Range Management and Plant Functional Types

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Plant Functional Types: New Developments for an Old Idea

A changing context

One of the recurrent themes in plant ecology and range management is the need to scale information from specific case studies towards broader ecological patterns and processes. Information must be interpreted and applied at larger scales because the most serious challenges to natural resource management operate at regional and global scales. *A central problem encountered when scaling vegetation responses to regional levels is our limited ability to quantify and interpret complex floristic responses involving a large number of individual species*. This provides a strong justification for the development of a more generalized pattern of vegetation responses involving a manageable number of plant groups that have similar life history strategies and responses to environmental stress and disturbance (McIntyre, 1999).

The concept of plant functional types provides a promising tool to bridge the gap between specific, detailed studies and broader scale problems. Plant functional types are sets of plants exhibiting similar responses to environmental conditions and having similar effects on the dominant ecosystem processes (Gitay and Noble, 1997). The classification of plant species into similar groups based on their morphological and physiological traits provides new insights into the dynamics of vegetation change and associated ecological processes.

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Plant functional groupings are potentially useful communication tools for land managers, who may not necessarily relate to taxonomic units, particularly when dealing with species-rich natural rangelands. As a contribution to the above problem we provide: (i) a description of the concept of plant functional types and their potential contribution to natural resource management; (ii) insight into the ecological basis of plant functional types and ways in which they might be identified; and (iii) an overview of the application and relevance of plant functional types to rangeland management with emphasis on vegetation response in grazed systems.

The concept of plant functional types

The search for a plant classification, which can account for how plants respond to their environment, is at least as old as the Linnaean classification. This is an acknowledgement that plants originating from phylogenetically distant groups may possess similar ecological traits, if they evolve in similar types of environments. The following examples illustrate the importance of environmental selection pressures on plant form and function.

- Succulent, spiny species within a range of families including Cactaceae, Chenopodiaceae, Euphorbiaceae, Fouquieriaceae and Asphodelaceae are well adapted to arid environments.
- Numerous shrub species from unrelated families in the fynbos biome have evolved a low stature, with small, evergreen, sclerophyll leaves (Bond, 1997), suggesting that these traits are strongly selected in this environment.

Conversely, plants with close phylogenetic relationships, growing under very different environmental contexts, can, over evolutionary time, exhibit very different morphology and physiology. For example:

- South American species of *Acacia* are deciduous, with tender, highly palatable compound leaves, while Australian species in the same genus are evergreen, often with tough, mostly unpalatable phyllodes.
- *Salix humboldtiana* is a fast-growing temperate–subtropical tree while *Salix arctica* is a forb-like dwarf that grows in the Arctic tundra.

These examples also provide justification for classifying unrelated taxa on the basis of morphological and physiological traits. *The clear involvement of environmental selection pressures on plant form and function provides the basis for development of plant functional types.* The definition of plant functional types presented here reflects two important issues. First, how do plants respond to selection pressures such as those arising from climate and disturbance? Although similar traits can be selected for in phylogenetically unrelated species, there can be more than one solution or strategy for survival in specific environments. This implies that a number of plant functional types may occur in any particular vegetation type. For example, in the fynbos described above, an alternative plant functional type that co-occurs with the dominant low growing shrubs are grass-like forms, converging in appearance, from the Poaceae, Cyperaceae and Restionaceae (Bond, 1997). However, while such clear examples can exist, the task of identifying plant functional types can be extremely difficult and often involves identifying a small number of discrete ‘types’ from an array of more or less continuous variation between plant species. A second important issue in the search for plant functional types concerns how plants influence major community and ecosystem processes and, therefore, the main ecosystem services to human populations.

Response Plant Functional Types and Effect Plant Functional Types

Groups of plant species which respond to the abiotic and biotic environment in similar ways can be defined as response plant functional types (Landsberg, 1999; Walker *et al.*, 1999). This approach to the classification of plant functional types is the most common and the oldest one. It attempts to answer the questions: ‘What kinds of plants tend to thrive in particular environments?’ and, ‘How many plant strategies for survival exist in a particular environment?’ The most widely recognized and implemented response plant functional type system is the Raunkiaer’s Life Form Classification (Raunkiaer, 1934), which groups plants according to the position of the meristems that enable plants to persist through unfavourable seasons. Other examples of widely used response plant functional type classifications are the distinction between ‘increaser’ and ‘decreaser’ species based on their response to grazing (Dyksterhuis, 1949), and the prediction of species responses to fire and grazing based on vital plant attributes (Noble and Slatyer, 1980).

