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A general framework for analysing diversity in science, technology and society

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This paper addresses the scope for more integrated general analysis of diversity in science, technology and society. It proposes a framework recognizing three necessary but individually insufficient properties of diversity. Based on 10 quality criteria, it suggests a general quantitative non-parametric diversity heuristic. This allows the systematic exploration of diversity under different perspectives, including divergent conceptions of relevant attributes and contrasting weightings on different diversity properties. It is shown how this heuristic may be used to explore different possible trade-offs between diversity and other aspects of interest, including portfolio interactions. The resulting approach offers a way to be more systematic and transparent in the treatment of scientific and technological diversity in a range of fields, including conservation management, research governance, energy policy and sustainable innovation.

Keywords: diversity; disparity; variety; uncertainty; portfolio analysis

1. INTRODUCTION

'Diversity' is a concept that features prominently in a variety of disparate disciplines. Alongside the main focus in ecology (Odum 1953; May 1975; McCann 2000), the term arises repeatedly in the physical (Shevchenko *et al.* 1996), life (Maynard Smith 1989) and information sciences (Kauffman 1993), as well as in social (Grabher & Stark 1997), economic (Geroski 1989) and policy (Gillett 2003) studies. In particular, diversity is a prominent theme in science and technology policy (Nowotny *et al.* 2001).

That this should be so is not unusual in itself. Whether for substantive or superficial reasons, technical terms like this are constantly being adapted to new applications. What is interesting about the concept of diversity is that, across radically different contexts, it refers repeatedly to a remarkably similar and particular set of properties. Despite much pertinent work (Hill 1973; Peet 1974; Pielou 1977; May 1981; Weitzman 1992*a*; Solow & Polasky 1994*a*), there is presently relatively little cross-disciplinary research on the general characterization of diversity.

The present paper seeks to address this challenge. It begins by identifying the general properties of diversity that are common to the many contrasting fields in which it arises. It moves on to explore how these properties relate to each other and discuss the issues that emerge in trying to articulate them. It then proposes a novel general diversity heuristic with which systematically to characterize diversity across a variety of fields, and with particular reference to conservation management and technology policy. The paper ends by illustrating the practical application of this framework in examining relationships between diversity and other issues of interest.

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2. WHY IS DIVERSITY OF INTEREST?

Before embarking on this analysis, it is worth asking why we might want to address diversity in such general terms at all? There already exists a host of specialized approaches in particular disciplines (Stirling 2006*a*). The answer here is twofold. First, it will be argued that—even in many specialist applications—well-established understandings of diversity can sometimes be circumscribed or challengeable. In such cases, a more general diversity heuristic may be useful as a reference, complement or catalyst. Second, there are fields—such as science and technology policy—where diversity is prominent in discussion, but remains undefined or analytically neglected. Here, a general heuristic offers value as a means to more systematic or robust understandings.

Policy debates in many areas of science and technology yield numerous reasons for an interest in diversity. In the history, philosophy and sociology of science, interactions among a diversity of disciplinary perspectives are held to be important means to enhancing rigour (Merton 1973) and creativity (Kuhn 1970). In research strategy, diverse portfolios offer flexibility in the face of uncertain future progress (Rosenberg 1996) and promote learning across programmes (David & Rothwell 1996). More broadly, institutional and technological diversity are seen as

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stimuli for innovation (Rosenberg 1982; Landau *et al.* 1996; Grabher & Stark 1997) and productivity (Aoki 1996). Accordingly, it is repeatedly urged (including by *Nature* (Gibbons 1999; Anon. 2004) and the Treasury (Treasury 2006)) that the governance of science be 'opened up' (Stirling 2005) to include more diverse public constituencies and interests (Wynne 1995). In risk regulation, the inclusion of diverse views is likewise cited as a way to inform more robust policy decisions (Fineberg 1996; Hong & Page 1998; Royal Commission on Environmental Pollution 1998).

Similarly, in debates over precaution (Stirling 2006*b*) and sustainability (Brooks 1986), the pursuit of diverse technology strategies is highlighted as a 'resource pool' (Breznitz 1986) providing flexibility (Collingridge 1983) and resilience (Folke *et al.* 2002) in the face of ignorance (Stirling 2006*c*) and surprise (Norgaard 1989). This is also true in fields like energy policy, where technological and fuel diversity have long been a major focus in discussions of supply security (Willrich 1975; International Energy Agency 1985; Kaijser *et al.* 1991; Stirling 1994; Grubb *et al.* 2006). In a world where choice among scientific and technological pathways is often a matter of intense political contention, then, diversity features both as an input and an output—pursuing a mix of strategies informed by a variety of perspectives can help accommodate otherwise irreconcilable social interests and values (James 1990; Grabher & Stark 1997).

Looking at innovation more widely, diversity is a key focus of attention in economics (Gatsios & Seabright 1989; Geroski 1989), yielding many varieties of portfolio theory (Lumby 1984; Brealey & Myers 1988). Less-formalized notions of diversity are prominent in strategies for addressing wider challenges, like market concentration (Finkelstein & Friedman 1967), institutional momentum (Hughes 1983), autonomy (Winner 1977), entrapment (Walker 2000) and lock-in (Arthur 1989). Diversity is consequently a major theme in systems (Johnson & Longmeyer 1999) and organization (Grabher & Stark 1997) theory, bibliometrics (Axarloglou & Theoharakis 2003), evaluation (Rafols & Meyer 2006), engineering (Cohen 1985) and regional (Dosi 1992), development (Norgaard 1994) and employment (Blackaby *et al.* 2002) policy. Beyond this, diversity is prominent in crucial efforts to promote religious, cultural, racial, and gender equality (Atkinson 1970) and pluralism (US Department of Agriculture Subcommittee on Extension Diversity of the Personnel and Organization Development Committee 1998). The concept of diversity is truly of pervasive interest.

