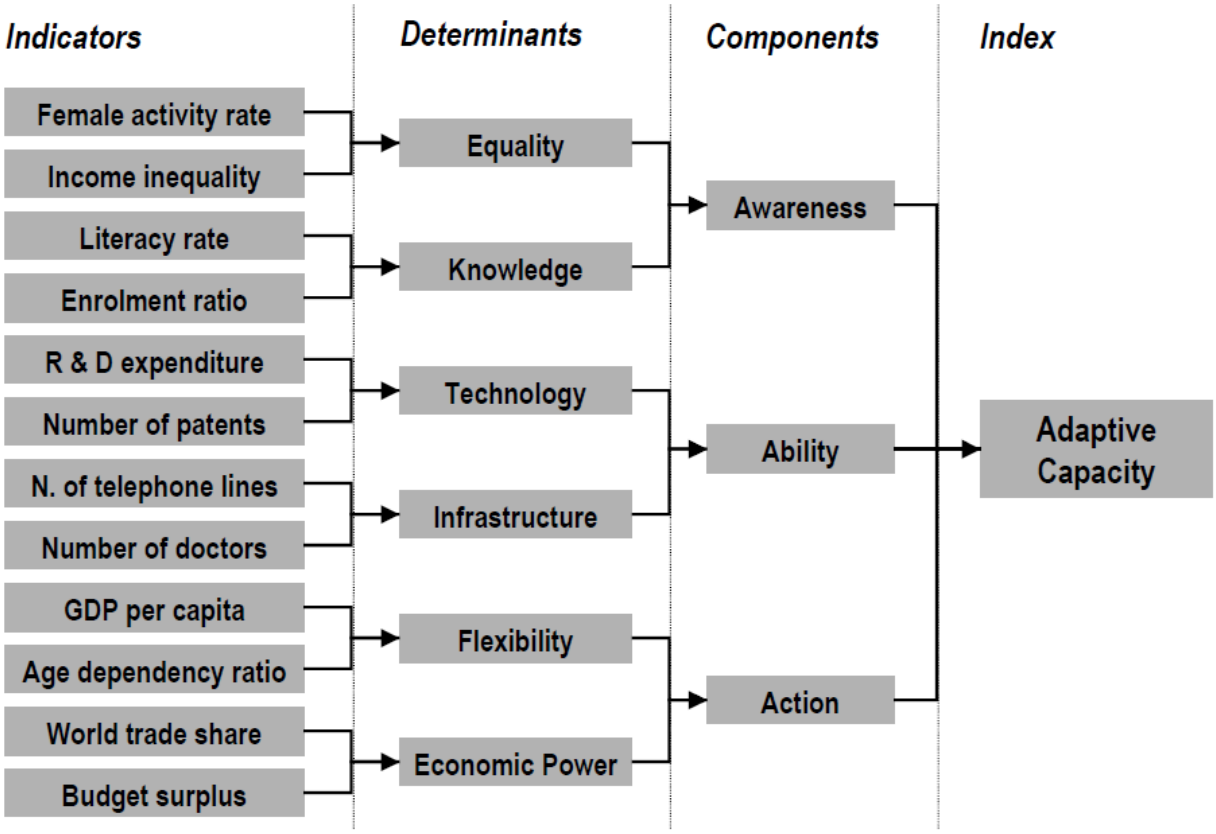

Figure 6: Development of the adaptive capacity index in the ATEAM project. Source: Schröter et al. (2004).

Relevance to CLIMSAVE

A similar approach can be adopted in CLIMSAVE, drawing on the capital stocks as the determinants of adaptive capacity (referred to as coping capacity in CLIMSAVE). This is elaborated further in section 3 below. We will face the same problem as in ATEAM relating to the unknown way in which the (indicator of) capacity combines with the measures of potential impacts (exposure and sensitivity) to give residual impacts and vulnerability. Overcoming this is a joint issue for the adaptive capacity and vulnerability methodologies. Data are unlikely to permit formal modelling of this relationship, and the most likely avenue for solution - bearing in mind that the purpose of CLIMSAVE is not prediction but rather exploration of scenarios – is extension of a fuzzy logic rule set relating capitals to coping capacity to one relating capitals to vulnerabilities.

2.4 The World Bank Total Wealth methodology

It is not at present feasible to estimate wealth directly by summing observed or estimated values for the five categories of capital. However, Hamilton and Hartwick (2005) note that economic wealth is equal to the present value of future market income, where market income equals what is spent on market goods and services plus net investment in various types of capital.

This is the basis of the World Bank (2006; 2011) method for estimating economic wealth, in a top-down fashion, based on projected levels of future market income and discount rates. World Bank (2011, "The Changing Wealth of Nations"; and 2006, "Where is the Wealth of Nations?") seeks to measure the Total Wealth of nations, defined as the present value of future consumption that is sustainable, discounted at a rate of time preference of 1.5 percent, over 25 years. This measure of total (or comprehensive) wealth is based on the principle that current wealth must constrain future consumption. The calculation of total wealth requires adjusting levels of consumption to take account of rates of saving adjusted for depletion of produced and natural capital: when depletion-adjusted saving is negative, countries are consuming natural resources, jeopardizing the prospects for future consumption.

The Total Wealth measure is further broken down into:

- **Produced capital**: machinery, structures, equipment and urban land.
- **Natural capital**: agricultural land, protected areas, forests, minerals and energy.
- **Intangible capital**: this is measured as a residual (the difference between total wealth and produced and natural capital) and *implicitly* includes measures of **human capital** and **social/institutional capital** (factors such as the rule of law and governance that contribute to an efficient economy).

Produced capital is estimated using the perpetual inventory method that derives capital stocks from the accumulation of investment over time, making allowance for depreciation over a certain period. The aggregate capital stock value at time t is given by the formula $\sum_{i=0}^{m-1} I_{t-1}(1-a_i)^i$ where a is the depreciation rate (in practice, usually constant), m is the life span for capital (the World Bank uses 20 years), and I is investment. Urban land is valued as an additional 24% of this (because country-specific data are not available).

Natural capital is the sum of crop, pasture land, timber, non-timber forest benefits, protected areas, fossil fuels and minerals. Cropland wealth is calculated as the net present value of the return to land (rents from cultivating crops) using a discount rate of 4 percent over a 25 year time horizon. Future rents are projected based on annual growth rates of 0.97 percent and 1.94 percent in developed and developing countries, respectively. A constant rental rent of 30 percent of revenues is assumed across all crops considered and countries. Pastureland wealth is similarly calculated, with future rents being projected based on annual growth rates of 0.89 percent and 2.95 percent in developed and developing countries, respectively, and a constant rental rate of 45 percent of revenues used to calculate returns to pastureland.

Timber wealth is calculated as the present discounted value of rents from roundwood and fuelwood production, discounted at 4 percent and over the time to exhaustion of the forest (if unsustainably managed). Non-timber wealth is estimated as the present value of the returns from annual non-timber goods and benefits: watershed and recreation benefits, based on unit values multiplied by forest area. Protected areas are estimated as the opportunity cost of preservation, calculated as the minimum of wealth derived from alternative uses of land such as growing crops and livestock: this is a proxy measure that does not fully take into account the value of protected areas to society.

Subsoil assets (fossil energy and mineral) wealths are calculated as present value of rents from extraction, discounted at 4 percent, over the exhaustion time of the resource, or 25 years, whichever is shorter.

Gross savings is the difference between gross national income and public and private consumption, plus net current transfers. **Net savings** involve further adjustment for the consumption of fixed capital (the replacement value of capital used up in the process of production), energy depletion, mineral depletion and net forest depletion.

Net foreign financial assets, the balance of a country's total financial assets and financial liabilities, are included as part of intangible capital in World Bank (2011), though we might view these separately as **financial capital** – reflecting the ability of a nation to claim resources by calling in debts from overseas.

"Intangible wealth" may sound a little nebulous but the World Bank reports that this is both the largest single component of wealth, across all income groups, and also the fastest growing. Across time, and across nations, development is a process of building total wealth, and also changing the composition of wealth. Most countries start out with relatively high dependence on natural capital (agricultural land, forests and/or oils and minerals) and some then use these assets to build more wealth, especially produced, human and social capital.

The rapid growth of intangible capital is partly a reflection of better education in most countries, but a large part is due to improved institutions, governance and social factors that contribute to better, more efficient use of all of a country's capital stocks. Lack of social capital, corruption, poor planning and so on can lead to inefficient investments: for example Pritchett (2001) estimates that for many developing countries, for each dollar invested, less than 50 cents worth of useful capital is created. Intangible capitals are difficult to measure, and indeed the World Bank approach is to treat them as a balancing item – that part of Total Wealth that is not accounted for by produced capital, natural capital or foreign transfers.

Relevance to CLIMSAVE

The methodology is not perfect – it is a best available estimate, based on incomplete data, and the kind of simplifying assumptions that are necessary to derive simple measures at a national level for 'capital stocks' that are in reality a combination of a vast array of complex elements. There could be several advantages, nevertheless, in starting from this characterisation:

- It is internationally recognised and the result of many years of major research effort;
- It is based in an overall coherent, though imperfect, model of the relationship between national wealth and human well-being;
- For the natural capital measure in particular, the measurements tie in quite well with

the CLIMSAVE IA Platform: the meta-models will produce estimates of forest areas, cropland, pastureland and protected areas, and we could use these to measure the natural capital within each time slice;

- The agricultural value calculations used assume rates of growth in productivity: these are variables in the IA Platform which can be altered by adaptation options (e.g. investments in improving yields), and it should be possible to use the growth rates from CLIMSAVE within a calculation of natural capital, further enhancing the link between the IA Platform and the capital measures;
- The measurements are in monetary terms, meaning (a) that all the capital stocks are measured in the same units, and (b) that it becomes possible to define the cost-effectiveness of options in terms of the impact on the combined measures of these capitals, Total Wealth.
- Data are available for 2005, but also for 1995 and 2000: we can look at changes over that period, and use this to consider likely future changes (see Figures 7 and 8).

In high income OECD countries, the World Bank estimates that 81% of wealth falls into the intangible category, with 17% produced and 2% natural (see Figure 7). However this understates the importance of natural capital, for a number of reasons, so part of the estimated intangible capital is in fact natural. Under natural capital, the wealth accounts include agricultural land, forest land, protected areas, four energy resources and 10 major metals and minerals. Other minerals, fisheries, water and hydropower, are not included due to lack of data. Further, the calculations do not take full account of the idea of critical natural capital – in other words the life-support systems that enable economic activity, and human life, to carry on.