On the other hand, *groups of plants which have similar effects on the dominant ecosystem processes, such as productivity, nutrient cycling and trophic transfer, can be defined as effect plant functional types* (Landsberg, 1999; Walker *et al.*, 1999). Effect plant functional types and response plant functional types can, and often do, overlap to various degrees. They can be identified using the same methodological steps (both a priori and a posteriori approaches, see below). The basic distinction between effect plant functional types and response plant functional types is the kind of question underlying the study. In the case of effect plant functional types, the crucial questions are ‘What is the functional role of species in ecosystems?’ (Lawton, 1994) and ‘Does a loss of biodiversity compromise ecosystem function?’ (Schulze and Mooney, 1994). These questions address the effect of various plant types on ecosystem dynamics. Circumstantial evidence is accumulating that supports the occurrence of biotic control of ecosystem and landscape processes (Schulze and Mooney, 1994; Mooney *et al.*, 1996; Chapin *et al.*, 1997), but this concept remains the focus of considerable debate. Examples of classification systems based on effect plant functional types are much less common than those based on response plant functional types, although the work of Grime (1977) and Leps *et al.* (1982) are early examples of the incorporation of ecosystem effects into functional classifications of plants. Subsequent reference to plant functional types will cover both response plant functional types and effect plant functional types unless specified otherwise.

Approaches for Identifying Plant Functional Types

A priori and a posteriori approaches

The application of the plant functional type approach to range management and vegetation assessment obviously requires identification of meaningful plant functional types. Two main approaches exist for their development: (i) define plant functional types before the study is carried out (a priori approach); and (ii) identify plant functional types based on the selection of multiple plant traits at the end of the study (multivariate or a posteriori approach).

Most plant functional type classifications have been determined a priori by selecting a single criterion to define types prior to data collection (e.g. bud position, C_3 or C_4 photosynthetic pathway, grasses or forbs, geophytes, therophytes, or hemicryptophytes). In contrast, a posteriori approaches have become increasingly common in recent years. This approach is based on the identification of multiple traits of numerous species and the important plant traits for developing plant functional types are defined a posteriori, following analysis of these multiple traits. The strength of the a posteriori approach is that it attempts to establish, through statistical correlation, actual links between a putative trait and its functional role in the ecosystem. This approach provides a means for rigorously testing functional classifications.

Several research groups in different parts of the world have taken the a posteriori approach, building extensive databases and defining plant functional types and ‘best’ traits (e.g. Montalvo *et al.*, 1991; Díaz *et al.*, 1992; Leishman and Westoby, 1992; Chapin *et al.*, 1996; Díaz and Cabido, 1997; Grime *et al.*, 1997; Reich *et al.*, 1997; Wardle *et al.*, 1998; Lavorel *et al.*, 1999). These studies vary in scale from very detailed (e.g. Díaz *et al.*, 1992; Boutin and Keddy, 1993; Golluscio and Sala, 1993) to very coarse (e.g. Chapin *et al.*, 1996; Díaz and Cabido, 1997), and from responses mostly to climate (e.g. Chapin *et al.*, 1996; Díaz and Cabido, 1997; Reich *et al.*, 1997), to resource availability *in situ* (e.g. Golluscio and Sala, 1993; Grime *et al.*, 1997), or to disturbance (Montalvo *et al.*, 1991; McIntyre *et al.*, 1995; Lavorel *et al.*, 1999).

Typically, in the a posteriori approach, numerous traits are initially considered but only a few of them prove useful in defining the main trends of variation among species. Those traits prove to be good candidates for further investigation. In general, vegetative traits (e.g. canopy height, specific leaf area, leaf and plant longevity, position of dormant buds) tend to define clearer groups than regeneration traits (e.g. seed size, dispersal mode, pollination mode, flowering phenology), and the two groups of traits are not consistently related. *It is frequently observed that fundamental plant traits do not vary independently, but rather they tend to be associated in consistent patterns of specialization, or plant syndromes* (see Landsberg *et al.*, 1999, for an exception). This suggests that there are physiological trade-offs between major processes including growth rate, herbivore defence and resource storage that plants are unable to overcome (e.g. Grime, 1977; Chapin, 1980; Coley, 1983). Plants are also assumed to make trade-offs between abundant resources to effectively acquire scarce resources to promote growth and survival (Chapin, 1980). The existence of recurrent sets of highly correlated traits has some practical implications. If these associations among traits can be proven consistent, it would not be necessary to measure all traits in order to identify plant syndromes and develop plant functional types. However, considerable work is still required to be able to confidently predict trait correlations (syndromes) in an unstudied vegetation type.