3. POTENTIAL DOWNSIDES OF DIVERSITY

Of course, it must be noted that—in all these areas and despite the benefits—appeals to diversity sometimes represent little more than rhetoric (Matthews & McGowan 1992). Although diversity is an irreducible property of a system (rather than of its individual elements), it is repeatedly invoked in policy debates as if it were a unique quality of a particular system element or 'option' (Stirling 1994)—sometimes one that might actually be favoured for rather different reasons (Lawson 1992). Exploiting the 'apple pie' connotations of diversity can be useful in advocating otherwise weak or marginalized positions.

Even where the benefits are substantive, it is rare indeed that diversity offers a 'free lunch' (Weitzman 1992*a*). Indeed, by definition, deliberate diversification involves prioritizing options that are otherwise assigned relatively low performance (Brooks 1986; David & Rothwell 1996). In addition, there are typically trade-offs between diversity and transaction costs (Williamson 1993) and with foregone benefits like accountability (Grabher & Stark 1997), standardization (Cowan 1991) and economies of scale (Matthews & McGowan 1992). The value of the diversity premium (Ulph 1988) that is warranted in any context will be a function of the relative performance attributed to individual options and the contributions that each makes to diversity (Stirling 1994). Both are subjective judgements, offering ample scope for disagreement.

What is needed, then, is a systematic framework for exploring the implications of—and relationships between—different perspectives on the implications of diversity (Bruno *et al.* 1991; Mercier & McGowan 1996). Such a framework should ideally be applicable equally across the range of contexts in which diversity is of interest. It is to this task that the discussion will now turn.

4. THE UBIQUITY OF DIVERSITY

At root, diversity is an attribute of any system whose elements may be apportioned into categories (Leonard & Jones 1989). Science comprises diverse disciplines (Gomez *et al.* 1996); compounds diverse isomers (J. Bradshaw 1996, unpublished work); crystals diverse structures (Shevchenko *et al.* 2006); amino acids diverse sequences (Wright *et al.* 2005); phyla diverse taxa (Sneath & Sokal 1973); ecologies diverse species (Forey *et al.* 1994); agronomies diverse crops (Pimm 2004); technologies diverse forms (Anon. 2003); investments diverse shares (Brealey & Myers 1988); products diverse attributes (Lancaster 1979); archaeologies diverse assemblages (Leonard & Jones 1989); cultures diverse communities (Haughton & Mukerjee 1995); literatures diverse perspectives (Serebnick & Quinn 1995); networks diverse actors (Callon 1992); and individuals diverse psychologies (Junge 1994). In all these areas (and others), we find ostensibly different but convergent concepts of diversity.

In many of these fields, the properties of diversity are most usefully addressed in relation to some specific empirically or theoretically grounded parameters that are particular to the structures of the systems in question (Magurran 1988). In finance theory, for instance, the parameters of interest are the covariance coefficients reflecting past patterns in the movements of stock prices (Brealey & Myers 1988). In characterizing chemical diversity, fundamental combinatorial rules play crucial roles (J. Bradshaw 1996, unpublished work). In palaeontology and conservation biology, the strictly bifurcating structure of phylogenetic trees provides a useful framework (Humphries *et al.* 1995). The discipline of mathematical ecology is an area in which diversity

Table 1. Selected non-parametric measures of diversity properties (Stirling 2006*f*,*o*). N, number of categories of elements; ln, logarithm (usually natural); p_i, proportion of system comprises category i; n, number of attributes displayed by elements; σ, standard deviation of attributes within categories; μ, mean of attributes within categories; $f(d_{ij})$, function of distance in disparity space between categories i and j; $D_W(S)$, aggregate disparity of system S; $d_W(i, S\backslash i)$, distance in disparity space between category i and the nearest remaining element in S if i is excluded.

property addressed	name	form
variety	category count (MacArthur 1965)	N
balance	Shannon evenness (Pielou 1969)	$\left(-\sum_i p_i \ln p_i\right)/\ln N$
disparity	Weitzman (1992*a*) (Solow & Polasky (1994*a*))	$\max_{i\in S}\{D_W(S\backslash i)+d_W(i,S\backslash i)\}$ $f(d_{ij})$
variety/balance	Shannon & Weaver (1962)	$-\sum_i p_i \ln p_i$
	Simpson (1949)	$\sum_i p_i^2$
	Gini (1912)	$1-\sum_i p_i^2$
variety/balance/ disparity	Junge (1994)	$\left(\sigma/\left(\mu\cdot\sqrt{n-1}\right)\right)\cdot\left(1/\sqrt{N}\right)\cdot\left(\sqrt{N-1}-\sqrt{N\sum_i p_i^2-1}\right)$

concepts have been particularly thoroughly investigated (Magurran 1988). Here, a family of parametric diversity measures derive from the pervasive power-law structures displayed by species-abundance distributions within and between real ecosystems (Southwood 1978).

Yet, even in these fields where diversity is relatively well parameterized, non-parametric diversity measures are often still applied. Examples developed in ecology and applied elsewhere include species counting (MacArthur 1965) and various mathematical functions of the proportional representations of relevant species (Magurran 1988; table 1). Even in some of the most mature fields of development, then, parametric measures of diversity are often substituted by more generally applicable non-parametric indices (May 1981). Such approaches are even more relevant in the majority of fields discussed previously, where there exists no uniquely plausible parametric basis for structuring understandings of diversity.

5. A COMMON FRAMEWORK

It is when viewed in a non-parametric fashion, simply as a property of the apportioning of elements or options in any system, that the remarkable similarity and particularity of interdisciplinary understandings of diversity becomes clear. In short, diversity concepts employed across the full range of sciences mentioned previously display some combination of just three basic properties. These I will call 'variety', 'balance' and 'disparity' (Stirling 1994). Each is a necessary but insufficient property of diversity (Sokal & Sneath 1970; Clarke 1978; Stirling 2006*d*). Although addressed in different vocabularies, each is applicable across a range of disciplines and aggregated in various permutations in quantitative indices (Hill 1973). Despite the multiple disciplines and divergent contexts, there seems no other obvious candidate for a fourth important general property of diversity beyond these three (Stirling 2006*e*).