The CLIMSAVE IA Platform allocates various land uses taking account of water supply and food supply, and we could assume that within the boundaries of the meta-modelling system the critical natural capital constraints are being respected – one of the functions of the outputs of the platform is to flag up where there are major threats to critical functions and supplies. Alternatively, we could derive our measure of natural capital directly from the IA Platform outputs.

UNECE (2009) notes that economic wealth calculated in this way is sensitive to assumptions about future income and to the choice of discount rate. This can be seen as a weakness from the perspective of making predictions. However, it does lend itself reasonably well to a scenario-based approach in which the future levels of income are features of the scenarios, and the objective is not prediction but rather exploration of the consequences of different scenarios.

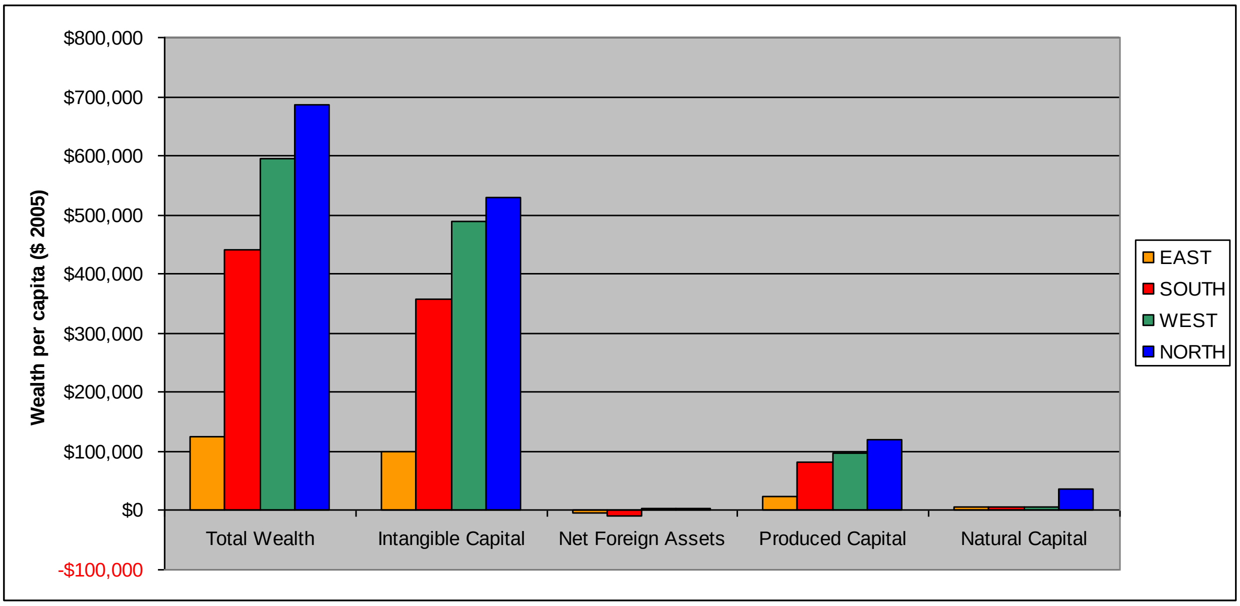

Figure 7: Capital estimates for regions of Europe in 2005. Source: calculated from World Bank data.

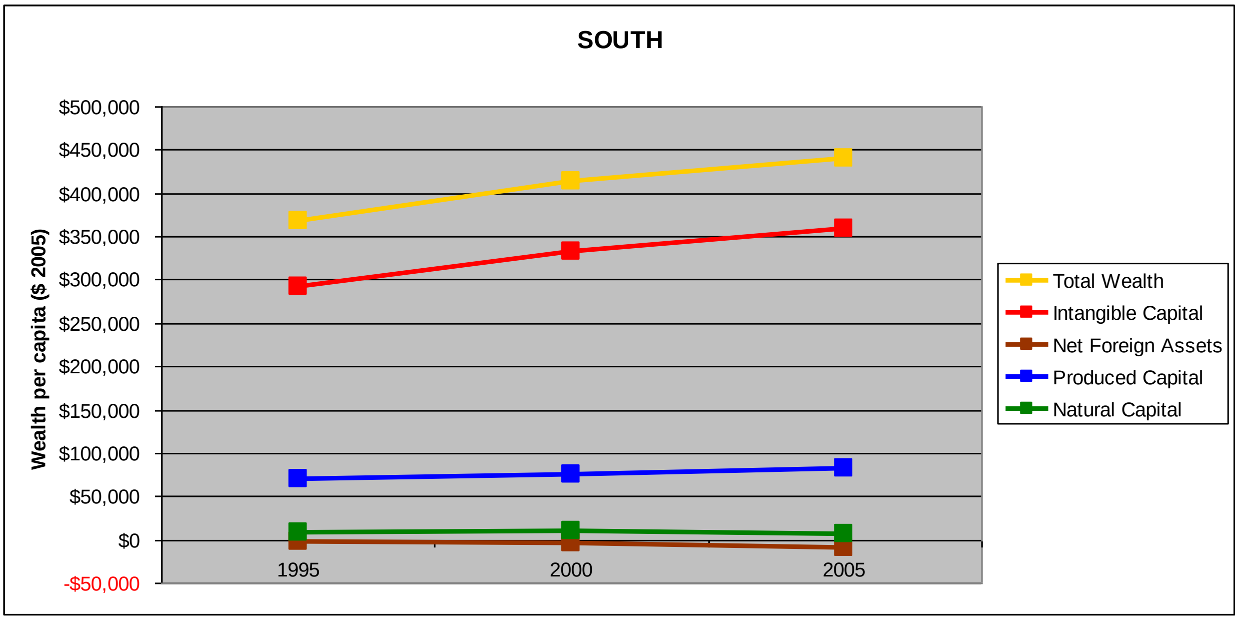

Figure 8: Time series for wealth: example of southern Europe. Source: calculated from World Bank data.

2.5 Using capitals in modelling: GUMBO

GUMBO[1] (Boumans et al., 2002) is a simulation model of the integrated earth system, aiming to assess the dynamics and values of ecosystem services. GUMBO uses estimates of the five capital stocks, and associated flows, differentiated by scenario, as an integral part of the modelling.

GUMBO is a meta-model combining simplified forms of several existing dynamic global models in both the natural and social sciences. The current version of the model contains 234 state variables, 930 variables in total and 1715 parameters. GUMBO itself is not spatially explicit, but the development of MIMES (Multi-scale Integrated Models of Ecosystem Services, see Figure 9) (Boumans and Costanza, 2007) seeks to add this. GUMBO is constructed as a stand-alone dynamic systems model, but the modelling makes use of relationships based on outputs of more complex and computationally demanding models. It is a compromise aiming to be complex enough to include the production and interconnections among the major global ecosystem services, while at the same time remaining simple enough to be distributed and run on a desktop.

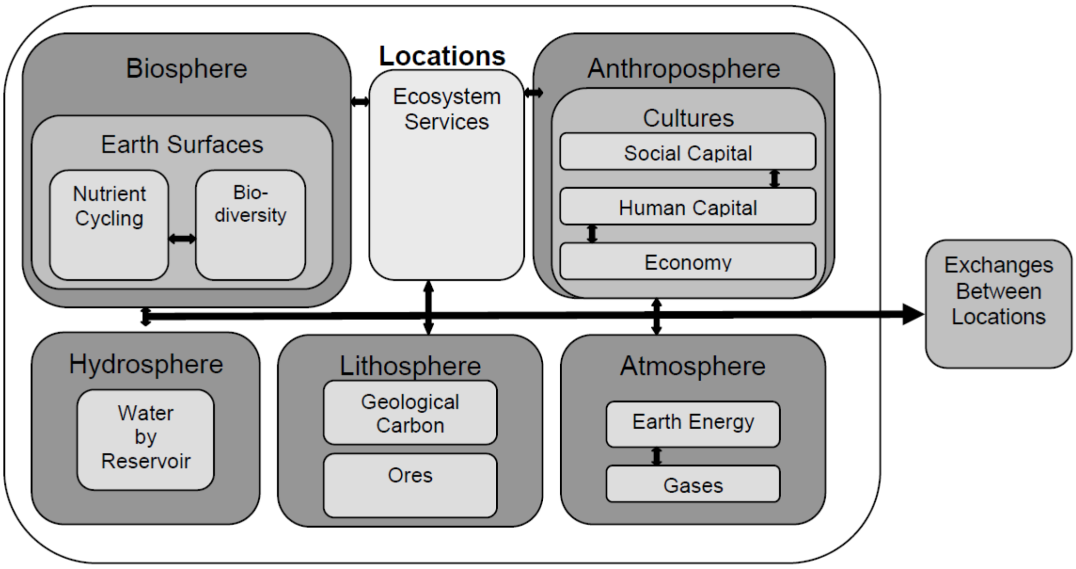

Figure 9: Structure of the GUMBO/MIMES model. Source: Boumans and Costanza (2007).

GUMBO is sub-divided into five 'spheres' (see Figure 9) and 11 biomes, covering the entire surface area of the planet (open ocean, coastal ocean, forests, grasslands, wetlands, lakes/rivers, deserts, tundra, ice/rock, croplands and urban). The relative areas of each biome change in response to urban and rural population growth, Gross World Product (GWP), and

[1] See also http://ecoinformatics.uvm.edu/projects/the-gumbo-model.htm and http://ecoinformatics.uvm.edu/GUMBO/GUMBO.ppt.

changes in global temperature. Among the spheres and biomes, there are exchanges of energy, carbon, nutrients, water and mineral matter.

Ecosystem goods and services are represented by 10 aggregate categories for the output from natural capital: soil formation and erosion, gas regulation, climate regulation, nutrient cycling, disturbance regulation, recreation and culture, waste assimilation, water, harvested organic matter, and raw materials. These combine with renewable and non-renewable fuels, built capital, human capital (knowledge and labour) and social capital to produce economic goods and services, and social welfare. GUMBO calculates the marginal product (i.e. value) of ecosystem services in the production and welfare functions.

