Adaptation to Climate Change:

Formulating Policy under Uncertainty

Leo Dobes
Crawford School of Economics and Government, Australian National University
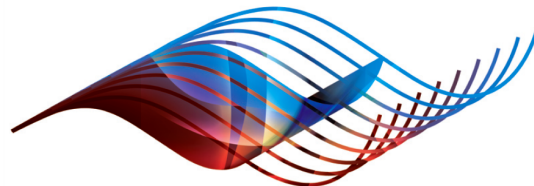
Abstract
Economists were able to formulate and recommend policy approaches for reducing emissions of greenhouse gases (mitigation) by drawing on an existing body of economic theory related to externalities. However, no comparably straightforward approach has yet emerged in the adaptation literature, possibly due to the diffuse nature of climatic effects that may occur in very diverse geographical locations. By acknowledging that the hallmark of future climate change effects is uncertainty, rather than readily identifiable and deterministic outcomes, it is possible to formulate coherent policy approaches. Recognising that there are differing degrees of uncertainty is a key aspect to making policy formulation more realistic.

CLIMATE
Economics & Policy

The **Centre for Climate Economics & Policy** (ccep.anu.edu.au) is an organized research unit at the Crawford School of Economics and Government, The Australian National University. The working paper series is intended to facilitate academic and policy discussion, and the views expressed in working papers are those of the authors. Contact for the Centre: Dr Frank Jotzo, frank.jotzo@anu.edu.au.

ADAPTATION TO CLIMATE CHANGE: FORMULATING POLICY UNDER UNCERTAINTY

Leo Dobes
Adjunct Associate Professor
Crawford School of Economics and Government
The Australian National University
Leo.Dobes@anu.edu.au
Personal page: http://www.crawford.anu.edu.au/staff/ldobes.php

Abstract

Economists were able to formulate and recommend policy approaches for reducing emissions of greenhouse gases (mitigation) by drawing on an existing body of economic theory related to externalities. However, no comparably straightforward approach has yet emerged in the adaptation literature, possibly due to the diffuse nature of climatic effects that may occur in very diverse geographical locations. By acknowledging that the hallmark of future climate change effects is uncertainty, rather than readily identifiable and deterministic outcomes, it is possible to formulate coherent policy approaches. Recognising that there are differing degrees of uncertainty is a key aspect to making policy formulation more realistic.

Key words: adaptation, climate change, risk, uncertainty, unknown unknowns,

JEL codes: G11, H43, O44, Q54

Introduction

Economists have been able to successfully formulate policy responses for reducing emissions (mitigation) by drawing on a long history of relevant economic theory. Notwithstanding considerable debate, including at the political level, the key approaches proposed were carbon pricing and its alternative of trading a fixed quantum of emissions. The task was made easier because scientists nominated specific greenhouse gases whose increased atmospheric concentrations are considered to cause climatic change.

No comparably straightforward approach has emerged in the literature on adaptation to climate change. The effects of climate change will differ between even proximate geographical areas. Nor is it possible to forecast with any accuracy the localised timing, intensity or frequency of the effects of climate change, or even the number of people affected. Unlike mitigation, a public good on a global scale, adaptation may be a private good or a public good. Further, the amorphous nature of climate change means that there is no common quality that captures the essence of 'adaptation' activity.

Unsurprisingly, a farrago of perspectives exists; invariably reflecting the special interests or conceptual frames of the proponents. Preston (2010) advocates regulation combined with judicial review, while McDonald (2010, pp. 257) raises the possibility of increased uncertainty arising from tort litigation due to different geographical circumstances. Insurers are paying increasing attention to extreme events and new forms of reducing their exposure to them (e.g. Kunreuther & Michel-Kerjan, 2009). Planners and engineers tend to look to the presumed safety of increased standards (e.g. Standards Australia/Standards New Zealand 2009) and tighter design guidelines (e.g. Engineers Australia 2004; Royal Academy of Engineering 2011). Prioritised fortification of infrastructure is espoused by du Vair et al (2002). Julia & Duchin (2007) consider world trade to offer an efficient adjustment mechanism for agricultural outputs, and Mendelsohn (2006) takes a similar position for traded goods more generally. Hallegatte et al (2007) draw on mean rainfall and temperatures in 17 European cities as analogues of a future climate and its economic impact on Paris. Historians have also sought to draw on cases such as the abandonment of Viking settlements in Greenland (Orlove 2005) and Van der Eng (2010) shows that well-functioning regional rice markets in Java in the 1930s ameliorated the effects of drought. Petheram et al (2010) remind us that knowledge held by indigenous peoples may provide useful lessons for adaptation. Woodruff et al (2006) appear to favour early action to avoid health hazards of climate change, while proponents of 'clumsy muddling through' like Verweij & Thompson (2006) would probably prefer to hasten slowly in the face of 'wicked problems' such as climate change. Finally, Butzengeiger-Geyer et al (2011) review market mechanisms that have been advocated for mitigation, with a view to applying them to adaptation, although they concede that it would first be necessary to define a 'unit' of adaptation.

However, the two most popular policy approaches appear to be 'risk management' and various forms of composite indexes, including Multi-Criteria Analysis. Both approaches pose significant risks of maladaptation; the inefficient utilisation of community resources. Their growing use in government policy formulation merits serious, critical review.

Risk management is increasingly the approach of choice in framing policy on adaptation to climate change (Jones & Preston 2011, p. 296; Australian Government 2010a, p. 15). It involves the identification of risks facing an individual or organisation, quantification of the

likelihood of the risk, specification of the potential consequences, and implementation of action to reduce the risk. Because it relies on identification and quantification of risk, its use in analysing the effects of uncertain climate change is incongruous. Randall (2011, p. 76) notes that 'ordinary risk management' approaches reflect 'bell-curve thinking' because they focus on most likely outcomes, whereas climate change outcomes are more realistically represented as skewed, extreme-value, fat-tail distributions.