Variety is the number of categories into which system elements are apportioned. It is the answer to the question: 'how many types of thing do we have?' This aspect of diversity is highlighted (for instance) in the use of species-number indices in ecology (McIntosh 1967); the simple enumeration of firms or products in economics (Cohendet *et al.* 1992; Kauffman 1993; Llerena & Llerena 1993; Saviotti & Mani 1995) or the counting of fuels or technologies in energy policy (UK Department of Energy 1988). *All else being equal, the greater the variety, the greater the diversity.*

Balance is a function of the pattern of apportionment of elements across categories. It is the answer to the question: 'how much of each type of thing do we have?' Analogous to statistical variance (Pielou 1977), this can be represented by a set of positive fractions, which sum to unity (Laxton 1978*a*). Referred to as 'evenness' in ecology (Pielou 1969) and 'concentration' in economics (Finkelstein & Friedman 1967), this is captured by the Shannon–Wiener (1962), Gini (1912) and Simpson (1949) indices (table 1). As the Herfindahl–Hirschman index, the latter is used in the US to regulate market share (US Department of Justice and the Federal Trade Commission 1992). *All else being equal, the more even is the balance, the greater the diversity.*

Disparity refers to the manner and degree in which the elements may be distinguished (Runnegar 1987). It is the answer to the question: 'how different from each other are the types of thing that we have?' It is judgements over disparity, which (often implicitly) necessarily govern the resolving of categories used to characterize variety and balance. This is addressed by an array of taxonomic indices in palaeontology (Williams & Humphries 1994), conservation biology (Solow *et al.* 1993) and economics (Nguyen *et al.* 2005)—usually based on some form of distance measure. *All else being equal, the more disparate are the represented elements, the greater the diversity.*

6. SOME GENERAL CHALLENGES

The consequence of this threefold understanding of diversity is a recognition that each property constitutes the other two (Stirling 2006*g*). This in turn highlights difficulties with diversity concepts and associated indices—in whatever discipline—that focus exclusively on subsets of these properties (Eldredge 1992). This is a matter of significant, but relatively neglected, scientific importance. The relevance is amplified by the tendency for apparently technical questions over diversity to acquire high profile policy salience—as in fields like ecological conservation (Forey *et al.* 1994), market regulation (US Department of Justice and the Federal Trade Commission 1992), energy policy (UK Department of Trade and Industry 1995) and research (Nowotny *et al.* 2001) strategies. In such areas, as we have seen, ostensibly arcane scientific questions over the definition and measurement of diversity are laden with (and conditioned by) large-scale institutional, economic and political interests (Lawson 1992).

Variety and balance, for instance, cannot be characterized without first considering disparity. It is on this basis that a taxonomy of elements is defined and partitioned (May 1990). An ecological community comprising 20 varieties of beetle is less diverse than the one comprising less than 20 species drawn from different insect, reptile and mammalian taxa (May 1990). Likewise, an electricity system is less diverse if it comprises equal contributions from lignite, brown coal, oil and gas than if it is an equal mix of coal, nuclear and renewable energy (Stirling 1994). However, a category like 'renewable energy' might itself be judged highly diverse if it is equally apportioned into wind, solar, hydro, tidal, biomass, landfill gas, etc. The focus of attention in each case is neither on variety nor balance, but on disparity (Stirling 1995). Taking variety or balance as proxies for diversity can thus be highly sensitive to subjective construction and partitioning of taxonomies and to arbitrary linguistic conventions concerning the implicit bounding of categories.

Conversely, the relevance of disparity to diversity often depends on the pattern of apportionment across categories. Yet, such apportionment may sometimes be neglected. This is necessarily so in palaeontology due to limited evidence on species abundance (Gould 1991). Ecological structures and the reproductive potential of germplasm can likewise make interest in genetic diversity quite independent from questions of abundance (Solow *et al.* 1993). Yet, problems can arise if disparity is taken as a complete representation of diversity in conservation biology. This is because, used on their own, disparity measures fail to discriminate between species represented by viable or non-viable populations (Forey *et al.* 1994). Similarly, an energy portfolio comprising a 90% contribution from one of three highly disparate resources might reasonably be judged less diverse than a portfolio comprising an equal contribution from three less disparate options (Stirling 2006*h*). This crucial feature is not addressed by understandings of diversity in terms of disparity alone. Taking disparity as a proxy for diversity ignores the balance with which a system is apportioned.

7. AGGREGATION, ACCOMMODATION AND ARTICULATION

It is rare indeed that a concept as pervasive as the notion of diversity should display such similar properties across such disparate fields. Despite the high profile attention, the scientific and policy challenges remain relatively underexplored. This is curious, since the present threefold non-parametric understanding of diversity is relatively tractable. In particular, it is striking that—for given categories of elements—all the three properties are quite readily amenable to quantification: variety is an integer (enumerating categories); balance is a function of a set of fractions summing to unity (apportioning elements); and disparity a function of a matrix of distances (differentiating elements).

This said, it is difficult indeed to contemplate any single general index of diversity that could *aggregate* properties of variety, balance and disparity in a uniquely robust fashion. Even where these properties are already integrated in existing indices, there remain serious queries over the different weightings to apply in aggregation. This is true, for instance, of the families of 'dual concept' (Junge 1994) indices used in ecology and economics to aggregate variety and balance (table 1). The logarithm base taken in Shannon and the value of the exponent taken in Simpson–Herfindahl (Stirling 2006*i*) can each have implications for the relative weightings assigned to variety and balance (Hill 1973). Yet, the consequences for analysis are rarely explored in practice (Stirling 2006*j*). In short, even popular 'non-parametric' indices like these are nonetheless parameterized at a fundamental (if implicit) conceptual level. These underlying parameter values might reasonably be varied, yielding differing pictures of diversity (Kempton 1979).