Selection of important plant traits

The initial selection of plant traits to be considered in a functional type analysis represents a critical step in the search for functional types. Evaluation of the maximum number of variables has not proven to be a good approach because it often results in extensive species lists that make this task operationally unfeasible and/or economically prohibitive for most research groups. The introduction of numerous variables that are strongly correlated (e.g. individual plant biomass and plant height) may lead to severe distortion in the multivariate analysis. Therefore, *a relatively small number of traits is required for a plant* *functional type methodology that will be adopted by a large number of researchers and that will be sufficiently robust for global comparisons. These traits must meet the following criteria: (i) ecologically relevant with respect to the processes and scale of interest (e.g. climate, soil quality, grazing, fire); (ii) feasibility for rapid and standardized measurement in various regions and vegetation types; and (iii) the procedures must be cost-effective.*

Ideally, the list of plant traits to be evaluated to identify plant functional types would be attained by a general consensus among research groups. *A standardized approach would facilitate global comparisons and increase the potential for identification of general patterns of vegetation responses.* Complete consensus regarding key traits and specific protocols to measure them is unlikely, nor is it totally desirable, as continued exploration of new traits will build our knowledge. Nevertheless, there have been several new contributions to the issue of trait selection, notably Westoby's (1998) leaf–height–seed (LHS) scheme and Hodgson *et al.*'s (1999) operational definition of Grime's CSR scheme. A further contribution to the issue of trait selection was achieved in 1998, as part of GCTE Task 2.2.1, when a diverse group of scientists agreed on a core list of traits considered to be of general importance in the identification of plant functional types (Weiher *et al.*, 1999; Table 7.1). It is important to stress, however, that even a core list of traits will require further refinement in order to usefully describe specific ecological variables (e.g. see grazing-related core traits, McIntyre *et al.*, 1999) or environments. For example, plant phenology can show considerable inter-annual variation in arid

Table 7.1. The common core traits proposed by Weiher *et al.* (1999).

Trait	Function
Seed weight	Dispersal distance, longevity in seed bank, establishment success, fecundity
Seed shape	Longevity in seed bank
Method of seed dispersal	Dispersal distance, longevity in seed bank
Vegetative growth	Space acquisition
Specific leaf area, leaf water content	RGR, plasticity, stress tolerance, evergreenness, leaf longevity
Height	Competitive ability
Above-ground biomass	Competitive ability, fecundity
Life history	Plant longevity, space-holding ability, disturbance tolerance
Onset of flowering	Stress avoidance, disturbance avoidance
Ability to resprout after a disturbance	Disturbance tolerance
Density of wood	Plant longevity, carbon storage

environments that limits its diagnostic value in these regions and C_3 versus C_4 metabolism may not be a useful trait in temperate-cool regions, but it may be a key trait for modelling large-scale data sets.

Calibration between 'soft' and 'hard' traits

As discussed above, there is a strong case for the adoption of easily measured structural–functional traits, such as those proposed by Box (1996) or Díaz and Cabido (1997). This is a legitimate approach in its own right. However, its strength would be substantially increased if the 'soft' (i.e. easily measured) traits could be calibrated against 'hard' traits that have a direct and well-established relationship to ecosystem function (e.g. decomposition rate, nutrient content) but evaluating them is often time-consuming. The process of calibration between 'soft' and 'hard' traits is in the early stages of development in most regions of the world, although some promising results have recently emerged. For instance, Díaz *et al.* (1999b) showed a significant association between the 'soft' traits of specific leaf area and leaf toughness and the 'hard' traits of leaf N content, palatability for invertebrate herbivores and decomposition rate, over a very wide spectrum of plant families and growth forms. This process of calibration among traits may substantially enhance the applicability of plant functional types to various management applications by making the process more cost-effective.