Composite indexes are popular in many spheres, including league tables of 'most liveable' cities, the benchmarking of 'international competitiveness' of different economies, the Human Development Index, environmental hazards, and the vulnerability or adaptive capacity of communities in the face of climate change. Multi-Criteria Analysis, based on a similar approach to composite indexes, is also promoted as a means of assessing adaptation measures that might be taken to meet the challenges of climate change. Dobes & Bennett (2009) highlight the highly arbitrary and mathematically flawed nature of the composite index technique. Persson (2011, p. 9) notes that the 'scientific community is in disagreement on the feasibility of indices'. Critiques can also be found in Cox (2009), Fuessel (2009), Pollitt (2010) and Wolff et al (2011).

Indeed, the hallmark of climate change is uncertainty. Combinations and permutations of different meteorological events, regional and seasonal differences, the unknown timing, intensity or frequency of extreme events, the emergence of new technologies, the relationship between greenhouse gas emissions and their atmospheric concentrations over time, changes in global production patterns and volumes, natural phenomena such as volcano eruptions, population levels and movements, modelling (simulation) of climate change, etc, all combine to generate significant uncertainty about the specific future effects of climate change at the local level. According to IPCC (2011, p. 9), 'even the sign of projected changes in some climate extremes [in the coming two to three decades] is uncertain'. There is now a growing awareness that uncertainty in our knowledge is a key policy issue (e.g. Hallegatte 2009). Linear, deterministic measures such as fortifying infrastructure or imposing regulatory controls are unlikely to produce optimal adaptation outcomes.

Economists have traditionally adopted a distinction between 'risk' and 'uncertainty', and have focused unduly on the former (Woodward and Bishop 1997, p. 505) in policy advice and analysis. However, there are different forms and degrees of uncertainty, ranging from a reasonable amount of knowledge through to total 'ignorance'. This paper expands the traditional approach to incorporate broader concepts of uncertainty where there is even no awareness of the nature of the uncertainty, let alone its probability of occurrence.

It is assumed throughout that adaptation should make efficient use of the community's resources. Climate change can be thought of as a pervasive economic shock that will potentially affect all sectors of the economy, albeit in different ways. Economically efficient adjustment will help ensure that society's well-being will be reduced less than otherwise.

Knightian uncertainty and the Rumsfeldian matrix

It has been a common starting point for economists[1] to distinguish risk and uncertainty along the lines espoused in1921 by Knight (2009, p. 9):

---

[1] For example, Woodward & Bishop (1997) and Randall (2011). Quiggin (2008) focuses on the post World War II expected utility and state-contingent approaches, but acknowledges the early contribution of Knight (1921), as well as Keynes.

'It will appear that a measurable uncertainty, or "risk" proper, as we shall use the term, is so far different from an unmeasurable one that it is not in effect an uncertainty at all. We shall accordingly restrict the term "uncertainty" to cases of the non-quantitative type.'

Knight (2009, original 1921, p. 121) elaborates on his definition as follows:

'The practical difference between the two categories, risk and uncertainty, is that in the former the distribution of the outcome in a group of instances is known (either through calculation a priori or from statistics of past experience), while in the case of uncertainty this is not true, the reason being in general that it is impossible to form a group of instances, because the situation dealt with is in a high degree unique.'

Clearly, Knight was concerned with cases where at least the event in question could be identified, even if its probability of occurrence could not always be estimated. In this sense, his formulation of uncertainty is incomplete, because he does not include instances where even the event itself is unknown and unforeseeable, not merely unpredictable.

Figure 1 Known and unknown aspects of climate change

	known **probability**	**unknown** **probability**
known **event or** **consequence**	(I) 'known knowns' (e.g. increased local temperatures for longer periods will affect crop cycles)	(II) 'known unknowns' (e.g. rising ocean temperatures may increase the intensity of cyclones but the frequency of occurrence is not known)
unknown **event or** **consequence**	(III) 'unknown knowns' (e.g. an indigenous person knows of a rare pest that will thrive in a warmer climate but has not told the responsible authorities about it)	(IV) 'unknown unknowns' (ex post only: e.g. corroded sewer pipes due to reduced water flow in adaptation to drought)

'Unknown unknowns' – events that can neither be foretold in character, nor predicted in probability of occurrence – were a term of art in military circles well before 2002 when U.S. Defense Secretary Donald Rumsfeld famously occasioned considerable, albeit misplaced, mirth in the media with his use of the term in the context of the war in Iraq. Such cases can by definition become apparent only after the fact, once they have occurred and their nature

revealed to the world at large. They represent total uncertainty or 'ignorance' of a kind not addressed by Knight.

Figure 1 integrates the Knightian dichotomy with the 'Rumsfeldian' approach. It borrows Knight's distinction between knowledge or measurability of probability and lack of it: shown in the columns. The events to which the probabilities refer are shown in the rows as being either known in character, or not. In this case, the events refer to future effects of climate change. Similar tables have been presented by others (e.g. Bammer et al 2008, p. 293) but from perspectives other than climate change. The categorisation of risk and uncertainty in Figure 1 is only illustrative and should not be taken to represent a definitive taxonomy[2].

The lens of Rumsfeldian uncertainty allows us to examine adaptation to climate change in a more systematic manner than merely focusing on a deterministic approach based on currently identifiable effects of climate change.