The model is calibrated using historical data on 14 key variables with observations over 1900 to 2000 (land use, CO_2 concentration in the atmosphere, global mean temperature, economic production, population, and so on). The model is then run with a suite of scenarios, within bounds set by the calibration data and assumptions about 'reasonable' rates of change in key parameters and investment policies. Model runs include a base case and four others reflecting different assumptions about the style of global government (globalised versus balkanised) and about the capacity of the planet and its resources (optimistic versus pessimistic) known as the 'Star Trek', 'Big Government', 'Mad Max' and 'Eco-Topia' scenarios – these are rather similar in broad context to the UKCIP scenarios: 'World Markets', 'Global Sustainability', 'Fortress Britain' and 'Local Stewardship'. Model users can then change the assumptions/parameters within the scenarios and observe the results, although of course the validity of the modelling is likely to be reduced the further assumptions go beyond the range of the calibration data.

The economic component of GUMBO draws together three groups of inputs – the production of ecosystem goods, the production of ecosystem services, and the economic production based on socio-economic stocks of social capital, knowledge, labour force and built capital. These feed into the overall production of goods and services for satisfying human needs; waste is modelled as a negative feedback. The total production is divided into personal consumption, and savings rates for the main capital stocks, including natural capital (Figure 10).

A key feature of GUMBO is modelling dynamic processes including feedbacks among human technology, economic production and welfare, and ecosystem goods and services. Dynamic processes modelled in GUMBO include carbon, nitrogen and water cycles, human population, changes in the capital stocks and so on. These linkages make it possible to estimate the costs and benefits associated with specific changes, by calculating the marginal product of ecosystem services in both the production and welfare functions.

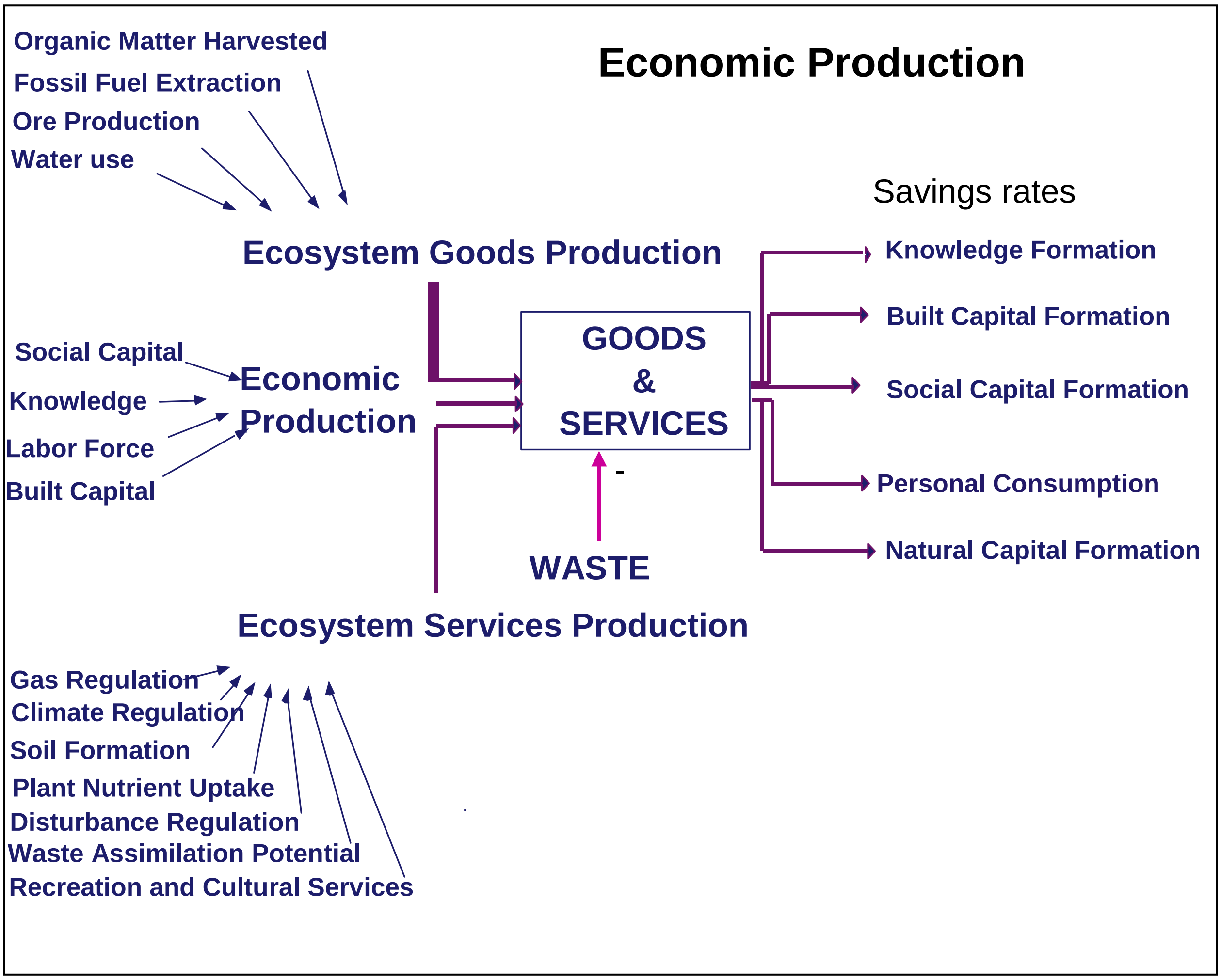

Figure 10: Capitals in the GUMBO model.

GUMBO gives global projections for key aggregate variables, and results are at the broad strategic and advocacy levels. For example:

- All the scenarios show agricultural production, human population, and ecosystem service values, peaking before 2050 and then declining significantly (though the details differ across scenarios).
- The overall value of ecosystem services, in terms of their relative contribution to both the production and welfare functions, is shown to be significantly higher than GWP (4.5 times in the preliminary version of the model); this ratio also increases then falls over time.[2]
- "Skeptical" investment policies are shown to have the best chance (given uncertainty about key parameters) of achieving high and sustainable welfare per capita. This means increased relative rates of investment in knowledge, social capital and natural capital, and reduced investment in built capital and consumption.

[2] http://ecoinformatics.uvm.edu/GUMBO/GUMBO.ppt

Relevance to CLIMSAVE

The main objective in creating the GUMBO model was not to predict the future with any great accuracy, but rather to scope possible scenarios, provide a simulation tool to facilitate participation in modelling and scenario exploration. In this respect, the objectives of GUMBO are similar to those of CLIMSAVE, though of course CLIMSAVE has a much more specific focus; also, CLIMSAVE is spatial and static, whereas GUMBO is dynamic but non-spatial. Thus the way that GUMBO uses the capital stocks, modelling their evolution over time (see savings rates in Table 8) cannot be adopted directly in CLIMSAVE.

Table 8: Capital saving rates and consumption in different GUMBO scenario

Scenario	Baseline	Big Govt	Eco-topia	Mad Max	Star Trek
Human Capital	0.016	0.022	0.022	0.01	0.01
Social Capital	0.16	0.18	0.46	0.05	0.02
Built Capital	0.15	0.1	0.1	0.2	0.2
Natural Capital	0.15	0.3	0.3	0	0
Consumption	0.52	0.40	0.12	0.74	0.77

Nevertheless, the successful use of scenario-dependent capital stocks in GUMBO can be seen as a form of 'proof of concept' for the principle of using capital stocks in CLIMSAVE. We could also use the rates from the GUMBO model alongside the stakeholder projections for scenario-dependent changes in capital stocks and GDP to develop projections for capital levels in future scenarios. The scenarios in GUMBO and the two CLIMSAVE case studies are different and adjustment may be needed to allow for this.

2.6 European assessment of the provision of ecosystem services

The most recent relevant development on mapping spatially-explicit ecosystem service provision is presented by Maes et al. (2011), the first phase of work towards a European atlas of ecosystem services. This uses the NUTSx statistical area as the spatial mapping unit: NUTS 3 units for most EU countries and NUTS 2 units for Belgium, The Netherlands and Germany. This choice is mainly determined by the economic valuation that follows the biophysical mapping: indicator maps (Table 9) are available at finer spatial resolution but the assessment of trade-offs in ecosystem services is at present feasible only at a specific NUTS level depending on the services.

Table 9: Spatial indicators in the European atlas of ecosystem services. Source: adapted from Maes et al. (2011).

Capacity	Flow	Benefits
Forest capacity to produce timber Timber stock (ha, m^3)	Timber increment Average dry matter productivity in forests (m^3 $year^{-1}$)	Products for fuel, construction and paper Round wood production (m^3 $year^{-1}$)

Potential production of agro-ecosystems Total area of cropland (ha) Agricultural limits for soil (ha)	Realized crop production (t ha^{-1} $year^{-1}$)	Realized crop production (t ha^{-1} $year^{-1}$)
Potential livestock production The total area of grasslands suitable for grazers The density of grazing livestock	Total livestock production derived from grazing on (unimproved) grassland (t ha^{-1} $year^{-1}$)	Livestock production of grazers (t NUTS2 $year^{-1}$)
The reserves of renewable fresh water Total area of inland water bodies and inland wetlands (ha)	Total annual renewable freshwater supply (m^3 $year^{-1}$) by surface waters	Total annual freshwater consumption per sector
Potential of ecosystems to store water Soil infiltration capacity (mm) Capacity of ecosystems to retain and process pollutants and excess nutrients Nitrogen retention (%)	Total amount of water stored (m^3 $year^{-1}$) Total number of floods mitigated Total amount of pollutants removed annually (t ha^{-1} $year^{-1}$) Total amount of water purified	Prevented flooding Total population protected Clean water for drinking, recreation and other uses
Capacity of ecosystems to store greenhouse gasses: Carbon storage (t)	Annual carbon fixation Carbon fixation (gC m^{-2} $year^{-1}$)	Carbon offsets (m^3 CO_2 eq $year^{-1}$)
Capacity of ecosystems to moderate the impact of storms and to prevent flooding Total area of coastal wetlands ha)	Total number of storms mitigated	Total damage prevented Total population protected
Capacity of ecosystems to capture and remove air pollutants Deposition velocity of air pollutants on leaves (m $year^{-1}$) Leaf area index Critical loads	Total amount of pollutants removed via dry deposition on leaves (t ha^{-1} year-)	Effect on air quality Contribution to clean air
Potential of ecosystems to retain soil and to avoid erosion Area of forest in vulnerable zones	Total amount of soil retained (t ha^{-1} $year^{-1}$)	
Pollination capacity of ecosystems Distance to crops (km) Crop dependency (%) Pollinator abundance (nests per km^2)	Increased yield of crops attributable to pollination Crop dependency × Annual production (t $year^{-1}$)	Contribution to realized crop production (t ha^{-1} $year^{-1}$)
Capacity to maintain the soil's biological activity Soil quality indicator Soil organic carbon (%)	Increased yield of crops attributable to soil quality (t $year^{-1}$)	Contribution to realized crop production (t ha^{-1} $year^{-1}$)
Capacity of natural ecosystems to provide recreation Recreation potential × accessibility	Number of visitors	

Relevance to CLIMSAVE

The assessment derives spatially explicit indicators for 13 ecosystem services, many of which can also be mapped using CLIMSAVE outputs. Others could be addressed via manipulations of the CLIMSAVE outputs, based on relationships between current levels of the service and current measurements of the CLIMSAVE output variables. This would allow comparison of CLIMSAVE results for 2020s and 2050s with the present day.