Plant Functional Response Types: Climate and Disturbance History

Although the concept of response plant functional types is intuitively appealing, and they have been sought since the earliest days of ecology, it is still difficult to predict what response plant functional types will predominate under different frequencies and/or intensities of disturbance, such as grazing, fire or flooding. For example, the presence of aerenchyma in roots and of a persistent seed bank seem important traits in defining response plant functional types in areas with seasonal droughts and floods; the presence of thick bark, lignotubers and serotinous seeds seem important in fire-prone areas; and leaf toughness and nutrient content, architectural plasticity and bud position seem important in some areas chronically subjected to grazing. As documented by Noy-Meir and Sternberg (1999), even two disturbances which involve removal of above-ground biomass, such as grazing and fire, are associated with different sets of plant traits in the same geographical area.

An added level of complexity in trying to identify key plant traits associated with disturbance response is the consideration of disturbance history. The predominant plant groups or plant traits which appear under different grazing intensities, for example, seem to depend strongly on a combination of climate and evolutionary history of herbivory (Milchunas *et al.*, 1988; Milchunas and Lauenroth, 1993; Díaz *et al.*, 1999a). Different plant traits can predominate in areas with the same annual precipitation and livestock density, depending on whether grazing has been a strong selective pressure over evolutionary time or not. For example, heavy grazing is associated with high abundance of annual species in many regions. In the Eastern Mediterranean, however, heavy grazing promotes geophytes and legumes (Hadar *et al.*, 1999). Annuals do not substantially increase, since they represent most of the biomass in both grazed and ungrazed sites in this region, which has a very long evolutionary history of grazing (Perevolotsky and Seligman, 1998).

In summary, the question of 'What plant traits or types predominate under different grazing regimes?' does not have a straightforward answer. Most of the published evidence is related to very specific cases, is at the species level, and is scattered in the ecological, agronomic and phytosociological literature. At present, and before a more comprehensive framework is developed, the traits and response plant functional types likely to predominate in the face of different land-management situations are likely to be strongly site-specific, as illustrated in the next section.

Plant Functional Response Types in Grazed Systems

The application of response plant functional types to describe vegetation responses to grazing for application in range management and grassland agriculture is not a novel concept. The most recognized and most widely applied response plant functional type for grazing application is the concept of increaser and decreaser species associated with range condition and trend analysis (Dyksterhuis, 1949). A closely associated response plant functional type classification is based on the distinction among grass growth forms including short, mid and tall grasses (Arnold, 1955). These response plant functional types were initially based on empirical data, but specific plant traits were subsequently associated with species responses to grazing (Hendon and Briske, 1997; Briske, 1999). In fact, it is often assumed that grazing resistance is based on the occurrence of a relatively small number of traits, or even a single trait, associated with the developmental morphology or physiological function of individual species (Simms, 1992).

These response plant functional types have provided a large amount of valuable information concerning the relative responsiveness of plants to grazing. Several plant traits, including the location and availability of meristems, architectural attributes influencing palatability and residual leaf area following defoliation, have proved especially important to our understanding of grazing resistance in plants (Briske and Richards, 1995). However, an increasing number of cases exist where grazing resistance has not been effectively explained by the presence or absence of specific plant traits (e.g. Hendon and Briske, 1997). Although both traditional response plant functional type systems mentioned above are still used to various degrees, it has become clear that the plant traits traditionally associated with grazing resistance are not always sufficient to predict or interpret species responses to grazing (Noy-Meir and Sternberg, 1999). The limitations encountered by these traditional response plant functional types can be organized into three general categories: (i) the existence of multiple categories of resistance traits; (ii) the occurrence of trade-offs among categories of resistance traits; and (iii) the disproportionate expression of categories of resistance traits at various ecological scales (Briske, 1999).

Multiple categories of resistance

It has previously been emphasized that plant adaptation to stress and disturbance often involves the evolution of multiple traits (Grime, 1977). Similarly, recognition of several strategies of resistance to grazing demonstrates that more than a single trait is involved in determining the grazing resistance of plants (Simms, 1992; Briske, 1996). Inordinate emphasis on a small number of specific plant traits may have inadvertently diverted attention from the identification and interpretation of more pervasive strategies of grazing resistance.