'Known knowns' (quadrant I)

Quadrant I ('known knowns') corresponds approximately to Knight's conceptualisation of 'risk' in that both the event and its probability of occurrence are known, or at least foreseeable or discoverable. It also appears to match the concept of 'aleatory uncertainty', or the natural variability of the system under study, used by Compton et al (2009, section 1.2). An example might be the effect on crop cycles of higher minimum or maximum temperatures (e.g. Franks et al, 2007).

In the case of climate change, private individuals can be assumed to have sufficient knowledge to adapt to 'known knowns', provided that governments and the media disseminate information normally. The identification of any barriers (e.g. regulatory constraints) should also be relatively straightforward in such situations, and hence amenable to removal by the responsible jurisdiction.

Evaluation by either private individuals or by governments of proposed adaptation measures in situations where both the likely effects and their probabilities are known is readily addressed through individual investment analysis, or social cost-benefit analysis in the case of government. The magnitudes of flows of costs and benefits can be adjusted by their probability of occurrence, either directly or in decision-trees, to generated expected values. Discounting can be used to reduce expected values to present values.

A conventional Cost-Benefit Analysis is illustrated in Figure 2 as the construction of a dike in 2012 to prevent flooding. Arrows above the horizontal timeline represent the values of projected benefits; those below represent costs. It is standard to show costs and benefits as accruing at the end of each year. Figure 2 assumes certainty, or at least a very high level of confidence, about the value of future benefits and costs. Future values of costs and benefits are normally discounted back to the present – in this case the year 2012 – to obtain the Net Present Value of the project.

---

[2] In assessing 'medical ignorance', Kerwin (1993), for example, distinguishes 6 categories of uncertainty, including taboos (things that people are not supposed to know) and denial (things that are suppressed because they are too painful to know).

Figure 2: Typical Cost-Benefit Analysis under certainty
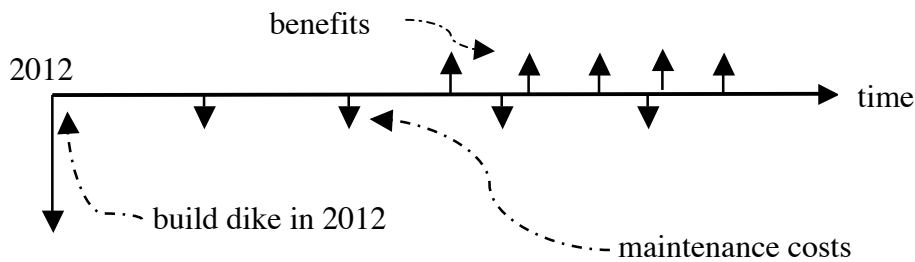
The textbook decision-criterion for conventional Cost-Benefit Analysis is invariably given as net present value needing to be greater than zero, implying that the present value of social benefits must exceed that of social costs. However, even negative net present values may turn out to be positive once quasi-option values (see 'real options' below) are added to the conventional result. In practice, decision-makers also need to take into account budget constraints and the net present values of alternative projects.

Where it is possible to specify the probabilities that are associated with the realisation of costs and benefits, it is possible to calculate expected values. The sum of the probability weighted set of n contingencies is the expected value of the net benefit [E(NB)] as in the following equation (discounting would be required to obtain the present value equivalent of the expected value):

$$E[NB] = p_1(B_1 - C_1) + \ldots + p_i(Bi - C_i) + \ldots + p_n(B_n - C_n)$$

Because it is possible to specify the probabilities, the 'expected value' approach can be considered to fall in the category of 'Knightian risk'. Indeed, in cost benefit analysis 'it is common practice to treat expected values as if they were certain amounts' (Boardman et al 2006, p. 170). Risk neutrality is an underlying assumption.

Efficient adaptation by the public sector to 'known knowns' may be subject to potentially significant capacity barriers. Where government adaptation measures are contemplated, they should be subjected to social cost-benefit analysis. But knowledge of economic appraisal methodologies among public servants is not pervasive; representing an important impediment to the efficient implementation of adaptation measures. Where governments consider adaptation measures in isolation – that is, in isolation from other potential projects like hospitals and schools – there is a further risk of so-called 'stovepiping' that can result in socially sub-optimal outcomes.

A further risk of socially sub-optimal outcomes lies in the popular use of 'damage costs avoided' as a measure of economic benefit. At best, damage costs avoided are a very poor proxy for the conceptually correct measure of 'willingness to pay' for adaptation measures, or the converse of 'willingness to accept' any negative aspects associated with climate change. Estimation of benefits on the basis of 'willingness to pay' to avoid floods of varying heights would ideally be carried out using a stated preference technique such as Contingent Valuation (Boardman et al, 2006, ch. 14; Bateman et al 2002), or Choice Modelling (Henscher et al 2005).

One reason for the use of 'damage costs avoided' is undoubtedly the dearth of 'willingness to pay' estimates. There is an arguable case for governments to fund a series of studies – preferably in the form of stated preference using Choice Modelling – to determine willingness to pay to ameliorate the effects of cyclones, floods, bushfires, etc, in different geographical regions. A national database along the lines of the Canadian EVRI[3] would be useful for evaluating mitigation works to limit the effect of 'normal' extreme events, as well as those attributable to climate change.

'Known unknowns' (quadrant II)

'Known unknowns' can be typified as events whose natures are known, but their probability of occurrence is not; a close approximation to Knightian uncertainty. The example given in Figure 1 is that of rising sea temperatures resulting in increased frequency or intensity of cyclones but without specific knowledge about the extent of the expected changes. This category appears to correspond to the term 'epistemic uncertainty' – lack of knowledge about the system which can be due to absence of reliable historical data, errors in measurement, etc – used by Compton et al (2009, section 1.2).