The services can also be expressed in terms of an aggregated value index (see Figure 11) and this could be directly useful as one means of presenting results within the IA Platform.

However, the ecosystem service measurements do not measure adaptive or coping capacity in any direct sense. They do relate closely to natural capital, and it could be argued that strong ecosystem service values do tend to imply greater resilience or coping abilities. In the context of developing indices of adaptive and coping capacities, these indices do not, therefore, constitute a full solution to the problem, but may well be useful in developing the index for the natural capital component.

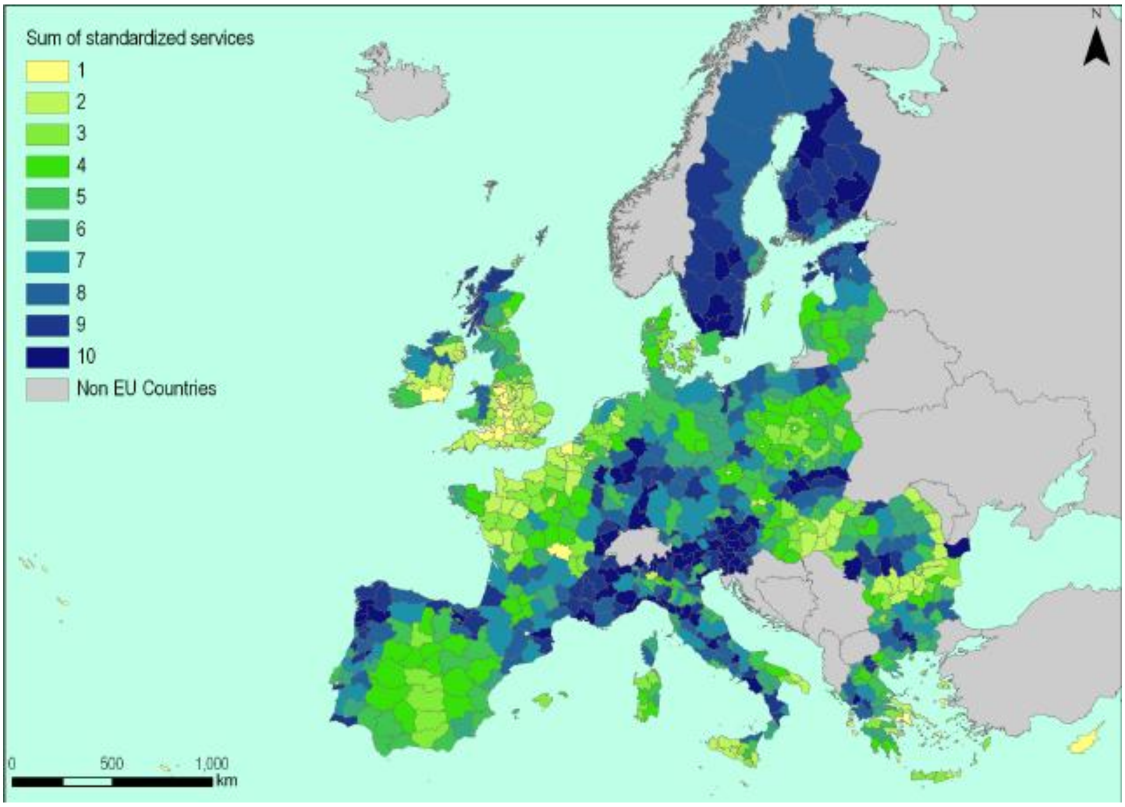

Figure 11: Total ecosystem service value index aggregating 13 services. Source: Maes et al. (2011).

2.7 The framework for ecosystem capital accounting in Europe

Ecosystem accounts are being developed by the EEA as part of the System of Environmental-Economic Accounts, aiming to supplement the UN System of National Accounts with information on the environment and natural capital. The overall process will deliver synthesis results across Europe by 2012 when the EEA will publish the first European Ecosystem Assessment (Eureca!). The purpose is to broaden the scope of the variables taken into account in policy-making in order to improve understanding of the interdependence and interactions between the economy and the environment. Ultimately, these ecosystem accounts will yield new indicators and aggregates, in both physical and monetary units, for assessing the efficiency of natural resource use, its contribution to economic well-being and growth, the use of ecosystem services within and outside the market, and the short- and longer-term constraints associated with the need to maintain natural capital, and the related benefits and costs. Key indicators and aggregates include (see Figure 12):

- Ecosystem resource accessible surplus: the level of resources that can be used without jeopardising ecosystem reproduction functions;
- Demand for (accessible) ecosystem services per capita, a measure of ecosystem contribution to well-being;
- Total ecosystem capital potential, defined as the biomass accessible while sticking within critical limits;
- Ecosystem Capital Degradation (ECD) covering overuse and consumption of ecosystem capital, and taking account of embedded degradation in imports/exports.

Plans for further development include using these accounts to adjust National Accounts aggregates, with two balance sheets of assets and liabilities running alongside each other (one in physical units, the other monetary).

Below, we discuss briefly the tables of most interest in the CLIMSAVE context. Further details are given in Weber (2011).

The land-cover stocks and flows basic account (Table A) measures, in km², the land-cover stocks and changes in the ecosystem statistical units used for accounting. Land-cover stocks cover artificial surfaces, large to medium farm arable land and permanent crops, pastures, mosaic farmland (small farms, mixed land cover), forest cover, natural grassland, scrubland, natural mosaics, open space with little or no vegetation, wetlands and water bodies. Land cover flows are presented by type (land development processes, urban sprawl, land-use intensification, land restoration processes, rotations, natural processes and steady state) and in gross and net changes compared with a base year.

The ecosystem capital carbon/biomass account (Table B) measures the Net Ecosystem Accessible Carbon Surplus (NEACS) in soil, vegetation and fisheries and its use. It covers stocks below and above ground, net primary production, and use through harvesting. The Net Ecosystem Carbon Balance (NECB) indicates the sustainability of carbon/ biomass use.

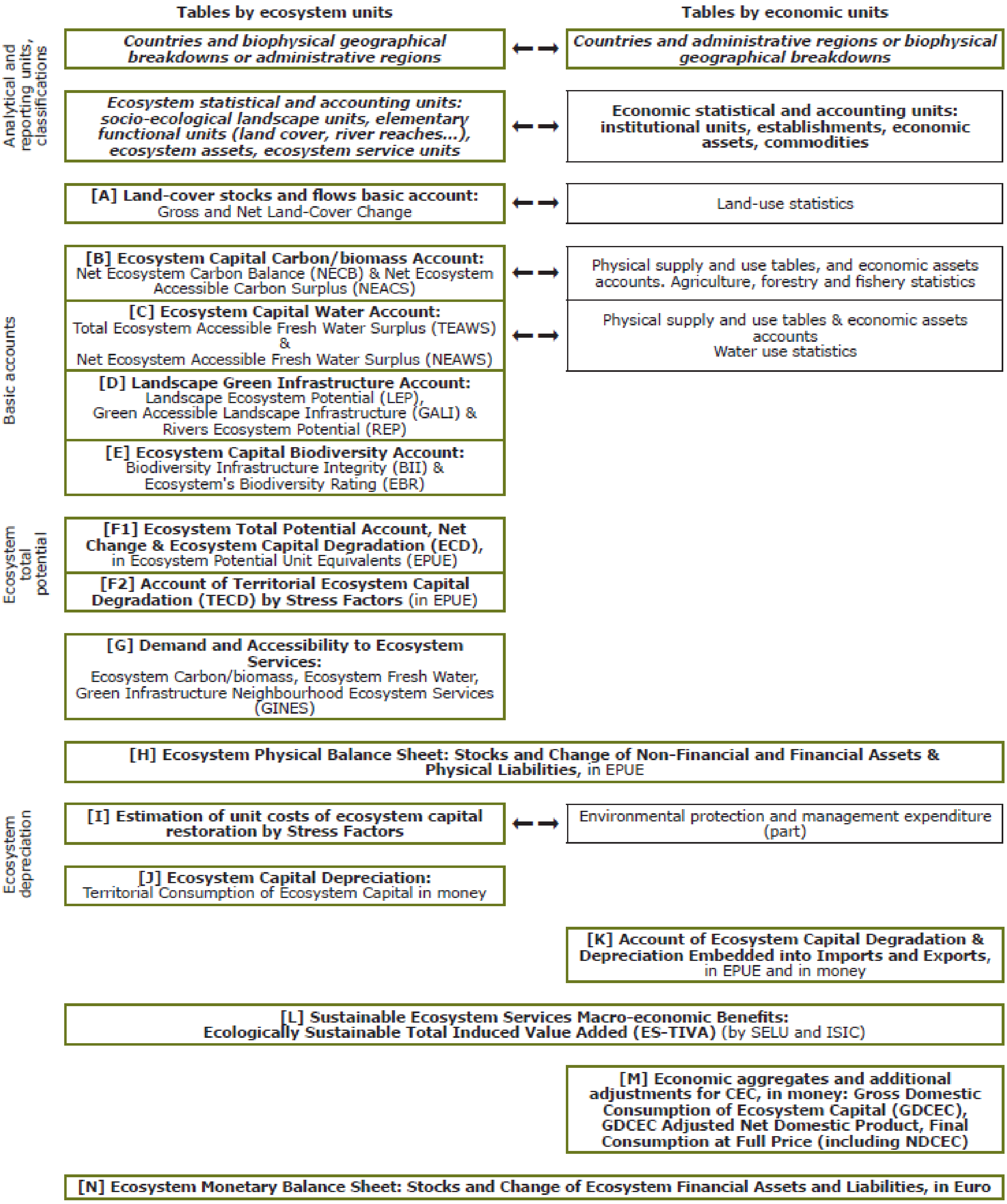

Figure 12: Simplified ecosystem capital accounting structure. Source: Weber (2011).