Temporal variation displayed by various resistance traits further challenges the development of effective response plant functional types to evaluate plant responses to grazing. The dynamic expression of morphological and physiological traits, including canopy architecture, various inducible defences and compensatory physiological processes, has been documented within and between species (Briske and Richards, 1995; Briske, 1996). Species with a high degree of phenotypic plasticity may even shift the expression of grazing resistance from a tolerance to an avoidance strategy with an increasing intensity of grazing (Hodgkinson *et al.*, 1989). In other cases, traits may be difficult to recognize because they represent more of a life history expression than a distinct morphological or physiological trait. This is clearly illustrated by the ‘phenological trait’ associated with the extended display of green biomass by perennial grasses to annual grasses in Mediterranean grasslands (Noy-Meir and Sternberg, 1999). Examples of the dynamic expression of various resistance traits indicate that grazing resistance does not represent a static value that can invariably be assigned to individual species in all situations.

Effective interspecific comparisons of grazing resistance are constrained by our inability to incorporate multiple resistance traits into a standardized expression applicable to various growth forms, life history strategies and phenological stages. Grazing tolerance is by definition based on the rate or magnitude of biomass production following defoliation (Rosenthal and Kotanen, 1994; Briske, 1996). However, insight necessary to prioritize or weight the various traits and processes associated with growth following defoliation, including leaf and shoot number, canopy height and volume, biomass partitioning to various organs and reproductive effort, is very limited. *A limited understanding of the relative importance of specific plant traits has impeded the development of a comprehensive interpretation of grazing resistance in plants.*

Trade-offs among resistance categories

The expression of grazing resistance by plants can be divided into tolerance and avoidance strategies (Rosenthal and Kotanen, 1994; Briske, 1996). The tolerance strategy promotes rapid leaf replacement following defoliation while the avoidance strategy minimizes the frequency and intensity of grazing. Although both strategies contribute to grazing resistance, the specific traits involved are very likely unique to a particular strategy (Westoby, 1999). Tolerance is associated with traits that contribute to rapid leaf replacement following defoliation while avoidance is associated with traits that defend plants from grazing. An attempt to identify traits without recognition of the unique strategy involved would very likely produce inconsistent results as the absolute expression of tolerance and avoidance varies among species (Westoby, 1999). For example, decreaser species may rely on tolerance mechanisms for grazing resistance to a greater extent than increaser species because tolerance traits are closely correlated with the competitor strategy of the first group (Briske, 1996). In contrast, large investments in grazing avoidance may divert resources from growth and potentially reduce the expression of grazing tolerance. The expression of greater tolerance by dominant compared to subordinate species can be suppressed prior to the expression of avoidance mechanisms because grazers can potentially remove biomass more rapidly than it can be replaced by tolerance mechanisms. Selective grazing of dominants compared to subordinate species would potentially shift the competitive advantage from dominants to subordinates and induce a shift in species composition.

The tolerance and avoidance strategies of grazing resistance have only recently been placed in a conceptual framework to hypothesize that the relative expression of these two strategies may determine the productivity and composition of grazed plant communities (Augustine and McNaughton, 1998). Grazing tolerance is assumed to be of equal or greater importance than grazing avoidance (i.e. selective grazing) in systems where highly palatable species retain dominance. The reverse is assumed to be the case in systems where dominants are replaced by subordinate species. Although this interpretation is highly plausible, the relative expression of grazing tolerance and avoidance has not been quantified for most species or vegetation types and the potential trade-offs between these two strategies of grazing resistance are only currently being considered (Mauricio *et al.*, 1997).

Expression of resistance at various scales

The initial response plant functional type classifications analysed in the previous section were developed in the mid-20th century, when a more reductionist view of science prevailed. *Emphasis on individual plant traits associated with grazing resistance makes is difficult to incorporate and interpret associated processes occurring at higher ecological scales* (Briske, 1999). There is increasing recognition that *individual plant responses to grazing may not directly scale up to communities or landscapes because grazing conveys indirect, as well as direct effects.* Indirect grazing effects involve both biotic and abiotic processes external to plants in contrast to the direct removal of photosynthetic and meristematic tissues (McNaughton, 1983). Important indirect effects known to mediate plant responses to grazing, include selective grazing among species (Anderson and Briske, 1995), grazing-modified competitive interactions (Caldwell *et al.*, 1987) and drought-grazing interactions (O'Connor, 1994). Indirect grazing effects may be of equal or greater importance than the direct effects of grazing in determining vegetation responses, but they are often minimized or excluded from investigations designed to assess grazing resistance based on specific plant traits.