Beyond this problem of aggregation, there lies the further challenge of *accommodating* different possible understandings of disparity. Here, the picture will necessarily depend on whatever are seen as the salient dimensions of difference. In some cases, there may exist some well-established (or even objectively determined) criteria. This is the case, for instance, with taxonomies of genetic distance in evolutionary ecology, which can be assumed to display a strict branching form (Weitzman 1992*a*). It is also true where differences between diverse options can usefully be reduced to a single factor, such as historic covariance in financial stock (Brealey & Myers 1988) or fuel (Awerbuch *et al.* 2006) prices. Even in these areas, however, the assumptions necessary for such parameterization are sometimes heroic (Myers 1984; Malkiel 1989). Where categorization and variance are more complex, as in Junge's (Junge 1994) proposed application in psychology (table 1), such approaches are lacking in applicability and robustness (Stirling 2006*k*).

Generally speaking, notions of difference determining characterizations of diversity will depend on perspective and context. For instance, understandings of diversity in the field of conservation biology may reasonably refer not just to species abundance and genetic distance, but also to notions of ecological, agronomic or cultural value (Norton 1987; Solow & Polasky 1994*a*). Likewise, notions of energy diversity may reflect contrasting criteria, such as the form and provenance of fuels or equipment, geographical patterns in extraction and transport or key features of associated infrastructures (Stirling 1994). In general, these kinds of disparities in science and technology reflect complex webs of relationships, and so cannot readily be reduced to discrete branching taxonomies, as assumed, for instance, in Weitzman's index (table 1; Weitzman 1992*a*).

Beyond the aggregation of different properties of diversity and the accommodation of different perspectives on disparity, there remains a third and final challenge of *articulating* diversity with other properties of interest in analysis or evaluation. Alongside diversity, for instance, the different species or habitats constituting ecosystems may also be assessed in terms of their conservation, agronomic, socio-cultural or aesthetic landscape qualities and values. Likewise, an energy portfolio may also be assessed in terms of criteria, such as operational efficacy, financial performance, security of supply, employment intensity or environmental impacts. These other aspects may to some extent be independent from diversity, but will also interlink in various ways—reflecting the structure and composition of the system and interactions between its elements. In particular, they may define many different criteria under which diversification could have positive or negative implications, of a kind that should be included in appraisal. Rather than being isolated as a narrow consideration in its own right, then, any useful framework for analysing diversity should ideally allow for ready articulation of these kinds of wider aspects.

These challenges of aggregation, accommodation and articulation conspire against aspirations definitively to capture diversity, even within a single discipline. They are all the more formidable as obstacles to a general framework for understanding diversity, of a kind that might be applicable across different empirical fields. However, this is not a challenge that is specific to the threefold characterization of diversity described here. Instead, it is a more pervasive problem that is intrinsic to any general notion of diversity—irrespective of whether or not this is acknowledged.

8. A SYSTEMATIC RESPONSE

To take seriously these problems of aggregation, accommodation and articulation does not necessarily lead to a counsel of despair over the potential for systematic general characterizations—or even quantifications—of diversity. A more positive starting point is the observation that the futility of seeking to derive a single definitive diversity *index* need not preclude the possibility of a flexible general *heuristic*. Like an index, a heuristic may be quantitative. But rather than aiming to measure diversity in some unconditional objective fashion, it offers an explicit, systematic basis for exploring sensitivities to the assumptions conditioning aggregation, accommodation and articulation.

For any particular perspective on the appropriate weightings for variety and balance and the salient dimensions of disparity, such a heuristic would behave as an index. It would accommodate different views on the salient attributes of disparity, aggregate these with consideration of variety and balance and allow systematic articulation with important system-level properties other than diversity. For applications involving a range of perspectives, this heuristic would allow systematic comparisons to be made between the implications of contending judgements. In other words, a heuristic characterization of diversity aims to combine the rigour, transparency and specificity of quantification with the applicability, flexibility and symmetry of qualitative approaches. The real challenge lies in achieving this, while minimizing the introduction of further complexity and contingency.

No existing diversity index addresses all three properties of variety, balance and disparity in an unproblematic way. However—based partly on criteria applied to the treatment of these individual diversity properties by researchers, such as Hill (1973), Pielou (1977), Laxton (1978*a*), Weitzman (1992*a*) and Solow & Polasky (1994*a*)—a series of non-trivial requirements are quite readily developed. One such set of desirable features of a general diversity heuristic (Δ) that help explicitly to address challenges of aggregation, accommodation and articulation as defined here are as follows.

- (i) *Scaling of variety*. Where variety is equal to 1, Δ takes a value of zero (Laxton 1978*b*).
- (ii) *Monotonicity of variety*. Where elements are evenly balanced and equally disparate, Δ increases monotonically with variety (Solow & Polasky 1994*b*).
- (iii) *Monotonicity of balance*. For given variety and disparity, Δ increases monotonically with balance (i.e. Δ is maximal for equal representation; Laxton 1978*c*).
- (iv) *Monotonicity of disparity*. For given variety and balance, Δ increases monotonically with the aggregate disparity between elements (Solow & Polasky 1994*c*).
- (v) *Scaling of disparity*. Where aggregate disparity is 0 (i.e. where all elements are effectively identical), Δ takes a value of zero (Weitzman 1992*a*).
- (vi) *Open accommodation*. Δ symmetrically accommodates any perspective on salient dimensions of difference under which elements can be differentiated (Solow & Polasky 1994*d*).
- (vii) *Insensitivity to partitioning*. For any given perspective on taxonomy, Δ is insensitive to alternative partitionings of elements into categories (Weitzman 1992*b*).
- (viii) *Parsimony of form*. Δ is as uncomplicated in structure and parsimonious in form as necessary to fulfil the above conditions.
- (ix) *Explicit aggregation*. Δ permits explicit aggregation of variety, balance and disparity, by reflecting divergent contexts or perspectives using weightings.
- (x) *Ready articulation*. Δ allows unconstrained articulations of diversity with other salient properties of the system as a whole or of its individual elements.