The ecosystem capital water account (Table C) measures the Total Ecosystem Accessible Fresh Water (TEAW) and the Net Ecosystem Accessible Fresh Water Surplus (NEAWS), adjusted for water stress during the vegetation growing season, and distinguishing between total and accessible stocks (due to physical or economic constraints of abstraction, pollution or time mismatch between availability and needs).

The landscape green infrastructure accounts (Table D) cover a number of indicators, notably (in the CLIMSAVE context) the Net Landscape Ecological Potential (NLEP). This aims to connect ecological potentials and human pressure via land use and detect impacts in a systematic way. The application to Europe (illustrated in Figure 13 is the combination of 3 different geographical datasets (layers, indices) spatially distributed on a 1 km² grid[3]:

1. The Green Background Landscape (GBL) index weights hectares of land cover according to their 'greenness', taking account of the intensity of human use, and the value of the area in the context of neighbouring areas, using smoothed values based on fuzzy logic. The data are computed and updated from Corine land cover.
2. The Stated Social Nature Value (SSNV) index is assessed via designation status. This is computed from a combination of European (Natura 2000), international and national (CDDA) designated sites maps. It captures features that cannot be seen by remote sensing: species richness/habitats of landscapes which have motivated designation for nature conservation.
3. The Mesh Effective Size (MEFF) index, capturing the fragmentation of landscape by roads and railways, which is not captured in the previous 2 layers. The indicator is the natural logarithm of "effective mesh size" (MEFF). The lower the effective mesh size, the higher the fragmentation.

Relevance to CLIMSAVE

The potential relevance to CLIMSAVE is similar to that discussed under section 2.6 above: the landscape and ecosystem accounting methods could be used to define the natural capital component of adaptive and coping capacity, and/or the indicators could be used as separate performance indicators within the IA Platform, as means of summarising the diverse outputs of the CLIMSAVE models in simpler aggregate indicators. The accounting indicators are explicitly spatial, and could be presented on a 1 km grid or at the NUTS2/3 resolution.

The most obvious candidate for an indicator of natural capital that integrates with CLIMSAVE outputs is the Landscape Ecological Potential. The first two components, Green Background Landscape and Stated Social Nature Value, could be calculated from outputs of the platform (perhaps with some simple adjustments/assumptions). The Mesh Effective Size is not directly a CLIMSAVE output, although there are related variables: urban sprawl is mapped, but the linear features of the transport network are not covered. There are four main options here:

- Omit the MEFF indicator, at the cost of losing comparability with the LEP.

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[3] Land accounts for Europe 1990-2000, *Towards integrated land and ecosystem accounting*, EEA Report No 11/2006 http://reports.eea.europa.eu/eea_report_2006_11/en

- Use the existing MEFF values, while accepting that this will underestimate fragmentation due to new infrastructure.
- Develop some scenario-dependent assumptions about the average increase in fragmentation, and use these simple multipliers to modify the existing MEFF values.
- Develop more complex scenario-dependent assumptions relating the MEFF to population density, urban land cover and other relevant CLIMSAVE variables, in effect developing a meta-model for the MEFF.

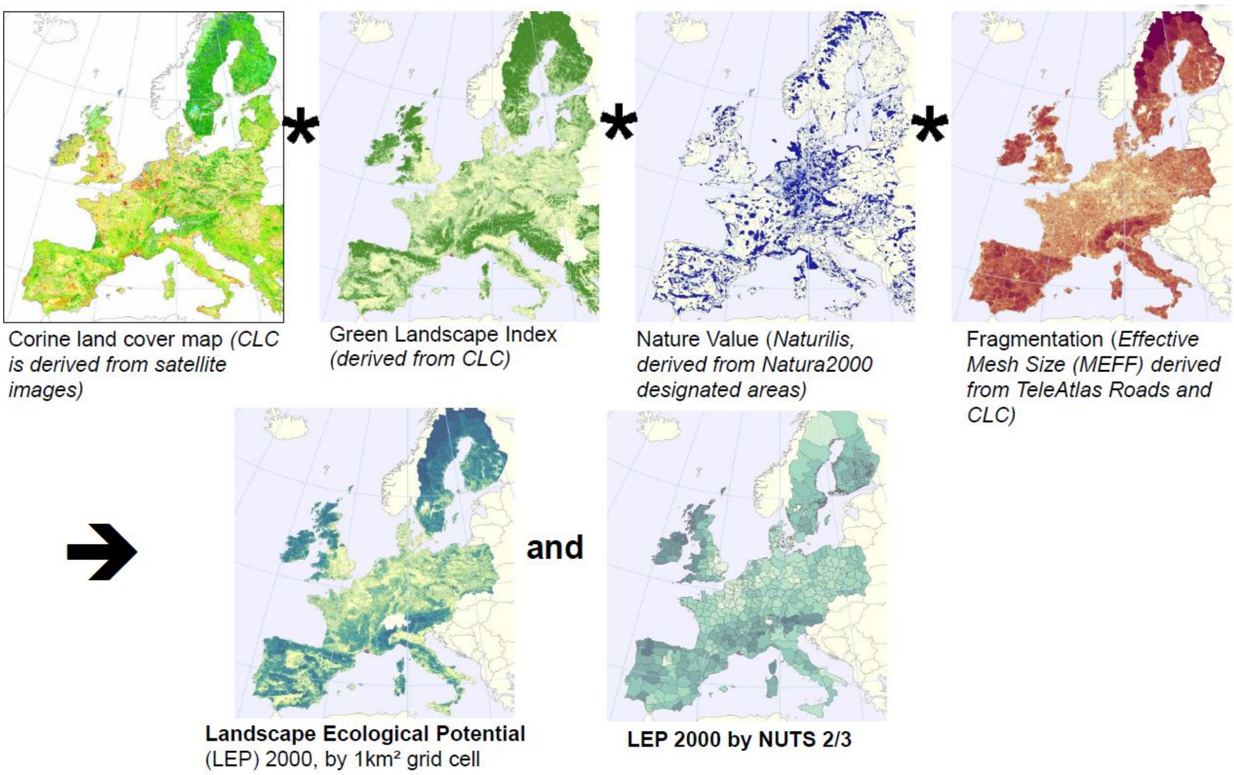

Figure 13: Calculation of Landscape Ecological Potential (LEP). Source: Weber (2011).

For more general reporting / summarising purposes, indicators from Tables A, B, C and D could all be relevant, though some would be easier to calculate than others based on CLIMSAVE outputs. Indicators from the other tables may also be of interest. This would not directly relate to the methodology for defining adaptive capacity, however, and we do not explore this further here. Rather, it will be further investigated within the CLIMSAVE work on developing metrics for cross-sectoral comparison, and more generally in the context of selecting a small number of summary indicators to present within the IA Platform.

2.8 Stakeholder-led assessment of capacity

In the absence of a full theory of adaptation, and given the exploratory, scenario-based and stakeholder-led nature of the CLIMSAVE methods, another option is to allow stakeholders to determine the key features of adaptive and coping capacity that they wish to see represented in the platform.

This could be attempted via workshops or semi-structured interviews, or through statistical methods based on surveys. The most open methods would allow free reign in discussion of the determinants; more restrictive methods would pre-select determinants for which data were available and ask stakeholders to prioritise or weight these variables in terms of their contribution to adaptive and coping capacity. This could be done directly, or indirectly, as in Alberini et al. (2006), who used conjoint choice questions to ask a sample of public health and climate change experts which of two hypothetical countries, A or B, they deem to have the higher adaptive capacity to certain effects of climate change on human health. The hypothetical countries are described by a vector of seven attributes. Probit models indicate that respondents regard per capita income, inequality in the distribution of income, universal health care coverage, and high access to information as important determinants of adaptive capacity. The estimated coefficients and country socio-demographics are used to construct an index of adaptive capacity for several countries. In panel-data regressions, this index is a good predictor of mortality in climatic disasters, even after controlling for other determinants of sensitivity and exposure, and for per capita income: the authors conclude that conjoint choice questions provide a novel and promising approach to eliciting expert judgments in the climate change arena.

Relevance to CLIMSAVE

Stakeholder workshops are an important part of the CLIMSAVE workplan, with the design of scenarios and the platform interface drawing heavily on stakeholder input. Allowing stakeholders to shape the adaptive and coping capacity measures is attractive, and could aid with buy-in to the idea of representing a complex reality via a framework of simple indicators. On the other hand, care is required to ensure that the method is feasible in terms of data availability and fits with the overall CLIMSAVE framework, and this might suggest starting from a pre-determined model and asking stakeholders to help develop scenarios using that model.

As a result of work along these lines, participants at the first round of stakeholder workshops held in May and June 2011 were presented with information on capital stocks and asked to consider how they thought these would evolve over the two future time slices (2020s and 2050s). The responses were limited to high or moderate increase/decrease, or no change. It would be possible to use these assumptions to develop quantitative predictions for the capital values, consistent with the assumed levels of wealth in future time slices – though this would require further assumptions, including on the relationship between GDP and wealth. Given the uses envisaged for the capital measurements – informing exploratory models of adaptive and coping capacity – it may be sufficient to leave them as qualitative variables.

2.9 Summary and implications for CLIMSAVE

Adaptive capacity can be considered as dependent on social, human, manufactured, natural and financial capitals. This begs questions of how to measure these capitals, how to combine them at different scales, and how to relate resulting measures to the needs of specific adaptation options (current adaptive capacity) and to the ability to cope with climate change in the future (future coping capacity), but nevertheless provides a starting point.

The general approaches above are promising for CLIMSAVE. There are several sources of information that can be drawn on to inform the development of the capital indicators, either top-down or bottom-up.

On the one hand, we can use the World Bank data to provide estimates of capital stocks for each region or country. These could be projected forward based on the scenarios, and indeed this task was set in the first stakeholder workshop.

The bottom-up approach used in the ATEAM project also has potential, and could be modified to fit with the five capitals model. Where possible, we might try to avoid using variables that have to be extrapolated on the basis of their past relationship with GDP and expected growth, perhaps using other scenario-derived variables. But the general bottom-up approach using fuzzy sets to combine indicators is likely to be useful.