Specific issues of temporal and spatial scale introduce additional complexity in the process of developing response plant functional types for grazing resistance. For example, grazing tolerance is often assessed by evaluating the short-term regrowth responses of plants while traits contributing to plant persistence over the long term often receive less attention. For example, rapid leaf replacement by new leaf initiation will promote tolerance, but if tiller initiation is suppressed following grazing, long-term plant persistence may be compromised. The spatial association among plants expressing various degrees of grazing avoidance may also influence the frequency and intensity of grazing at the patch scale. The protection a palatable plant derives from close association with unpalatable plants is referred to as associative defence (Hay, 1986). This may partially explain why a plant species may respond negatively to grazing in one environment, but positively in another environment. The relative expressions of grazing avoidance among various plant species may affect patterns of selective grazing without necessitating a change in the absolute expression of avoidance by individual species.

The challenges associated with the identification of response plant functional types for determining vegetation responses to grazing are great and further substantiate several cautionary considerations made previously. Response plant functional types developed for grazing will have to be regionally specific and clearly specify the ecological and managerial information to be provided and the scale at which it is to be applied. It is anticipated that the development of effect plant functional types will follow development of response plant functional types and will more effectively incorporate the indirect effects of grazing within ecosystems. *The challenges involved in selecting and interpreting plant traits associated with grazing responses must be recognized and addressed prior to the development of more effective plant functional types for grazing applications.* A synthesis of published work, considering different climates, vegetation types and evolutionary histories of grazing may represent an important step towards this goal.

Plant Functional Effect Types and Ecosystem Function

In contrast to the situation of response plant functional types and different combinations of climate, history and land use, *effect plant functional types and major ecosystem processes seem to be much more consistently linked across different ecosystem types*. Local dominance by species with specific plant traits appears to directly influence various ecosystem processes including productivity, nutrient cycling, trophic transfer, temperature buffering, flammability, etc. (Table 7.2). Sufficient evidence exists to support an evaluation, at least in comparative terms, of the magnitude, direction and rate of some ecosystem processes on the basis of the traits associated with the dominant species (see Díaz *et al.*, 1999c, for further evidence and discussion). It is important to stress, however, that links between plant traits and ecosystem function are much better understood in the case of vegetative traits (e.g. fast-growing plants with nutrient-rich leaves are associated

Table 7.2. Examples of individual plant traits that may influence processes of the community/ecosystem in which they are dominant. See Díaz *et al*. (1999c) for references and more detailed explanation.

Individual traits	Community/ecosystem processes
Relative growth rate	Productivity
Leaf turnover rate	Nutrient cycling Production efficiency
Nutrient content	Nutrient cycling Carrying capacity for herbivores
Biomass	Flammability
Life span	Resistance
Canopy structure	Water interception and runoff Temperature buffering Soil stability
Secondary growth	Carbon sequestration
Root architecture	Water uptake
Reserve organs	Resilience
Pollination mode	Expansion over landscape
Persistent seed bank	Resilience
Seed number	Expansion over landscape
Dispersal mode	Expansion over landscape
Presence of root symbionts (e.g. mycorrhizae)	Nutrient cycling Rate of succession

with high decomposition rate and high productivity at the ecosystem level) than in the case of regenerative traits (such as phenology or pollination and seed dispersal modes).

It has been recognized that the amount of plant biomass, regardless of species composition, has a strong influence on ecosystem function. However, it appears that species richness confers resilience to plant communities (Landsberg, 1999; Walker *et al.*, 1999). Therefore, effect plant functional types defined on the basis of biomass production may contain a wide range of species that are capable of maintaining similar productivity. This is based on the concept of functional redundancy (Walker *et al.*, 1999) which implies that members of the same effect plant functional type can perform similar ecosystem functions. Consequently, *species may replace each other to varying degrees without a loss of ecosystem function because functionally equivalent species represent a greater range of ecological tolerances to buffer environmental changes.*

Once the main response plant functional types have been identified for a region, it should be possible to translate them into effect plant functional types to analyse the consequences of dominance by specific plant groups for at least the most obvious ecosystem processes and services. These may include the magnitude and seasonality of biomass production, carrying capacity for livestock and wildlife, flammability, water retention and soil protection. The number of species within each effect plant functional type should provide an indication of the resilience of the ecosystem processes as previously indicated. Therefore, the degree of species and trait specificity required in plant functional types is dependent upon the ecological and managerial information sought. If the focus is on present-day ecosystem performance, an evaluation of only the main dominants (e.g. those with > 10% cover) should be sufficient. However, if ecosystem resilience to various disturbance regimes is being evaluated over the long term, species richness within plant functional types would become highly relevant and an evaluation of the entire local flora may be appropriate.