9. A GENERAL DIVERSITY HEURISTIC

No established diversity index satisfies all these criteria. Yet, there is one relatively straightforward quantitative heuristic, which is not specifically discussed in the literature reviewed thus far (table 1), but which does

Table 2. Four variants of Δ and links with diversity properties and measures.

property	α	β	equation (9.2): $\Delta=$	equivalents (cf. table 1)	interpretation
variety	0	0	$\sum_{ij} d_{ij}^0$	$(N^2-N)/2$	scaled variety
balance	0	1	$\sum_{ij} p_i \cdot p_j$	(Gini)/2	balance-weighted variety
disparity	1	0	$\sum_{ij} d_{ij}$	(Solow & Polasky 1994*a*)	disparity-weighted variety
diversity	1	1	$\sum_{ij} d_{ij} \cdot p_i \cdot p_j$	D	balance/disparity-weighted variety

offer a starting point. This is the sum of pairwise disparities, weighted in proportion to contributions of individual system elements (D),

$$D = \sum_{ij(i \neq j)} d_{ij} \cdot p_i \cdot p_j, \tag{9.1}$$

where p_i and p_j are proportional representations of elements i and j in the system (balance) and d_{ij} is the degree of difference (disparity) attributed to elements i and j. The summation is across the half-matrix of $(N^2-N)/2$ non-identical pairs of N elements ($i \neq j$). In the special case where all d_{ij} are equal (scaleable to unity), D reduces to half Gini (table 1). In the special case where one element dominates the system ($p_i \rightarrow 1$), D is a member of the family of measures introduced by Polasky & Solow (table 1).

In the absence of definitive parametric understandings of system structure, the simplest way to conceive of disparities between elements is as a distance between points in disparity space (Solow & Polasky 1994*a*). Each perspective will yield a unique n-dimensional disparity space, representing judgements over the salience of n different attributes of system elements. The attributes can be rated in cardinal, interval or binary yes/no terms. Here, a Euclidean n-space offers the most parsimonious and generally applicable framework. With suitable normalization and weighting, the relative magnitudes of the resulting distances can be scaled to reflect divergent notions of specific disparities or different geometries in disparity space (Kruskal 1964). In particular, a Euclidean n-space involves less restrictive assumptions and greater consistency than the ultrametric space required by the Weitzman index (table 1; Solow & Polasky 1994*a*; Stirling 2006*l*).

It is readily demonstrated that this heuristic, D, complies with criteria (i)–(vii). Compliance with criterion (viii) remains a matter of judgement, but it is difficult to imagine a solution to these criteria that is simpler or more parsimonious. As to criterion (ix), this raises a final notable feature of D, which can be illustrated by introducing just two further terms that are as follows:

$$\Delta = \sum_{ij(i \neq j)} (d_{ij})^{\alpha} \cdot (p_i \cdot p_j)^{\beta}. \tag{9.2}$$

If exponents α and β are allowed to take all possible permutations of the values 0 and 1, this yields four variants of the heuristic Δ. Each of these usefully captures one of the four properties of interest: variety; balance; disparity; and diversity (table 2).

Shifting the value of exponents α yields further variants of Δ, collectively addressing all the possible relative weightings on balance and variety/disparity. Of these, the reference case D ($\alpha=\beta=1$) does the same job as other widely used non-parametric measures like Gini, Shannon and Simpson, but with the major additional feature that it also captures disparity. Unlike the disparity measures proposed by Weitzman or Solow and Polasky (table 1), Δ also addresses variety and balance. Unlike the measure proposed by Junge (Junge 1994; table 1), Δ accommodates radically divergent perspectives on disparity and is relatively parsimonious in form. An entirely novel feature of Δ is that it systematically addresses alternative possible aggregations of these subordinate properties, according to perspective and context.

10. ARTICULATING DIVERSITY WITH OTHER SYSTEM PROPERTIES

This leaves unaddressed only criterion (x) concerning the articulation of diversity with other relevant system-level properties. As already mentioned, diversity is rarely a free lunch in decision making. Whether in fields like conservation management, research strategy or energy policy, the total value of any system will be a function not only of system diversity but of other properties of the system and its individual elements as well. In economics, for instance, diversity may provide an effective response to challenges like hedging ignorance, fostering innovation, mitigating lock-in and accommodating pluralism. But it will often require some compromise on other aspects of performance—such as cost, equity, environment or ethics. There will typically be constraints on the contributions of individual elements and portfolio effects resulting from their interactions (Geroski 1989).

In conservation management, Solow and Polasky show how their own proposed disparity function (table 1) can be adopted in a utilitarian fashion, articulating the value of ecological diversity with that attached to other possible evaluative criteria, such as possible medical applications that may be discovered in relation to individual species (Solow & Polasky 1994*a*). Other ecological system properties might also be included in this way, perhaps to address the importance of trophic webs or the value of keystone species (May 1975). In this vein, for example, Karr's index of biotic integrity articulates—with explicit subjectivity—further system-level considerations of ecological and biological health (Karr 1991).