Faced with uncertainty about either event outcomes or their likelihoods, decision-makers may resort to consulting experts, either individually or collectively. Consultation with individual experts is problematic because there is no clear decision-rule to guide the decision-maker on the choice of the most informed person. Elicitation of information from a group of experts – assuming that they are the 'most informed' group – using what is generally known as the Delphi method can also be problematic in a situation of uncertainty, because the lack of certainty is likely to produce differing views. For example, Arnell et al (2005) unsuccessfully sought the views of experts on the likelihood of rapid climate change due to the collapse of the thermohaline circulation, primarily because of the range of views expressed.

Projects involving cases of 'known unknowns' can be evaluated within a social cost-benefit framework using 'real[4] options' (see for example, Dixit & Pindyck 1994; Copeland & Antikarov 2001; Trigeorgis 1996; etc.) to augment net present values by taking into account the value of strategic flexibility. Examples of the application of the real options approach to adaptation to climate change can be found in Hertzler (2007), Dobes (2008), Howes and Dobes (2011), Linquiti & Vonortas (in press) and Dobes (2012, in press). However, the application of real options to adaptation issues has been very limited to date.

Individuals often use real options intuitively to maintain flexibility of action in the face of uncertainty. For example, a young couple buying a residence will often be uncertain whether they will continue to live there if they change occupations, whether they will have a large family or whether the residence might also be used for business purposes. In such circumstances, a 'real option' may be to purchase a smaller residence, but with sufficient land for future extensions if they prove warranted. The cost of the additional land in this example is effectively the premium paid for the right (but with no obligation) to extend the house in future once better information becomes available.

---

[3] Environmental Valuation Reference Inventory that is maintained by Canada and partially funded by a consortium of other governments <http://www.environment.nsw.gov.au/publications/evri.htm>

[4] 'Real' denotes 'physical' assets. The concept and evaluation methodology for real options is analogous to (financial) options on financial assets such as shares.

In one sense, real options are a compromise middle course between two investment extremes. On the one the hand, a full investment today may never be required, so that resources become a sunk cost. On the other hand, if no investment is made at all, there may be cause for regret if potential benefits are not realised. Like any other investment, real options involve risk. However, the downside risk is lower than for a full and immediate investment in the face of uncertainty.

Figure 3: Example of a 'real option' in building a dike
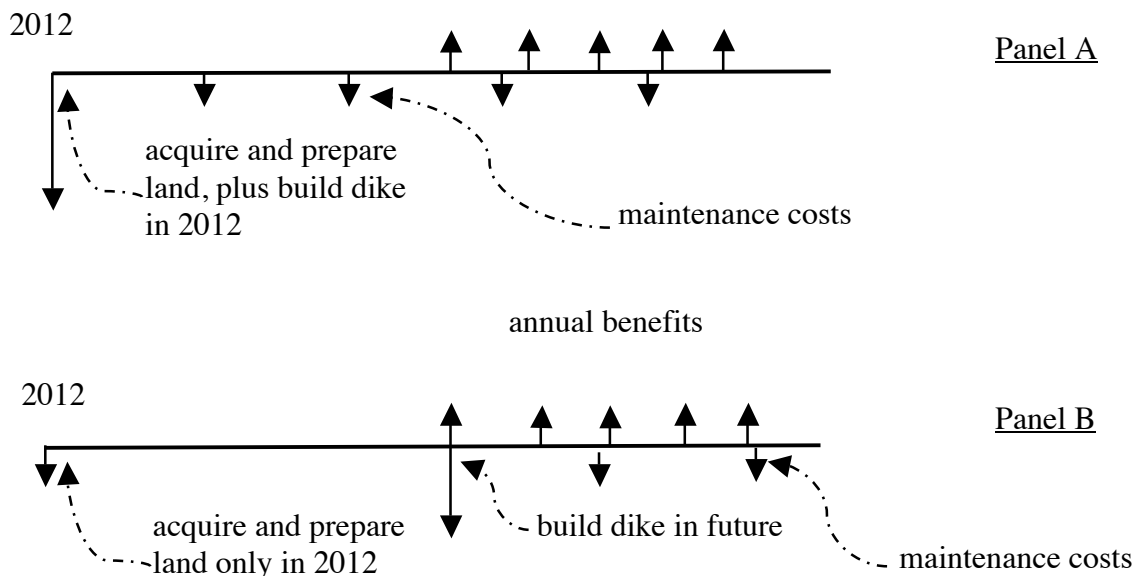
The concept of a 'real option' in the context of adaptation to uncertain climate change is illustrated in Figure 3. Panel B shows an alternative to immediate construction of a dike: only preparatory work is undertaken (e.g. acquisition and preparation of land) as an interim step that creates the option (but no obligation) of construction in the future. Panel A replicates the conventional Cost-Benefit Analysis presented in Figure 2 above: in effect the calculation of the Net Present Value in panel A establishes the value of the underlying asset if the option is exercised immediately, so there is no residual option value[5]. It therefore provides a point of comparison with Panel B where the option is only exercised at some future date.

The difference in Net Present Value between panels A and B is the 'option value' that reflects the value of strategic flexibility in the face of uncertainty, and the cost of acquiring and preparing the land is the 'premium' that must be paid to make available the opportunity to exercise future investment flexibility. The greater the degree of uncertainty, and the longer the period during which the option can be exercised, the greater is the value of the flexibility afforded by the option.