For CLIMSAVE, there is clearly an opportunity to make direct use of the platform outputs to model the natural capital component. The other components may draw partly on platform outputs and on the socio-economic scenarios. The ways in which this can be done are discussed in the next section.

3. Developing a methodology for CLIMSAVE

As explained above, there are three main requirements for the CLIMSAVE adaptive capacity work:

1. **Adaptive capacity:** determining how the adaptive capacity under each scenario may restrict the feasible range of adaptation choices from among the full set represented in the platform.
2. **Coping capacity:** deriving an expression of coping capacity that is based on the scenarios and the capitals, after accounting for the adaptation options selected by a platform user, that can be used within the methodology for identifying vulnerability hotspots.
3. **Adaptive potential:** using the platform to derive measures of maximum possible adaptation, or the most efficient combinations of adaptation options to reduce vulnerability.

Of these, the first two are the most important. The third is an extra piece of work that may be developed further in the work on cross-sectoral comparisons and cost-effectiveness. Below, we address these in turn, but first present some general considerations that apply to all, or pertain to the links between them.

3.1 General considerations for developing the methods

There are a number of concepts and observations that influence the way in which the methods can be developed. These include:

- spatial scaling properties and sector- and threat-specificity of measures;
- the non-fungibility of most capital types;
- the distinction between 'using' and 'using up' capitals; and
- validation of a capacity model.

Scaling properties and sector- and threat-specificity of measures

We could aim to derive generic, scenario-dependent measures of adaptive capacity or coping capacity for the whole geographic area covered by an assessment, to cover all modelled sectors, and all threats. We could then either use this measure as our sole reference point for adaptive or coping capacity, or work out ways in which the generic measure determines local or sectoral measures of capacity. This is essentially the approach advocated by Adger et al. (2004), who argue that assessments of vulnerability and adaptive capacity for individual countries "will be most useful when they consist of assessments of generic vulnerability and adaptive capacity, followed by assessments of vulnerability and capacity to adapt to the specific hazards that pose the greatest threat to human welfare and national economic development".

The alternative approach is to consider bottom-up assessments of adaptive and coping capacity at local scales, for specific sectors and/or to specific threats. The determinants of these specific capacities could be different, reflecting the particular characteristics. For the purpose of making comparisons across countries or regions, or between different scenarios, we would then need to develop ways of grossing up to derive generic indicators applicable at a broad scale.

As we move to consider more specific adaptive and coping capacity, for example at the sectoral or local level, indicators of specific capacities and vulnerabilities may need to reflect particular types of hazard and specific local contexts. So both top-down and bottom-up approaches might be useful.

Non-fungibility of capitals

With the exception of financial capital, the capital types are not fully fungible: that is, it is possible for example to have natural capital or manufactured capital that is very useful for a particular purpose or adaptation, but of little or no use otherwise. This makes it hard to relate a single measure of a particular capital stock to the adaptation potential of that stock. €10 million is the same sum irrespective of the context (although what it can buy does depend on the price level); 10,000 ha of agricultural land may have very different interpretations depending on context (for example, is the risk drought or flooding, and what is the contribution of that land in each specific context – can it be irrigated, can it be protected from flooding?). Similarly 1,000 PhDs in flood engineering might be great for dealing with rising sea levels, but not much use for dealing with invasive species or agricultural yields.

However, for the purposes of the project, we can be content with rather fuzzier characterisations of the capitals available for adaptation. We can assume, for example, that a society investing heavily in building up human capital, through education and training, is doing this across the board in appropriate ways, so that the general pool of expertise is growing in all dimensions, and we can focus on general education levels rather than specific skills.

Also, we probably do not need to attempt to present the measurements of capitals, and their relationships to adaptation options, to any great degree of precision. Rather, we could consider broad categories of capital levels (very high ... very low) and use these both for presenting information on capital levels, and for scoping the available adaptation measures.

Keeping it simple within the adaptation screen need not preclude measuring capitals more precisely within the scenarios and as an output of the platform. The background methodology for the World Bank figures is clear and can be adapted to fit the platform outputs – for example, using the platform calculations of agricultural land, forest areas and protected areas. Some adjustments may also be possible to improve the coverage of the measures, for example with water and hydropower, since better information will be available at the European level than globally.

"Using" versus "Using up" capitals

Not all capital types are necessarily reduced by an adaptation action, or in the process of coping:

- Financial reserves are run down by expenditures, but expenditure can also have a stimulating effect on an economy, with different multipliers depending on the kind of expenditure.
- Manufactured capital may be depleted by use, or may be used only temporarily (for example, machinery used for emergency flood defence work) and then returned to the pool of resources.
- Natural capital can be sustainably or unsustainably managed, and some forms of use need not use up the capital. Indeed in some cases use may be essential in order to maintain the productivity of the capital (for example, agricultural land, which may decline in agricultural value and potentially in other values – aesthetic, biodiversity –

if abandoned).

- Human capital may be used to a specific end, but can also be enhanced by being used (for example through training and knowledge transfer benefits, adaptive management and learning by doing).
- Social capital is complex and may sometimes be enhanced through use, or subject to a 'use it or lose it' aspect, but could also be reduced by overuse (e.g. repeated needs for non-reciprocated aid).

This suggests that in CLIMSAVE we should consider capitals not as stocks that are necessarily eaten into by adaptation actions, but rather as characteristics of a society that control which adaptation options are feasible, how much financial cost they entail, and/or how effective they will be. The capital stocks would become features of specific socio-economic scenarios and of land use (forests, agriculture, protected areas), that would scope aspects of the adaptation options.

This means that in the first part of the adaptive capacity work, we do not have to worry about how specific adaptation options 'consume' capitals, and can leave the platform users free to explore the full range of options without considering cumulative effects of capital constraints. Instead, we can simply flag which options may be infeasible given the levels of capital present in certain scenarios. Consumption of natural capital would be reflected in any case via the land use modelling in the platform. Given that we focus only on 6 sectors, the other constraints are less likely to be binding anyway – there is scope at the societal level to source capital from outside these sectors – so this would probably be an acceptable first approximation, bearing in mind the need to return to cumulative cost considerations when carrying out the cost-effectiveness theme of the project.

Validation of models

However we construct an index of capacity, the question of validation will arise. Our objective is to use the measure of coping capacity in the vulnerability assessment, with vulnerability (or unavoided impacts) a function of sensitivity, exposure and coping capacity. This is challenging because there are no quantitative theoretical predictions for how (indicators of) specific components of coping capacity will change actual outcomes in any particular case. We assume that higher capacity leads to lower impact, but this is built on a set of non-quantitative assumptions.

In principle it could be possible to observe actual damages arising from extreme events, and develop a statistical relationship to explain the actual damages as a function of variables relating to threat, location and socio-economic factors. This is essentially similar to expressing vulnerability as a function of exposure, sensitivity and coping capacity, and the idea would be to separate out the part of the function that we call 'coping capacity'. However, in practice the data available are not sufficient to allow such validation.

An alternative approach of deriving detailed estimates of the coping requirements of specific situations (i.e. specific ways of responding to specific threats impacting on specific sectors and areas) and calculating the resource (capital) requirements of that would be even less practical.

For the ATEAM work, Metzger et al. (2006) recognise this problem and stress that their results allow “some general statements about the vulnerability of the ecosystem services to land use change, without quantifying the relative contribution of PI [potential impact] and AC [adaptive capacity]”. Figure 14 shows an example of their visual presentation of vulnerability (of a specific ecosystem service to a specific threat) that keeps separate the potential impact (i.e., with no adaptation/coping) and the adaptive capacity (which in CLIMSAVE we are calling coping capacity). The colour of a grid cell is determined by the size of the potential impact; the saturation is determined by the index of adaptive capacity.

This approach is effective in allowing both sets of information to be summarised, but does not reveal the net result: because the model does not link up AC and PI, the full nature of potential coping/compensation is not revealed. This is sufficient to flag areas where the potential impact is high and the adaptive capacity is low. Metzger et al. (2006) note the potential for more advanced methods to combine AC and PI in an overall assessment of expected impacts, for example via a fuzzy logic model, but stress that this would require a deeper understanding of how the adaptive capacity interacts with the potential impact to determine the final outcome.

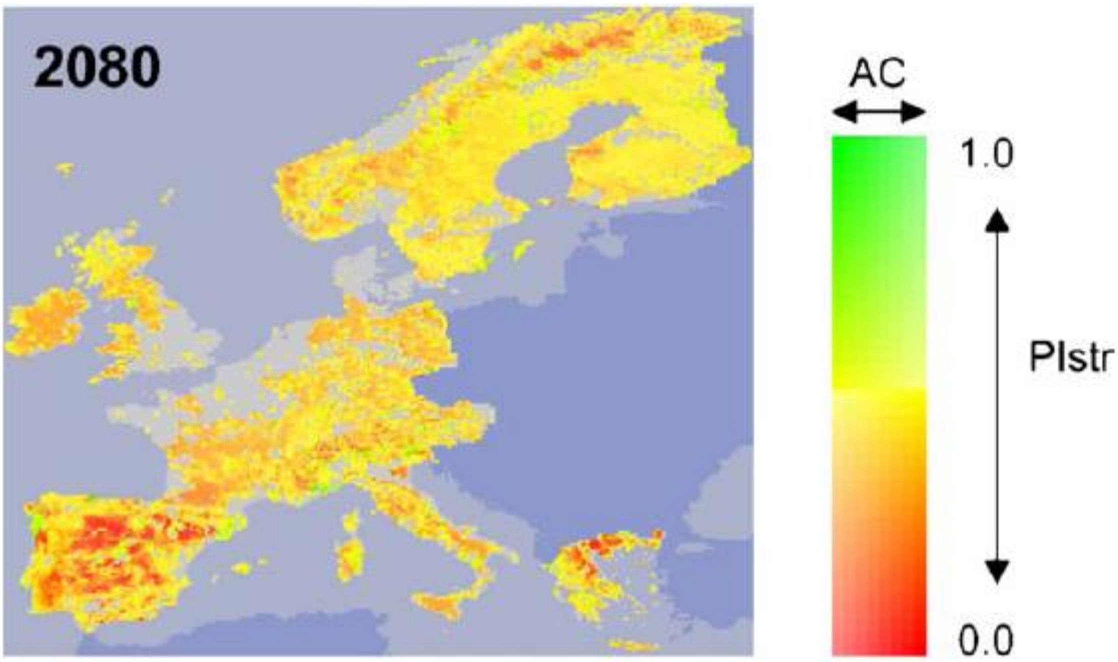

Figure 14: Vulnerability assessment from the ATEAM project. Source: Metzger et al. (2006).