Resolution of Plant Functional Types: Regional vs. Global Classifications

The existence of consistent plant specialization patterns and trade-offs between plant processes does not necessarily mean that we should seek a single plant functional type system that would be appropriate for all applications and scales (Gitay and Noble, 1997; Lavorel *et al.*, 1997; Lavorel and McIntyre, 1999). On the other hand, the utility of developing numerous specific-purpose functional type schemes has not been demonstrated either (Westoby, 1999). Applications concerning plant responses to general climatic conditions or resource availability would likely be best served by general allocation models with a small set of extreme types (e.g. Grime, 1977; Chapin, 1980). This approach may also represent the appropriate resolution required for development of various global vegetation models aimed at predicting vegetation responses to global change at a continental scale. On the other hand, that approach would be too coarse for local and regional management and conservation planning. In these cases, much more detailed plant functional types are required and they must be based on traits specifically tailored to the local environment and land-use considerations. In summary, *a nested hierarchy of plant functional types seems to be the most reasonable answer, since the challenges to be faced are multi-scale*. As recently pointed out by Grime (1998), *a small set of very general plant functional types, based in trade-off models, appears to be more appropriate to the prediction of vegetation processes at the global and trans-regional levels, whereas a much higher number of more precise plant functional types seems most useful for land-use planning at the regional to local levels.*

The Relevance of Plant Functional Types to Rangeland Management

The process of identifying plant functional types appears to be a highly academic exercise. It is reasonable then to ask whether they have any real relevance to rangeland management and managers. In so far as all effective communications require a simplification of complex information, we know that we need to identify plant functional types. We still have to identify useful groups. Questions such as 'Which biological features favour and which features disadvantage plants under grazing?' or, 'What are the main factors that determine the promotion of different plant traits by grazing?' are fundamental for appropriate management and conservation, as well as for the progress of range science, and have never been answered at a global scale. The plant functional type approach is arguably the only way forward to address these kinds of questions.

The relevance of plant functional types to rangeland ecology and management is clearly illustrated by previous attempts to develop these classifications and their continued use given the recognition that their application may not be appropriate in some cases, e.g. increaser/decreaser species. *The relevance of plant functional types resides in the need to integrate and generalize site-specific information to broader scales for management applications.* Provided that management questions are clearly defined in the context of a specific region, it should be relatively straightforward to identify general response plant functional types using key plant traits. *The plant functional type approach may prove to be most useful in rangeland planning and management at regional scales.* Specifically, it may provide greater insight into issues of vegetation response and their potential impacts on ecosystem function.

The major application of plant functional types at regional scales will be for monitoring ecosystem structure and function to evaluate ecological impacts and determine appropriate management responses. A simple example is the use of perennial tussock grasses as a response plant functional type relating to grazing in tropical grasslands and a effect plant functional type in terms of the capacity of perennial grasses to contribute to soil health and soil and water capture (Tongway and Hindley, 1995). This application is relevant to both land management agencies and producer groups.

Land managers may utilize plant functional types as both indicators of vegetation change associated with management activities and environmental changes as well as indicators of the sustainability of rangeland ecosystems. A potentially powerful aspect of plant functional types is that they do not require that land managers acquire in-depth taxonomic knowledge of the flora in a region, but rather rely on critical information associated with unique plant groups that may be intuitively simple to assess (e.g. stoloniferous, low-growing, early flowering). This information is more likely to be accessible to range managers and communities with a limited technical base. In some situations, local communities already have an intuitive, but sometimes surprisingly precise, knowledge of the biological traits possessed by different plants. An important future development will be to link plant functional types with important ecosystem functions to more effectively monitor rangelands and assess land-use and climate change on rangeland sustainability.

Rangeland monitoring, assessment and policy development on a continental scale will also require simplified models of vegetation change, and major efforts to identify plant functional types have been associated with global-scale modelling (Smith *et al.*, 1997). *Identification of appropriate plant functional types provides an essential underpinning of the knowledge relevant to national and international planning and policy-making.*

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Progress and Prospects

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