The decision criterion in a project that embeds an option is that the net present value of the project, *plus* the option value, should exceed zero. Note that the creation or embedding of an

---

[5] Note also that immediate and full investment is also envisaged by the strong version of the 'precautionary principle' that is often advocated by techno-scientific groups on the assumption of avoiding possible disasters.

option in a project may mean that it is justifiable on cost-benefit grounds, even if the Net Present Value of the project itself (i.e. without an option) is less than zero. Put another way, an adaptation project such as building a dike that does not commit all of its investment resources immediately may[6] be more socially beneficial in the face of uncertainty about climate change than one where all the funds are expended on the project at the outset. Some of the more accessible literature on identifying and valuing real options includes Brealey et al (2006, ch.22), Boardman et al (2006, chs. 7-8), *The Economist* (1999), Luehrmann (1998a, 1998b), Neufville et al (2006), Kester (1984), Borison (2005), Dixit & Pindyck (1994) and Linquiti & Vonortas (in press).

Current practice is for government funding appropriations to be geared towards immediate decisions on projects, with performance often measured in terms of expenditure against a predetermined schedule. Such systems implicitly assume certainty about the future. The apparent lack of an approach to 'budgeting under uncertainty' in conventional public sector fiscal arrangements thus represents an administrative barrier to efficient adaptation. Adaptation projects that may be found to be socially worthwhile once the option value is included in the net present value calculation may not be implemented, resulting in the loss of a potential benefit, a case of a 'regret', or opportunity cost to society.

Overcoming the administrative barrier of current budgeting approaches would require not only a review of fiscal practices, but also a change in mindset among public servants and politicians. A real options approach requires a degree of lateral thinking and intensive consultation with stakeholders to ensure that all possible alternatives – including interim solutions – have been considered before policy is formulated for consideration by governments. Real options are not merely an analytical tool – they also involve a broader approach to problems than deterministic or mechanistic responses. To the extent that cultural change within government can be instituted, it may well represent a 'no regrets' measure because it would improve general decision-making processes.

'Unknown knowns' (quadrant III)

A case not explicitly mentioned by US Defense Secretary Rumsfeld in his categorisation of uncertainty[7] was that of 'unknown knowns'. This category is more difficult than the other quadrants to conceptualise, but is sometimes taken to mean 'conscious ignorance': Bammer et al (2008, p. 293) give the example of riding a bicycle, an act that is harder to accomplish 'when thinking about the actions involved and their necessary sequence'. However, Taleb's (2007) example of the black swan seems more pertinent: even though Europeans, in their 'ignorance' were unaware of the existence of black swans, it was known to the inhabitants of Australia, and, probably, Asian traders who visited the shores of the continent. Smithson (2008, pp. 19, 24) gives the example of the Wollemi Pine[8]: while the general public is unaware of the location of the remnant grove, it is known to a small number of officials.

---

[6] Implementation of a real option is not guaranteed to produce a net present value greater than zero. Dobes (2010), for example, estimated the net present value of a Bluescope Buildings (Vietnam) house with the option of being demounted and moved was probably less than reconstruction of a Mekong delta equivalent with fixed stilts.

[7] An example that Mr Rumsfeld might validly have used could have been a breakdown in battlefield communications where information available to an intelligence unit is not transmitted to a local commander.

[8] Prior to discovery in 1994 of a grove of living specimens near Sydney, the Wollemi Pine (*Wollemia nobilis*) had been known only from fossils, some dating back 200 million years.

As with most categorisations, conceptual and philosophical caveats abound. For example, perspective or 'standing' is critical to the black swan example. To humanity as a whole, the black swan is more accurately presented as a 'known known', but to Europeans alone it was more of an 'unknown unknown'. Nevertheless this apparent classificatory problem provides an important lesson for transforming 'unknown knowns' into 'known knowns' and 'known unknowns' in the context of climate change.

Figure 4: The black swan: an 'unknown known', or a 'known known'?
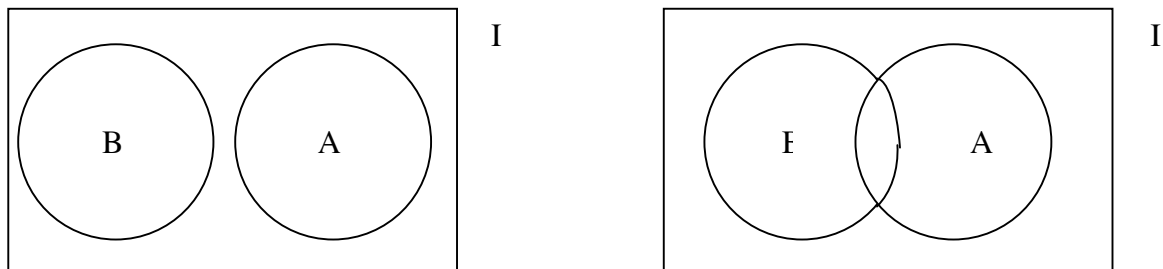
The Universal set I contains residents of Europe {B} and Australia {A}, but they cannot communicate with each other. $A \cap B = \varnothing$	The Universal set I contains residents of Europe {B} and Australia {A}, who can communicate with each other. $A \cap B > \varnothing$

A potential barrier to socially efficient adaptation is lack of adequate consultation with all stakeholders, to ensure that knowledge of 'unknown' black swans becomes more generally 'known'. The more encompassing the consultation, the more likely that a suitable adaptation measure is known to someone (even if unknown to most people) and can be implemented. Alternatively, someone may suggest a hitherto unconsidered inexpensive incipient solution or 'real option'. Genuinely detailed, extensive and open-minded consultation with the public is required on the part of responsible officials to surmount the 'unknown' component of 'unknown knowns'.