In these terms, then, the value assigned under a given perspective to any particular system under specific conditions ($V\{S\}$) can be expressed as the sum of the value due to the aggregate performance of individual system elements ($V\{E\}$) and an incremental value attached to irreducible portfolio-level properties including diversity ($V\{P\}$). If the net implications of diversity are adverse, then $V\{P\}$ can be negative,

$$V\{S\} = V\{E\} + V\{P\}. \qquad (10.1)$$

Long experience in the field of decision analysis (Vincke *et al.* 1992) shows that—just as divergent notions of difference can be represented as coordinates in an n-dimensional Euclidean disparity space—divergent valuations of individual system elements can hence be represented as coordinates in an m-dimensional Euclidean performance space (Stirling 2006*m*). The dimensions of this space represent any set of m performance criteria, each weighted to reflect their respective importance (Stirling 2006*n*). As with disparity, the selection, characterization and scaling of these criteria will vary across context and perspective (Stirling 1997). Although it is difficult to justify any single approach to aggregating performance across perspectives, decision analysis has shown that any single perspective can be uniquely captured by means of the following expression for the overall value attached to the performance of individual system elements $V\{E\}$:

$$V\{E\} = \sum_i \sum_c (w_c \cdot s_{ic}) \cdot p_i, \qquad (10.2)$$

where s_{ic} is the value attached to the performance of element i under criterion c; w_c is a scalar weighting reflecting the relative importance of criterion c (under the perspective and context in question) and p_i is (as in equations (9.1) and (9.2)) the proportional representation of element i in the system. It follows from equation (9.2) that the corresponding value attached to irreducible portfolio-level properties including diversity ($V\{P\}$) can then be expressed as follows:

$$V\{P\} = \delta \cdot \Delta' = \delta \cdot \sum_{ij(i \neq j)} (d_{ij})^{\alpha} \cdot (p_i \cdot p_j)^{\beta} \cdot \iota_{ij}, \qquad (10.3)$$

where Δ' represents an augmented form of the diversity heuristic Δ given in equation (9.2), which includes an additional term to reflect portfolio interactions (ι_{ij}). This is an array of scalar multipliers exploiting the pairwise structure of Δ' to express the effect on system value of synergies or tensions between elements i and j, respectively, as marginal positive or negative departures from a default of unity ($\iota_{ij} = 1 \pm \partial\iota$: for most systems, $\partial\iota \ll 1$). This serves as a means to capture a variety of system-level properties that—like diversity—are irreducible to individual elements. The coefficient δ scales expressions of portfolio value to render them commensurable with aggregate values of individual options in equation (10.2). For positive assessments of portfolio value, $0 < \delta < \infty$. From equations (10.1)–(10.3), we therefore obtain the following heuristic system-level articulation ($V\{S\}$) of the value attached to diversity, together with that assigned to other portfolio properties ($V\{P\}$) and to the performance of individual system elements ($V\{E\}$),

$$V\{S\} = \sum_i \sum_c (w_c \cdot s_{ic}) \cdot p_i + \delta \cdot \sum_{ij(i \neq j)} (d_{ij})^{\alpha} \cdot (p_i \cdot p_j)^{\beta} \cdot \iota_{ij}. \qquad (10.4)$$

It is in $V\{S\}$ that we have a means to address the final criterion (x) developed in §8, in that a diversity heuristic should allow systematic, unconstrained articulation of diversity with alternative characterizations of other salient properties of the system as a whole.

11. EXPLORING RELATIONSHIPS BETWEEN DIVERSITY AND SYSTEM VALUE

The interest of the heuristic $V\{S\}$ lies not in any attempt to derive some unconditional 'optimal' balance between the performance of individual elements, system interactions and diversity. Instead, with sensitivity analysis, $V\{S\}$ can be used systematically to explore different possible perspectives and assumptions concerning the contributions of these components to overall system value. For each perspective on the performance and interactions of individual elements, their disparities, the aggregation of diversity properties and the scale of the performance–diversity trade-off, there exists a particular apportionment of elements that yields some maximum overall value. By varying δ between zero and infinity, resolving the set of p_i that give a maximal value for $V\{S\}$ yields a continuum of all possible conditionally optimal systems. These range (respectively) from those that maximize value due to aggregate performance of individual elements (low δ) to those that maximize value due to portfolio interactions and system diversity (high δ).

For schematic data provided in the electronic supplementary material, annex A, figure 1 presents an illustration of this heuristic usage of $V\{S\}$. These data reflect one hypothetical perspective on the challenges associated with finding an appropriate balance between diversity and other aspects of landscape value in conservation management (Southwood 1977). Here, the focus of attention is not directly on species diversity, but on the contributions that might be made to this end by habitat diversity in the landscape (Gray 1997). This bears in mind that certain individual habitats may be seen to hold greater intrinsic conservation value than others and that there exist other economic, socio-cultural and aesthetic criteria for informing decisions over landscape management (Franklin 1993).

Consider, for the sake of illustration, a schematic case in which each of a series of habitat types (A, B, C and D) offers viable options across a discrete, contiguous landscape for which long-term land-use policy commitments are being made subject to a consultative process at a particular point in time. Under one hypothetical perspective, these habitats are mutually distinguishable under a set of four disparity attributes: (i) commercially managed mixed woodland, (ii) low-input mixed arable farming with wide field margins, (iii) close-grazed bryophyte-rich grassland, and (iv) low-intensity grazing of wildflower meadows. Depending on the perspective, it is these kinds of attribute that might constitute the distance metric (d_{ij}) in applying the heuristic Δ' in equation (10.4).