This challenge will arise again in CLIMSAVE, in the development of the vulnerability methodology. The coping capacity measure has to fit into that developing methodology and this may have a bearing on decisions we take regarding the creation of an index of coping capacity.

3.2 First phase of work: current adaptive capacity

The constraints on adaptation options are to be non-binding, in order not to limit the choices faced by platform users too much. The basic requirement is to develop an understanding of which levels of each adaptation option are consistent with each socio-economic scenario.

There are only four socio-economic scenarios for each case study (Europe and Scotland), and 20 adaptation options, and it would be possible to work through each option separately and set (flexible) limits on its feasible ranges for each scenario. Alternatively, the limits can be set in a two-stage process: first determining the capital requirements of the option, and then combining this with the levels of capitals in the socio-economic scenarios to determine the feasible ranges.

The second option has the advantage of greater transparency in that it is clear why a certain option has been ruled out or in, and may also aid consistency across scenarios (because the capital requirements are held the same). On the other hand, some adaptation options may have variable capital requirements – for example, an option that could be achieved with low human capital and high financial cost, or with high human capital and low financial cost – and so the same option might be achieved in different ways depending on the scenario, or depending on the location.

The location is especially important when we consider that the same adaptation option is implemented across the entire area represented in the platform – users are not setting different levels of each option for each grid cell, or even for different regions or countries. This would be possible in principle, but the added complexity for users of changing each option separately for a large number of different areas would render the platform impractical to use.

The concern regarding possible different capital requirements for different ways of implementing an adaptation option could be overcome by specifying the capital requirements as a fuzzy rule base rather than as strict minimum requirements: this would maintain the transparency (though it would be less immediately clear) and consistency while allowing for the diversity of specific actions potentially included under each adaptation option heading.

However, the capital framework may not be able to reflect adequately the relationship between scenarios and options. Some options may be inconsistent with some scenarios for reasons unrelated to capital stocks, but rather depending on the fundamental ethos, political framework and assumed dynamic of the scenario. It might be possible to incorporate such ideas into the capitals framework, but there is a risk of inconsistencies.

The only real need to specify the capital requirements of different options would be if we were to make binding capital-based constraints, or keep a running tally of capital 'used up' by the option. For the reasons discussed above, this is not recommended. It could be of interest to consider how the adaptation options influence future coping capacity, but this is for consideration under that section of the work.

It is also possible that there could be mutual incompatibilities, or synergies, across different adaptation options, in terms of their fit within a given scenario, or overall. For example, high levels of flood protection upgrade might be thought inconsistent with high levels of wetland creation. This will need to be dealt with on a case-by-case basis. In fact this gives another argument against reducing the constraints to a consideration of capital requirements, because it is quite possible that the capital requirements for both policies could be met, but they would still be incompatible.

Recommendation for assessment of current adaptive capacity

Practical considerations mean that it will be simpler to derive separate feasibility ranges for each scenario and adaptation option pairing. There is no need to derive strict limits based on capitals, or to specify in detail the capital requirements of each option. It is sufficient to flag to platform users those ranges of adaptation options thought to be feasible and consistent with the socio-economic scenario under consideration. When carrying out this work, it may be discovered that there are mutual incompatibilities, which will need to be dealt with on a case-by-case basis.

3.3 Second phase of work: future coping capacity

The basic conception is that the coping capacity index is a weighted function of the capital components, which are in turn weighted functions of other components or indicators (Figure 15). For both coping capacity and the vulnerability assessment there is a choice of model forms and methods. In particular, the model could be numerical or qualitative, and it could be driven by observed data or by assumptions.

The purpose of the model is to provide an indicator of the coping capacity that could be brought to bear to deal with climate change during a future decade. This is needed in order to feed into the vulnerability assessment that aims to detect hotspots of vulnerability to particular threats. Vulnerability is being defined as unavoided and unacceptable impacts. There is only weak knowledge (assumption driven) relating the components of coping capacity to their effect in buffering potential impacts. As the overall platform is exploratory, based on stakeholder-derived scenarios, a key possible source of information for defining the change in coping capacity and its components is the stakeholders and the scenarios themselves.

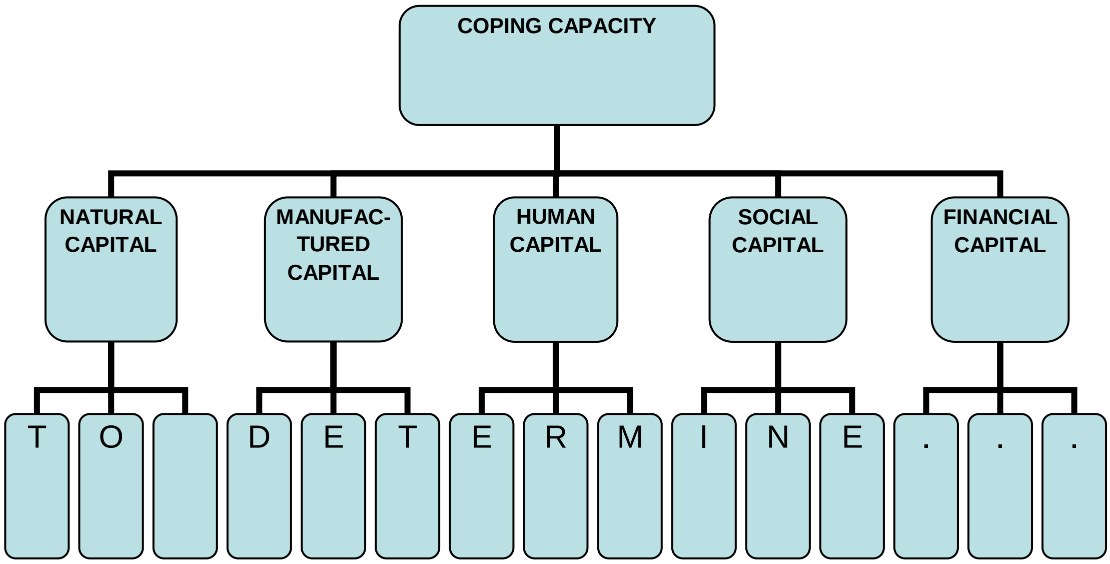

Figure 15: Basic concept for the coping capacity index.

This all points towards a qualitative model, using linguistic descriptors (very low... very high, for example) and constructed via a fuzzy rule base, rather than a crisp model using fixed weights. The overall coping capacity would be defined as a fuzzy function of the capitals, which themselves are defined as fuzzy functions of component or indicator variables.

This could be data-driven for the initial stages, based on the existing World Bank data for capital stocks (but attempting to separate human and social capital from the World Bank's 'intangible' category). By identifying representative clusters in the data, and assigning individual data points memberships of these clusters, it is possible to develop a set of fuzzy rules linking one set of data (capital indicators) to a set of associated data (measured capitals), without hypothesising any particular functional form for the relationship.

Developing a fuzzy model for capitals

There are two basic ways in which a fuzzy model might be implemented. The first option is to look at relationships between pairs of data series, building a number of rule bases, which may then be combined with some weighting factors based on prior knowledge or tuned to the data. The second option is to combine memberships for observations on several variables taken together, and use these to create rules for outcome states. This allows for interaction amongst the variables but this comes at the price of increased dimensionality. In effect, the first approach "solves" the dimensionality problem by restricting the scope for interactions among different input variables.

In the first method, an input data series and output data series are fuzzified (each point is assigned memberships to one or more fuzzy sets) and each pair of data points is used to derive a transformation rule (IF...THEN...). The simplest method only uses the highest memberships for each data point, and weights the final rule by the product of the memberships, though this has the problem that some data points (those with strong memberships of just one set each for input and output) contribute much more to the final rule base than others (those with intermediate memberships for input and output). Carrying out this procedure for all the observations, confidences for the rules with identical IF and THEN parts are added together to give total confidence factors. These are then normalised according to the IF part.

So, for example, there may be rules associating (say) high health expenditures to mid, high or very high human capital. The normalised confidence factor associated with the rule HM: "IF health expenditure HIGH, THEN human capital MEDIUM" is calculated by dividing the total confidence factor for HM by the sum of confidence factors HM + HH + HVH; that is, confidence factors are normalised such that they sum to one for each IF part in the rule base.

An additional rule base relating (say) education expenditure to human capital is derived in the same way, and so on for any further indicators to be used. The rule bases can then be combined using weighting factors, or using fuzzy operators that introduce some degree of compensation (for example the idea that high social capital could derive from strong scores on either 'bonding' or 'bridging' variables) or complementarity (for example the idea that high human capital requires both education and health together).

The second method would develop clusters for the input sets taken together, and then proceed as before. That is, the sets would be for {health, education} and the rules would be IF {low, low} THEN... and so on. This has the advantage of building the compensation/complementarity into the rule base: there is no need for arbitrary weighting factors or operators. The problem is that there are so many more possible rules: if each variable has five fuzzy sets (very low, low, mid, high, very high), then in the first method there are 5x5=25 possible rules relating health to human capital, and 5x5=25 possible rules relating education to human capital: total 50 possible rules, though in practice there will be fewer since some combinations will not arise. In the second method, there could be 5*5=25 possible input types and so 25*5=125 possible rules. In practice fewer clusters could be used to characterise the inputs (the cluster centroids could be determined using a clustering algorithm rather than through combining separate lists for the input variables) and this would reduce the problem somewhat. The number of clusters could be fixed in advance or the optimal number could be determined via a validity function.

Depending on the number of clusters used, and the size of the data set, there could be a problem with gaps in the rule base, i.e. feasible input combinations that have never been observed together. This could arise for several reasons:

- Data shortage: the combination is perfectly possible but just happens not to have been observed in a short data series.
- Impossible combination: the combination cannot arise for some reason integral to the dynamics of the system.
- Third factor: there is a third factor, uncontrolled for, which means that the combination was not possible in the historical period observed, but may be possible under other conditions (e.g. in the future, following climate change and adaptation).

This can be dealt with firstly by judicious choice of input variables (they should show good variation and should not be closely linearly correlated) and secondly by considering vectors of memberships rather than just the highest membership for any given input point. In other words, the rule base can be extended to incorporate not only the most likely rule but all possible associations. This also largely combats the problem that the creation of only one rule with each data point means that some points are weighted more highly in the final outcome than others.