Left to officials alone, there is a considerable risk that adaptation measures will be limited to the relatively narrow professional knowledge and concerns of those officials (Dobes 2009). For example, council engineers are likely to focus on ensuring that roads are 'climate-proofed' to ensure that they are accessible throughout the year for 'productive' purposes such as access to employment. Where this occurs, consumers' preferences are likely to be given lower priority in determining adaptation measures. Golf courses may well be neglected, even if local residents have a stronger preference to play golf 365 days a year than to travel by road to shops or to work. A socially better outcome might well be to allow intermittent flooding of the road to the shops and workplaces, but more certain access to the golf course. Again, a barrier to efficient adaptation is the lack of research into preferences (in the form of 'willingness to pay') of consumers.

'Unknown unknowns' (quadrant IV)

By definition, the category of 'unknown unknowns' (quadrant IV) represents total ex ante ignorance, being revealed only after an event has occurred. For practical purposes, the 'unknown unknowns' category is taken to mean events that would not normally be actively perceived, even by those who might have been expected to know. The Knightian definition of uncertainty does not encompass this perspective of total uncertainty because neither the event, nor its probability of occurrence is known.

Melbourne's sewers were designed with specific gradients to operate at a specific flow rate. Although the design engineers may have been aware of some risk at the time, there does not seem to have been any general anticipation of the possibility that water saving campaigns due to a prolonged drought or climate change would have the unintended consequence of reducing flow rates below minimal 'self-cleaning' transmission velocities. This aspect is probably most appropriately categorised as an 'unknown known' because design engineers would have been aware of a potential problem if flow rates were reduced, although most people would not.

However, an apparently entirely unforeseen outcome of greater deposition of biological matter in sewer pipes has been an 'increased … risk of sewer corrosion [from hydrogen sulphide gas build-up] and odours due to more concentrated and warmer sewage' (Melbourne Water, 2011). Although the possibility of greater deposition may well have been appreciated by design engineers, it is less likely that they would also have considered the further possibility of corrosion due to the increased production of hydrogen sulphide gas due to more concentrated and warmer sewage. It is at least arguable that this outcome of unexpected pipe corrosion could be classified as an 'unknown unknown'.

By definition, there is no ready means of analysing or appraising specific measures that can be used to adapt to 'unknown unknowns'. Ignoring problems such as expense and moral hazard, one adaptive response might be for governments to adopt the role of 'insurer of last resort' and cover the future costs of all extreme 'unknown unknown' events. However, blanket coverage of all potential adverse events would reduce the incentive on residents to undertake adaptation measures on their own account. Unless a way can be found to obviate such 'moral hazard' effects, governments acting as insurers of last resort could incur substantial costs, as well as inducing sub-optimal social outcomes.

A general lesson that can be drawn by analogy from the 'real options' approach is that flexibility is valuable in the face of uncertainty. Applied to a situation of 'unknown unknowns', it is at least arguable that adaptation can be achieved more efficiently in a socio-economic setting that is more flexible and organically responsive to change.

In particular, there are two areas where greater socio-economic flexibility would be merited:

1. Extensive use of the term 'governance' has tended to devalue and diffuse its meaning. However, it remains useful in the climate change context for denoting the coherence of policy formulation and distribution of jurisdictional responsibilities. Duplication or gaps in roles between different levels of government are likely to arise, given the uncertainty that accompanies climate change. This is especially true of the 'unknown unknowns' where entirely unexpected, unique situations may arise that require either particularly close coordination between different agencies, or the assumption of

responsibility by one of them in the prior absence of clearly defined legislative or political power.

One means of solving the issue is to establish a new coordinating agency with broad powers and ultimate responsibility for all climate change issues. However, an additional administrative layer is not guaranteed to provide the most efficient solution.

Where existing emergency services can deal satisfactorily with unexpected hazards such as fires and floods, it may best to retain their current responsibilities whether an event is due to climate change or not. The same is probably true for non-emergency services that are best able to incorporate ('mainstream') any additional considerations that may be required to address climate change. However, it may be worthwhile reviewing current institutional arrangements with regard to the principle of subsidiarity: with responsibility for action delegated to levels where it can be most efficiently implemented.

2. A comprehensive program of microeconomic reform would probably go a long way to increasing the flexibility of economic activity in adapting to climate change. Freer labour markets (including freer immigration policies), removal of 'exceptional circumstances' subsidies for farmers in perennially drought-affected areas, further deregulation of sectors such as trade, education, health services, etc, would all contribute to smoother structural adjustment in response to any economic shocks due to climate change. If climate change results in proportionately more 'unknown unknown' effects than 'known knowns', comprehensive reform may be more effective than addressing only the obvious barriers to 'known knowns'.

There is also a risk that limited, partial microeconomic reform will have unintended distortionary consequences along the lines of Lipsey & Lancaster's (1956-1957) General Theory of Second Best. This is potentially a problem where governments seek only to address barriers to adaptation in areas characterised by 'known knowns' because they are readily identifiable.

Despite the political difficulties that they would inevitably entail, comprehensive microeconomic reform and a review of institutional arrangements represent 'no regrets' measures because they would also help promote economic growth. Although growth in itself is not guaranteed to facilitate adaptation to climate change, it would make more resources available to the community to implement adaptation measures, or for other social needs.

Some concluding thoughts

Understandably, there appears to be considerable reluctance to consider climate change through the lens of uncertainty. Techno-scientific specialists in particular will prefer to stick to deterministic 'risk management' approaches, despite the fact that they are predicated on being able to identify and/or quantify the risk involved. The most recent standards for risk management (Standards Australia/Standards New Zealand 2009) skirt the important issue of uncertainty, and Jones (2008, p. 269) points out that even in 'the discipline of law there is no coherent discourse or even conscious or structured consideration of uncertainty – despite the fact that uncertainty is pervasive'.