Criteria applied in the evaluation of the individual habitat types might include a number of general ecological considerations, values attached to particular endangered species endemic to each habitat, the internal biodiversity of the habitat itself, as well as economic revenues for sustaining local livelihoods, aesthetic and

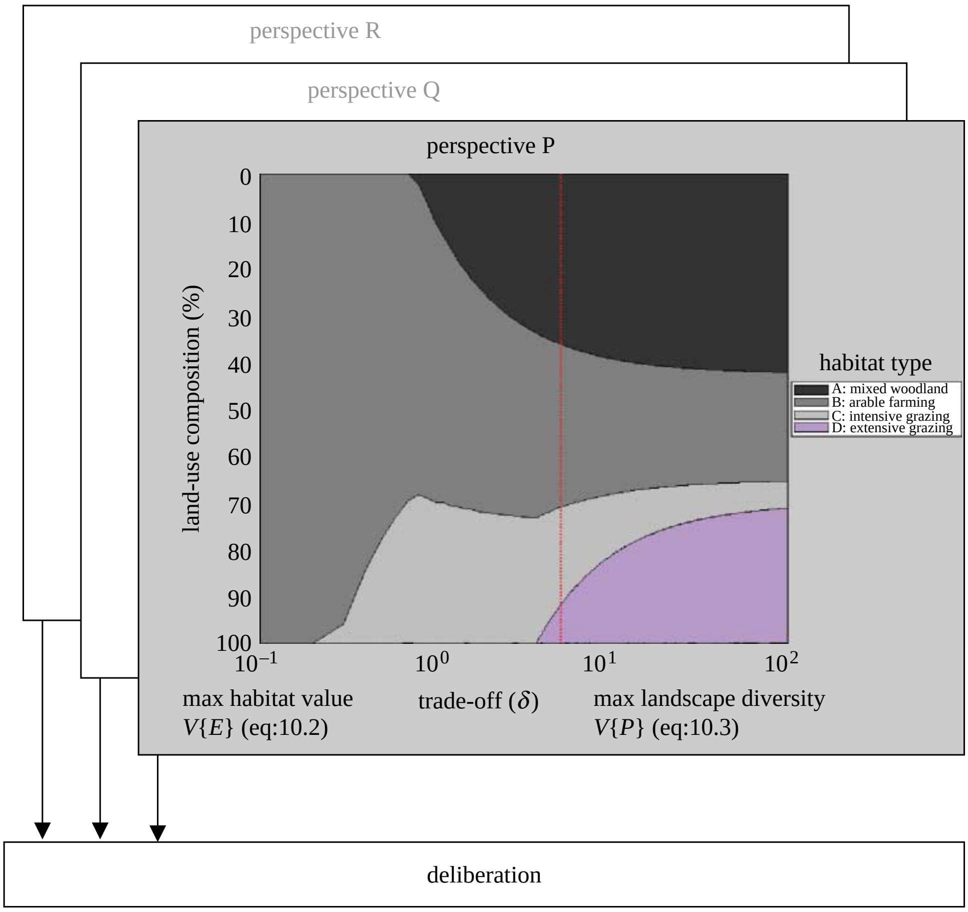

Figure 1. Schematic relationship between habitat diversity and other aspects of landscape value.

cultural–historical issues (of relevance also in indirect tourism revenues; Norton 1987). These constitute the basis for the performance measures (s_{ic}) and their respective weightings (w_c) in equation (10.4). Even if one of the four habitat types is evaluated much more positively than others, there may nonetheless be a benefit in sustaining habitat diversity as a means to support certain species and communities spanning different habitats and to address the conservation value of 'mosaics' as well as other landscape-scale economic and socio-cultural issues (Jennings 2000). Likewise, some system-level aspects of landscape value will derive from the presence of particular combinations of habitats—and their interfaces—in the mix (Ray 1991). These constitute the basis, respectively, for the diversity coefficient (δ) and the interaction term (ι_{ij}) in equation (10.4). For the purposes of the present illustrative exercise, the perspective in question is assumed to favour an aggregation of diversity properties in equation (10.4), in which both α and β take a value of 1 (thus, $\Delta = D$ in equations (9.1) and (9.2)).

Figure 1 displays the sort of outcome that can readily be derived from these kinds of input, as a heuristic articulation of the overall value attached to individual habitats with that deriving from their interactions and from diversity in the landscape. The shaded areas represent the composition of an optimal frontier (obtained using iterative optimization procedures provided in the MATLAB software), maximizing $V\{S\}$ for this dataset at varying values of δ (equation (10.4)). It shows the way in which the proportion of the landscape assigned to each of the four schematic habitat types (vertical axis, p_i, p_j in equation (10.4)) varies as progressively greater weight is attached to maintaining a diversity of habitats (horizontal axis, δ in equation (10.4)). The vertical dotted line shows the value of δ at which $V\{E\} = V\{P\}$ (equation (10.1)).

Of course, for the purposes of exposition, the present example is highly stylized. It is very simple and omits many important features—such as those relating to the geographical structure of the landscape in question (Mace *et al.* 1998). However, by repeating such an exercise iteratively as a way of exploring the implications of different assumptions or interpretations of uncertainty, this heuristic framework may therefore be used to assist the formulation of individual perspectives or to inform effective deliberation between contending disciplinary or stakeholder positions on this kind of decision over habitat diversity in the landscape.

To substantiate the more general applicability of this heuristic framework, figure 2 provides one further schematic in the rather different, but currently highly topical, field of energy policy (UK Department of Trade and Industry 2005). Here, the interest lies in constructing a mix of generating technologies at the level of an electricity system like that of the UK, such as to reconcile different possibilities and perspectives in the economic, environmental, energy security and wider social performance of the supply mix (Stirling 1994). Disparities here may be conceived in terms of the nature