Which method is better will need to be determined during the process of implementing this methodology. It depends largely on the extent of the dimensionality problem, i.e. on the number of input variables retained. The performance of the model could be tested either by omitting some countries from the data used to derive the rule base, and checking the rule predictions for those countries, or by omitting data for the year 2005, and checking the predictions derived based on 1995 and 2000 data. These approaches can be used to select the best predictor variables (inputs), bearing in mind that it is also necessary to select only those inputs that can be predicted for the future scenarios. Having determined the best inputs, the rule base can be re-calculated using the full data set (i.e. for all years and for all European countries).

The discussion above assumes a one-step relationship from indicators to capitals. For some capital types, it may be desirable to introduce an intermediate level – for example, social capital might be constructed from indicators of 'bonding' and 'bridging', which might themselves be constructed from raw data relating to each. The ATEAM research (see section 0) used a framework of indicators-determinants-components-index. Our 'components' are the capital stocks and they can probably be developed/modelled directly from the indicators, but this can be tested.

A subsequent step of 'defuzzification' could transform the rules to point estimates, but this involves substantial loss of information because single numbers tell us much less about the system than the sets of rules. It may be necessary to derive point estimates for the purposes of the vulnerability assessment and/or for graphical presentation. However for the purposes of moving from the capitals to the overall coping capacity index, the fuzzy structure of the data can be maintained.

Extending the capital measures to a coping capacity model

The coping capacity index can be constructed from a fuzzy combination of the component capitals. However, the procedure is a little different because we do not have independent observations of coping capacity, so we cannot derive rules directly from data. Rather we must combine them in essentially an arbitrary fashion, based on our (or stakeholders') conception of the role of capitals in constituting the ability to cope with future climate change.

This could be done by exhaustively listing all the possible combinations, or it could be done by first developing clusters based on observed combinations of capitals (i.e. grouping combinations that are similar) and deriving rules relating each cluster to an overall assessment of coping capacity.

The first approach may appear to be clearer but the number of rules risks being large; on the other hand the calculation could be based on simple weighting factors or operators, including compensation or complementarity where appropriate. Deliberation (perhaps with stakeholders) would focus on deciding how the capitals build up to make coping capacity, where they are required together, and where they can be traded off, and would tend to be more theoretical in nature.

The second approach may be better suited to a more experience-based assessment of coping capacity. By developing clusters, instead of having an exhaustive list of possible capital combinations, we would have characteristic capital combinations that could be identified with certain types of area (for example urban centres of Western Europe, rural hinterlands of Southern Europe) and the deliberation on rules linking these clusters to coping capacity would tend to be more based on views of the actual capacity of such areas.

Attention will also be required to the scaling up or down of the capacity measures. Again use can be made of weights and of compensatory or complementary operators, for example in scaling up from country-based assessments of capacity to an overall European indicator.

An important feature of the approach here – but also more generally – is that variation in the data is preserved in the assessment. Rather than developing a crisp weighting function combining inputs to give a single value for the coping capacity index (say 0.85), the model would give memberships for fuzzy sets (very high, high...). Depending on how the aggregation is done, there could be memberships of more than two sets – the simplest linear methods might replace that example of 0.85 with strong membership of 'high' and some membership of 'very high', for example, but more subtle approaches could distinguish between different ways in which the 0.85 has been reached. For example, the crisp methods could reach 0.85 via a situation in which all the capitals are quite high, or through a situation in which some are very high and some are low. These might be represented in the fuzzy model as, respectively, strong membership of 'high', some of 'very high' and low elsewhere, versus a situation with a more even spread of memberships, reflecting that the capacity is in some respects very high and in others quite low. This preservation of the variability may be useful, acting as a signal to take a closer look at the details in the context of any specific threat.

Although one objective is to develop such an overall representation of coping capacity, the more interesting use of the methods will be when examining the vulnerability of a particular receptor (e.g. sector variable, ecosystem service) to a given threat, in a given region. For this, it is likely to be preferable to go back a step and use the component capital indicators directly, rather than using the overall indicator. This would allow for the nature of the threat and receptor to determine the capitals that are required, and the form of any complementarity or compensation among the capitals. For example, a region might have generally low coping capacity due to low manufactured, financial and human capital variables, but, courtesy of high natural capital, be well protected against certain threats such as drought. In essence the idea would be to recreate the rule base for each kind of threat faced, taking account of the different capital needs of responding to each threat. The extent to which these rule bases would be different in practice remains to be seen, and it will be interesting to explore whether a general overall measure of coping capacity is adequate for assessing vulnerability or whether threat-specific or sector-specific factors play an important role.

Recommendation for assessment of future coping capacity

The next steps in implementing this method are:

- Construct data series for the capital components (based on World Bank). Determine centroids for each capital type for very low to very high levels.
- Source data series for candidate capital indicators, and assess these in terms of (a) their co-linearity and (b) our ability to project them either by correlation with scenario variables, direct inclusion in scenarios, or via the platform outputs.
- Generate rule bases (leaving out a random sample of data points) linking candidate indicator sets to capital sets. Attempt joint modelling using clusters defined over input data together, and if that is problematic, use separate rule bases for each indicator. Consider two-tier models (i.e. indicators, intermediate determinants, capitals) if appropriate.
- Compare results of different indicator sets/methods against predictions for the omitted data. Decide on the best fit overall for mapping the input variables to capitals.
- Determine clusters across the 5-dimensional set of capital values. Develop short descriptions of each cluster – what kind(s) of area(s) / situation(s) it represents.
- Develop a rule base linking these clusters to coping capacity.
- Revisit this analysis for specific threats and receptors: how do the capitals (which are generic features of an area) translate to the specific coping capacity for each threat / receptor?

3.4 Third phase of work: adaptive potential

The third possible part of the adaptive capacity method involves using the platform itself to derive the technological limit of adaptive potential (Lim et al., 2004; see section “Coping ranges and vulnerability”). However vulnerability is measured, we could define the baseline level of vulnerability as that which pertains under a given scenario set, and for a particular time slice, in the absence of any planned adaptation measures (the autonomous adaptation built into the platform cannot be removed). In such a situation, only instantaneous coping stands between exposure/sensitivity and a negative impact. We might then develop an index by fixing two arbitrary points, 0 and 1. Adaptive potential of zero would mean there was no scope to reduce vulnerability from that baseline. Adaptive potential of 1 could be defined as the ability to just manage to reduce vulnerability to zero. Adaptive potentials greater than 1 would be possible, when there is spare capacity (i.e. it would be possible to deal with even worse conditions). Alternatively (and more in keeping with the coping capacity method) this indicator could be considered in fuzzy form.

The potential would be determined by a batch run of the IA Platform to determine what is the best we could do, given all the possible settings for the input variables. Adaptive potentials could be defined for specific impacts, sectors, or whole economies. This does however imply definition of single performance / outcome indicators at each of these levels – or, at least, definition of thresholds of vulnerability – and the adaptive potentials would not be additive or even consistent. That is, we could have an adaptive potential of 1 or more for two sectors taken individually – say, water supply and biodiversity – but less than one for the two together, if the relevant adaptation options conflict. This is related to the general issue of "specific" versus "general" vulnerability and adaptive capacity (Adger et al., 2004). Adaptation to a specific risk – flooding for example – will reduce vulnerability to flooding, but may increase vulnerability to other risks, and even overall ('general' vulnerability) either directly through external impacts on other areas or sectors, or by reducing the capital stocks available for other adaptation or coping.

Adaptive capacity would then be limited by the adaptive potential, and could be less, if the capitals available are considered to limit the ability to apply particular adaptation options. And actual adaptation – the choices made by platform users – could again be different, because of different weightings applied to outcomes, unwillingness to take (bear the costs of) a specific adaptation option, and so on.

Recommendation for assessment of adaptive potential

At present, this possible line of work is not a priority, because it is not needed within the platform. We will need to return to this in the context of two later tasks:

- Task 4.1: Social, economic and environmental **metrics of impacts and sensitivity** will be developed for cross-sectoral comparison.
- Task 4.4: The cost-effectiveness of well-defined adaptation strategies (on project and policy levels) will be determined by valuing the **net cost of adaptation options** under climate uncertainty.

4. Discussion and conclusions

This deliverable has set out the way in which the CLIMSAVE project, and in particular the IA Platform interface, can define, measure and utilise the concept of "adaptive capacity". The methods presented here have evolved during the project to date, and may need to co-evolve further with the method for defining and measuring vulnerability. The adaptive capacity workplan can be split into three main parts, summarised below.

Current adaptive capacity

The first part of the adaptive capacity work involves determining how the adaptive capacity under each scenario may restrict the feasible range of adaptation choices from among the full set represented in the platform. After consideration of the possibilities, it was decided that there is no need to derive strict limits based on capitals, or to specify in detail the capital requirements of each option. It is sufficient to flag to platform users those ranges of adaptation options thought to be feasible and consistent with the socio-economic scenario under consideration. These constraints are indicative but not binding, in order to maintain maximum flexibility for platform users. Separate feasibility ranges will be derived for each scenario and adaptation option pairing. Where mutual incompatibilities are identified across options, these will need to be dealt with on a case-by-case basis.

Future coping capacity

The second part relates to *coping* within future time slices, and is not directly predicted by the platform. The adaptation options in the platform reduce vulnerability by decreasing sensitivity, and/or decreasing exposure, and/or increasing coping capacity. We need to derive an expression of coping capacity that is based on the scenarios and the capitals, after accounting for the adaptation options selected by a platform user.

This can be done by constructing a fuzzy logic rule base relating determinants/indicators of capitals to the capital stocks, drawing on World Bank data and other sources. A second step in the work will develop representative clusters for capital holdings in different areas, describe the areas represented, and build a rule base linking capitals to coping capacity. This will give our aggregate coping capacity indicator. We will then explore whether this analysis needs to be repeated for specific threats and receptors, recognising that the capitals required for coping may differ with these factors.

Adaptive potential

A possible third part lies in the recognition that actual adaptation may be less than adaptive capacity. The adaptive capacity is the maximum amount of adaptation possible, for any given combination of socio-economic and climate scenarios. This can be calculated by testing all the different possible combinations of adaptation options, taking into account capital constraints and the impacts on coping capacity. This is not directly part of the adaptive capacity work in the context of developing the IA Platform (it will use the platform, but will not be used within it) and can be left for further development in the context of later CLIMSAVE work streams on cross-sectoral comparison and cost-effectiveness.

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