Kerwin (1993, p. 172) recounts how Socrates, who was more aware of the extent of his own ignorance than many others, was pronounced by the Oracle at Delphi to be the 'wisest of men' because of his self-knowledge. Acknowledging uncertainty can provide a fecund basis for developing an improved level of knowledge, because it will eventually spur further inquiry and investigation. Once acknowledged, uncertainty is also more amenable to being managed. It is better to acknowledge and embrace uncertainty, than to limit ourselves to the bias of the comfort zone that we 'know'.

REFERENCES

Arnell, N.W., Tompkins, E.L. & W.N. Adger 2005, 'Eliciting information from experts on the likelihood of rapid climate change', *Risk Analysis*, vol. 25, no. 6, pp. 1419-1431.

Bammer, G. & M. Smithson (eds) 2008, *Uncertainty and risk. Multidisciplinary perspectives*, Earthscan, UK and USA.

Bammer, G., Smithson, M., & the Goolabri Group 2008, 'The nature of uncertainty', ch. 24 in Bammer & Smithson (2008), pp. 289-303.

Bateman, I.J., Carson, I.T., Day, B., Hanemann, M., Hanley, N., Tannis H., Jones-Lee, M., Loomes, G., Mourato, S., Ozdemiroglu, E., Pearce, D.W., Sugden, R., & J. Swanson 2002, *Economic valuation with stated preference techniques: a manual*, Edward Elgar, UK.

Boardman, A.E., Greenberg, D.H., Vining, A.R. & D.L. Weimer, 2006, *Cost-benefit analysis: concepts and practice*, 3rd edition, Pearson Prentice Hall, New Jersey.

Borison, A. 2005, 'Real options analysis: where are the emperor's clothes?', *Journal of Applied Corporate Finance*, vol. 17, no. 2, pp. 17-31.

Brealey, R.A., Myers, S.C. & F. Allen 2006, *Principles of corporate finance*, 8th edition, McGraw Hill Irwin, New York.

Bonyhady, T., Macintosh, A. & J. McDonald (eds) 2010, *Adaptation to climate change. Law and Policy*, Federation Press, Sydney.

Compton, K.L., Faber, R., Ermolieva, T.Y., Linnerooth-Bayer, J., & H-P Nachtnebel 2009, *Uncertainty and disaster risk management. Modelling the flash flood risk to Vienna and its subway system*, International Institute for Applied Systems Analysis, RR-09-002, Laxenberg, Austria.

Copeland, T. & V. Antikarov 2001, *Real options. A practitioner's guide*, Texere, New York.

Dixit, A.K. & R.S. Pindyck 1994, *Investment under uncertainty*, Princeton University Press, New Jersey.

Dobes, L. 2008, 'Getting real about adapting to climate change: using 'real options' to address the uncertainties' *Agenda*, vol. 15, no. 3, pp. 55-69. http://epress.anu.edu.au/agenda/015/03/pdf/15-3-AR-1.pdf

Dobes, L. 2009, 'People versus planners: social preferences for adaptation to climate change', Environmental Economics Research Hub, report no. 42, ISSN 1835-9728, The Australian National University, Canberra. http://www.crawford.anu.edu.au/research_units/eerh/pdf/EERH_RR41.pdf

Dobes, L. 2010, 'Notes on applying "real options" to climate change adaptation measures, with examples from Vietnam', Centre for Climate Economics and Policy, Crawford School of Economics and Government, Australian National University, Working Paper 7.10. http://www.crawford.anu.edu.au/research_units/eerh/pdf/EERH_RR75.pdf

Dobes, L. 2012 (in press), 'Sir Sidney Kidman: Australia's cattle king as pioneer of adaptation to climatic uncertainty', *The Rangeland Journal*, vol. 34.

Dobes, L. & J. Bennett, 2009, 'Multi-criteria Analysis: "Good Enough" for government work?', *Agenda*, vol. 16, no. 3, pp. 7-29. http://www.crawford.anu.edu.au/pdf/staff/leo_dobes/dobes_agenda_16_3.pdf

Engineers Australia 2004, *Guidelines for responding to the effects of climate change in coastal and ocean engineering*, Barton, Canberra.

Franks, S.J., Sim, S., & A.W. Weiss 2007, 'Rapid evolution of flowering time by an annual plant in response to a climate fluctuation', *Proceedings of the National Academy of Sciences*, vol. 104, no. 4, 23 January, pp. 1278-1282.

Fuessel, H-M. 2009, 'Review and quantitative analysis of indices of climate change exposure, adaptive capacity, sensitivity, and impacts', Background Note to *World Development Report 2010: Development and Climate Change*, Potsdam Institute for Climate Impact Research.

Hallegatte, S. 2009, 'Strategies to adapt to an uncertain climate change', *Global Environment Change*, vol. 19, pp. 240-247.

Hallegatte, S., Hourcade, J-C, and P. Ambrosi, 2007, 'Using climate analogues for assessing climate change economic impacts in urban areas', *Climatic Change*, vol. 82, pp. 47-60.

Henscher, D.A., Rose, J.M., & W.H. Greene 2005, *Applied choice analysis: a primer*, Cambridge University Press, UK.

Hertzler, G. 2007, 'Adapting to climate change and managing climate risks by using real options', *Australian Journal of Agricultural Research*, vol. 58, pp. 98-992.