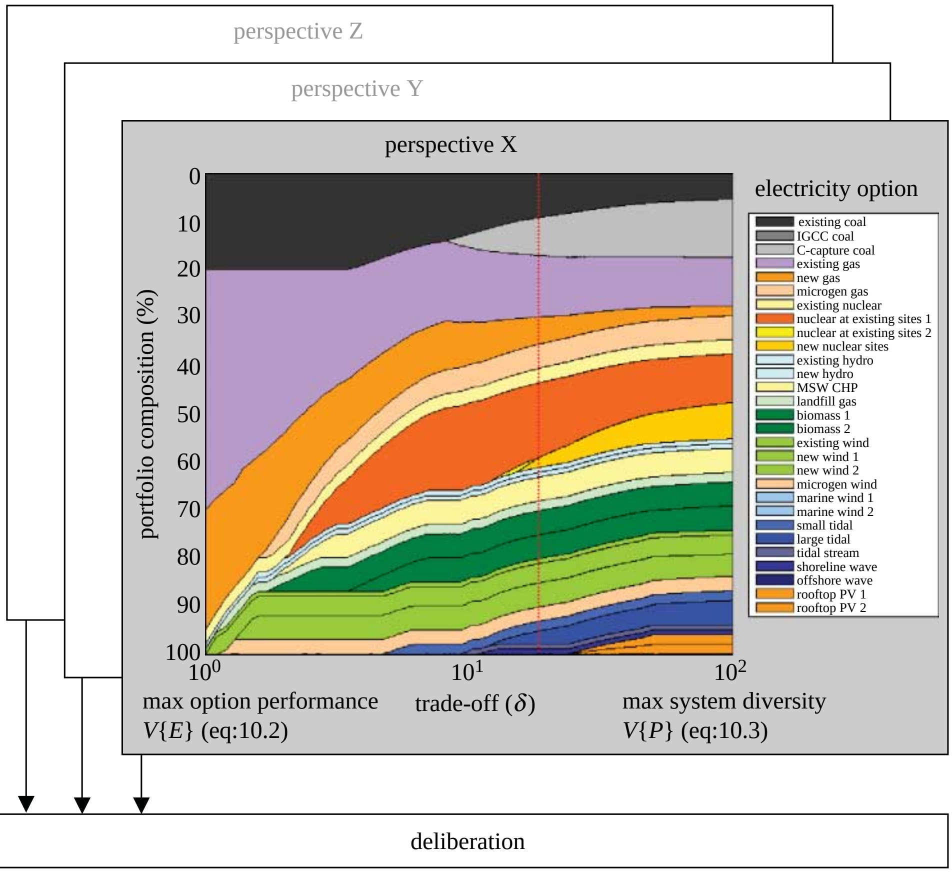

Figure 2. Illustrative performance–diversity trade-offs for the UK's energy portfolios.

and origins of the fuels and technologies concerned, as well as salient features of their respective institutional, commercial or socio-political contexts (Stirling 1996). Positive and negative economic, organizational and operational synergies between different technologies inform the modelling of interactions. Certain options are tightly constrained in terms of the available resource, or display reductions (from learning or scale) or increases (from depletion) in costs or impacts as the contributions rise. For illustrative data on all these aspects provided in the electronic supplementary material, annex B, figure 2 shows—for a particular hypothetical perspective—how the resulting conditionally optimal electricity portfolios vary as greater or lesser priority is placed on diversity.

Low values of δ in figure 1 may express high confidence in performance appraisals of individual technologies, with little concern over deep uncertainties to which diversity is a reasonable response. Likewise, low values of δ may imply that priority is attached to maximizing this performance, rather than the other benefits of diversity (in fostering innovation, mitigating lock-in or accommodating pluralism). On the other hand, high values of δ reflect a dominant interest in these benefits of diversity, with little concern over the resulting compromises on performance. Again, the value of this kind of heuristic framework is as a means more explicitly and systematically to inform analysis under individual perspectives, and to provide a basis for more effective and transparent deliberation between contending positions.

12. CONCLUSION

The present paper has outlined a framework for interdisciplinary analysis of diversity. The discussion began by noting many different reasons for an interest in diversity, not least in high profile areas of science and technology policy. Here, diversity offers a means to promote innovation, hedge ignorance, mitigate lock-in and accommodate pluralism. It offers one important strategy for achieving qualities of precaution, resilience and robustness that are central to sustainability.

To these ends, the paper identifies a general framework for understanding diversity in a range of different contexts and specialisms. This involves recognition of diversity as a function of three necessary but individually insufficient properties: variety; balance and disparity. Existing non-parametric diversity indices address only subsets of these three properties and/or raise questions over their underlying assumptions.

By reference to 10 quality criteria, the paper proposes a novel general diversity heuristic, D. A more general formulation (Δ) serves not just as a heuristic for diversity, but for each of the three subordinate properties as well, thus permitting systematic exploration of different possible weightings on variety, balance and disparity. As such, Δ may prove applicable in any fields in which diversity is presently discussed, irrespective of whether it has been definitively parameterized.

One way of using this heuristic is to systematically explore relationships between diversity and other aspects of portfolio performance. For instance, the framework might be used to elicit perspectives on probable performance and salient differences between contending research and development programmes, energy technology investments or habitat types in conservation management. By allowing exploration of trade-offs between diversity and performance—including consideration of system constraints and interactions—this offers a means to frame more effective policy deliberation. Similar applications suggest themselves in other areas, such as ecological analysis, research governance, innovation policy, urban planning, agricultural strategy and regional development. Indeed, the approach seems applicable anywhere where there is an interest in analysing system diversity—particularly, as a means to promote more inclusive, precautionary, resilient and sustainable applications of science and technology.

I am grateful to my colleague Ismael Rafols who drew my attention after acceptance of the present paper for publication to a recent discussion (Ricotta & Szeidl 2006) of an early rigorous derivation of the basic concept D in equation (9.1) under somewhat different criteria by Rao (1982), of which I was previously unaware.

Over the embarrassingly long gestation of this work, I have accumulated too many debts to acknowledge individually. More recently, Carlota Perez, Ismael Rafols, Sigrid Stagl and Ed Steinmueller all gave particular feedback on the present paper. I am especially grateful for the coding skills of David Waxman and Toby Champion, who built the MATLAB optimization tool on which the examples were calculated.

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