Howes, S. & L. Dobes, 2011, *Climate change and fiscal policy: a report for APEC*, chapter 5, Report no. 56563-EAP, World Bank, Washington DC. http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2011/02/01/000333038_20110201000150/Rendered/PDF/565630REV0ESW010Policy01Jan13112011.pdf

IPCC 2011, 'Summary for Policymakers', in Intergovernmental Panel on Climate Change *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* [Field, C. B., Barros, V., Stocker, T.F., Qin, D., Dokken, D., Ebi, K.L., Mastrandrea, M. D., Mach, K. J., Plattner, G.-K., Allen, S. K., Tignor, M. & P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Jones, J.S. 2008, 'Certainty as illusion: the nature and purpose of uncertainty in the law', ch. 23 *in* Bammer & Smithson (2008), pp. 269-286.

Julia, R. & F. Duchin 2007, 'World trade as the adjustment mechanism of agriculture to climate change', *Climatic Change*, vol. 82, pp. 393-409.

Kerwin, A. 1993, 'None too solid. Medical ignorance', *Knowledge: Creation, Diffusion, Utilization*, vol. 15, no. 2, pp. 166-185.

Kester, W.C. 1984, 'Today's options for tomorrow's growth', *Harvard Business Review*, vol. 62, issue 2, March-April, pp. 153-160.

Knight, F.H. 2009 (original 1921), *Risk, uncertainty, and profit*, (originally published by Hart, Schaffner & Marx; Houghton Mifflin Co.), new edition from Signalman Publishing, Orlando, Florida.

Kunreuther, H.C. & E.O. Michel-Kerjan 2009, *At war with the weather. Managing large-scale risks in a new era of catastrophes*, The MIT Press, Massachusetts, USA.

Linquiti, P. & N. Vonortas (in print), 'Real option analysis as a tool for valuing investments in adaptation to climate change', *Climate Change Economics*.

Lipsey, R.G. & K. Lancaster 1956-1957, 'The General Theory of Second Best', *Review of Economic Studies*, vol. 24, no. 1, pp. 11-32.

Luehrmann, T.A. 1998a, 'Investment opportunities as real options: getting started on the numbers', Harvard Business Review, July-August, pp. 51-67.

Luehrmann, T.A. 1998b, 'Strategy as a portfolio of real options', Harvard Business Review, September-October, pp. 89-99.

Mc Donald, J. 2010, 'Paying the price of adaptation: compensation for climate change impacts', chapter 10, pp. 234-264, in Bonyhady et al (2010).

Melbourne Water 2011, 'Adapting to climate change. The sewerage system', http://www.melbournewater.com.au/content/sustainability/climate_change/adapting_to_climate_change/the_sewerage_system.asp <viewed 3 December 2011>

Neufville, R. de, Scholtes, S., & Wang, T. 2006, 'Real options by spreadsheet: parking garage case example', *Journal of Infrastructure Systems* (American Society of Civil Engineers), vol. 12, no. 3, pp. 107-111.

Orlove, B. 2005, 'Human adaptation to climate change: a review of three historical cases and some general perspectives', *Environmental Science & Policy*, vol. 8, pp. 589-600.

Persson, A. 2011, 'Institutionalising climate adaptation finance under the UNFCCC and beyond: could an adaptation 'market' emerge?', Working Paper 2011-03, Stockholm Environment Institute.

Petheram, L., Zander, K.K., Campbell, B.M., High, C., & N. Stacey 2010, 'Strange changes: indigenous perspectives of climate change and adaptation in NE Arnhem Land (Australia)', *Global Environmental Change*, vol. 20, issue no. 4, pp. 681-692.

Pollitt, C. 2010, 'Simply the best? The international benchmarking of reform and good governance', ch. 4 in Pierre, J. & P.W. Ingraham (eds) 2010, *Comparative administrative change and reform*, McGill-Queen's University Press, Montreal.

Preston, B. 2010, 'The role of courts in relation to adaptation to climate change', chapter 7, pp. 157-201, in Bonyhady et al (2010).

Quiggin, J. 2008, 'Economists and uncertainty', *in* Bammer & Smithson (2008), pp. 195-203.

Randall, A. 2011, *Risk and precaution*, Cambridge University Press, UK.

Smithson, M. 2008, 'The many faces and masks of uncertainty', ch. 2 *in* Bammer & Smithson (2008), pp. 13-25.

Standards Australia/Standards New Zealand 2009, *AS/NZS ISO 31000:2009. Risk management – principles and guidelines*.

Taleb, N.C. 2007, *The black swan. The impact of the highly improbable*, Random House, USA.

Trigeorgis, L. 1996, *Real options. Managerial flexibility and strategy in resource allocation*, MIT Press, Massachusetts, USA.

Van der Eng, P. 2010, 'Market responses to climate stress: rice in Java in the 1930s', *Australian Economic History Review*, vol. 50, no. 1, pp. 62-79.

Verweij M. & M. Thompson 2006, *Clumsy solutions for a complex world. Governance, politics and plural perceptions*, Palgrave Macmillan, UK.

Wolff, H., Chong, H., & M. Aufhammer 2011, 'Classification, detection and consequences of data error: evidence from the Human Development Index', *Economic Journal*, June, vol. 121, issue 553, pp. 843-870.

Woodruff, R.E., McMichael, T., & C. Butler 2006, Action on climate change: the health risks of procrastinating', *Australian and New Zealand Journal of Public Health*, vol. 30, no. 6, pp. 567-571.

Woodward R.T. & R.C. Bishop 1997, 'How to decide when experts disagree: uncertainty-based choice rules in environmental policy', *Land Economics*, vol. 73, no. 4, pp. 492-507.